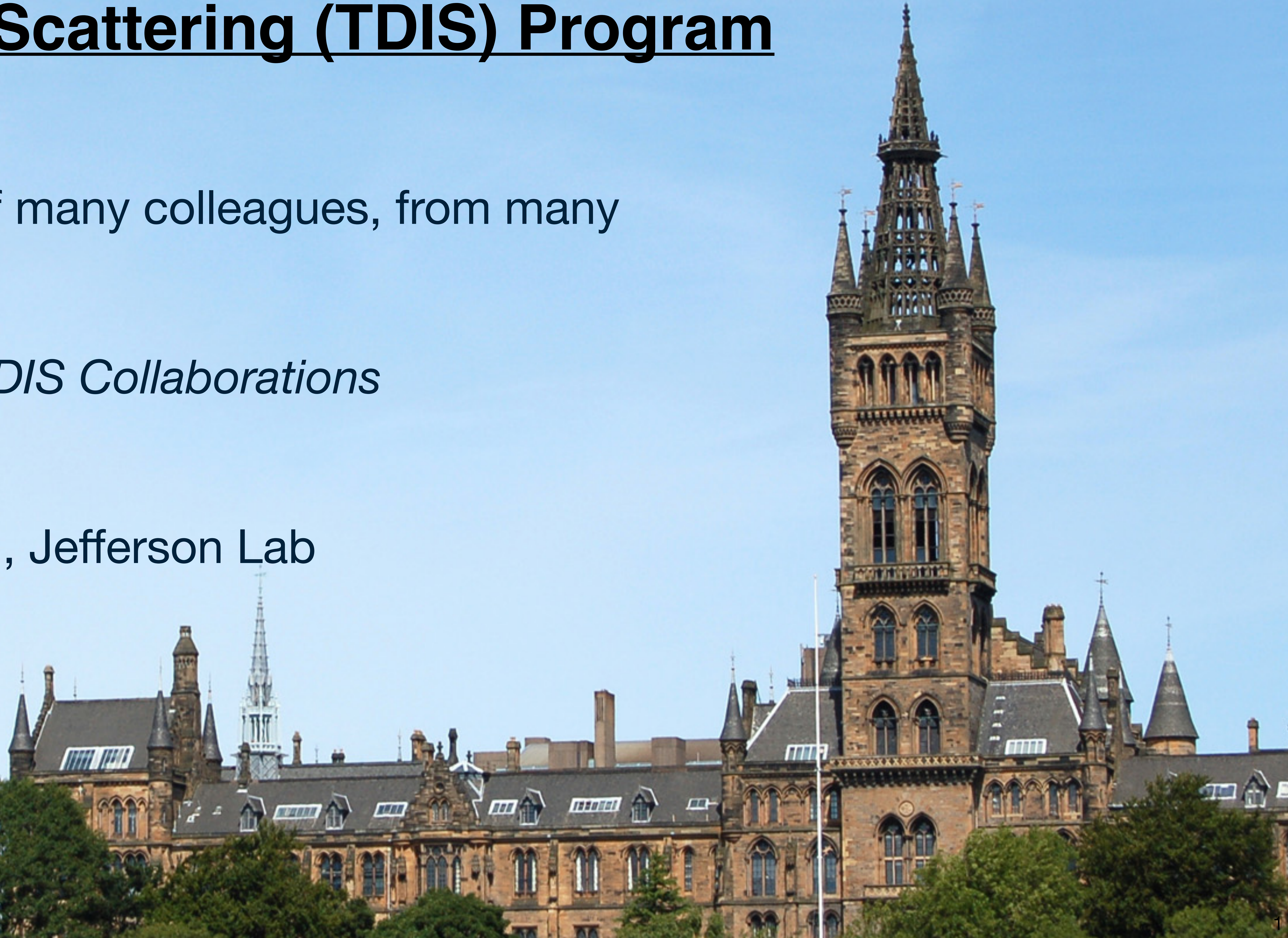
University of Glasgow

Tagged Deep Inelastic Scattering (TDIS) Program

Rachel Montgomery on behalf of many colleagues, from many institutions and within:

Jefferson Lab *Hall A, SBS and TDIS Collaborations*

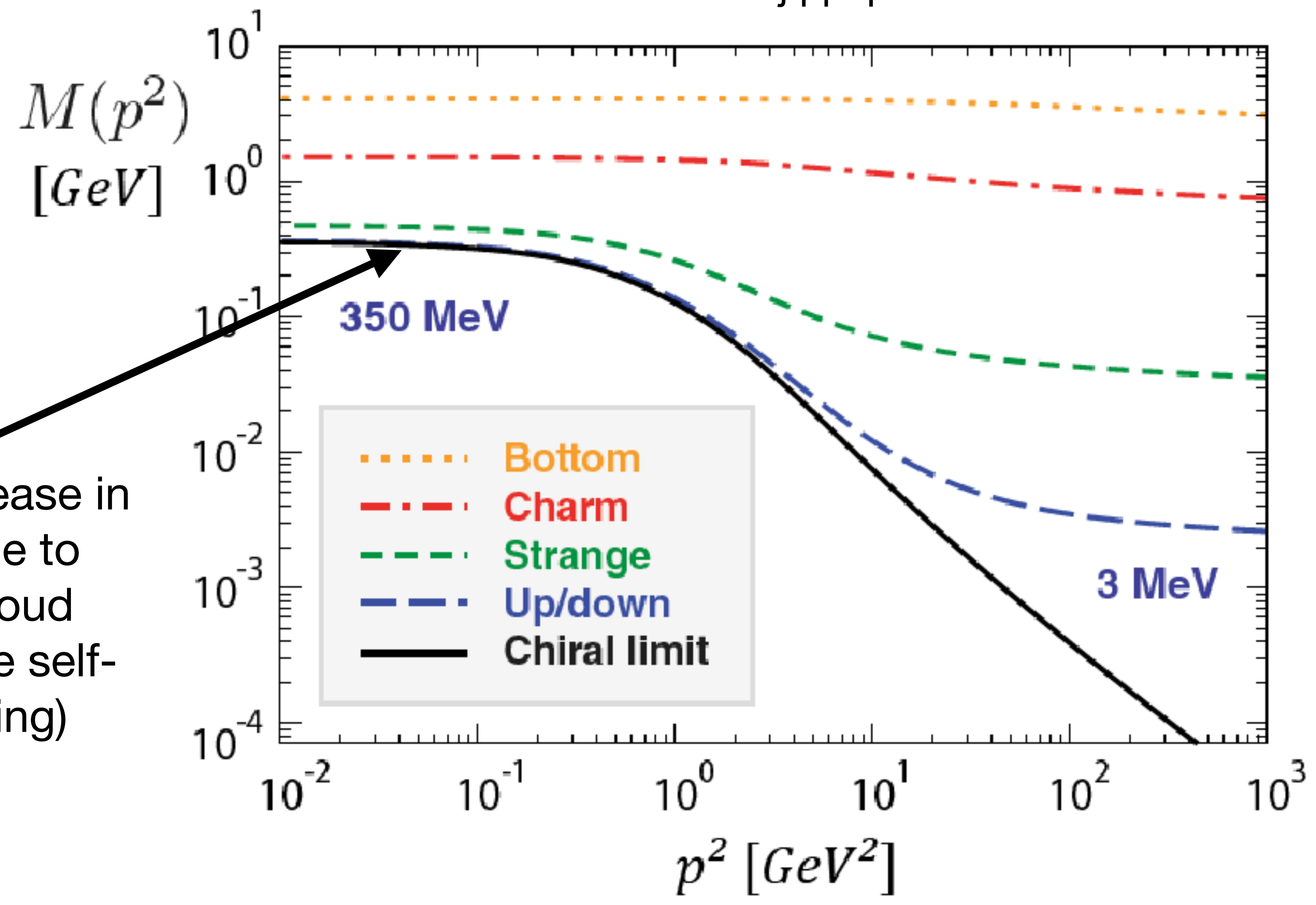
2024 SBS Collaboration Meeting, Jefferson Lab
13/09/24



Emergent Hadronic Mass (EHM)

C.D. Roberts et al.
DOI: 10.1016/j.ppnp.2021.103883

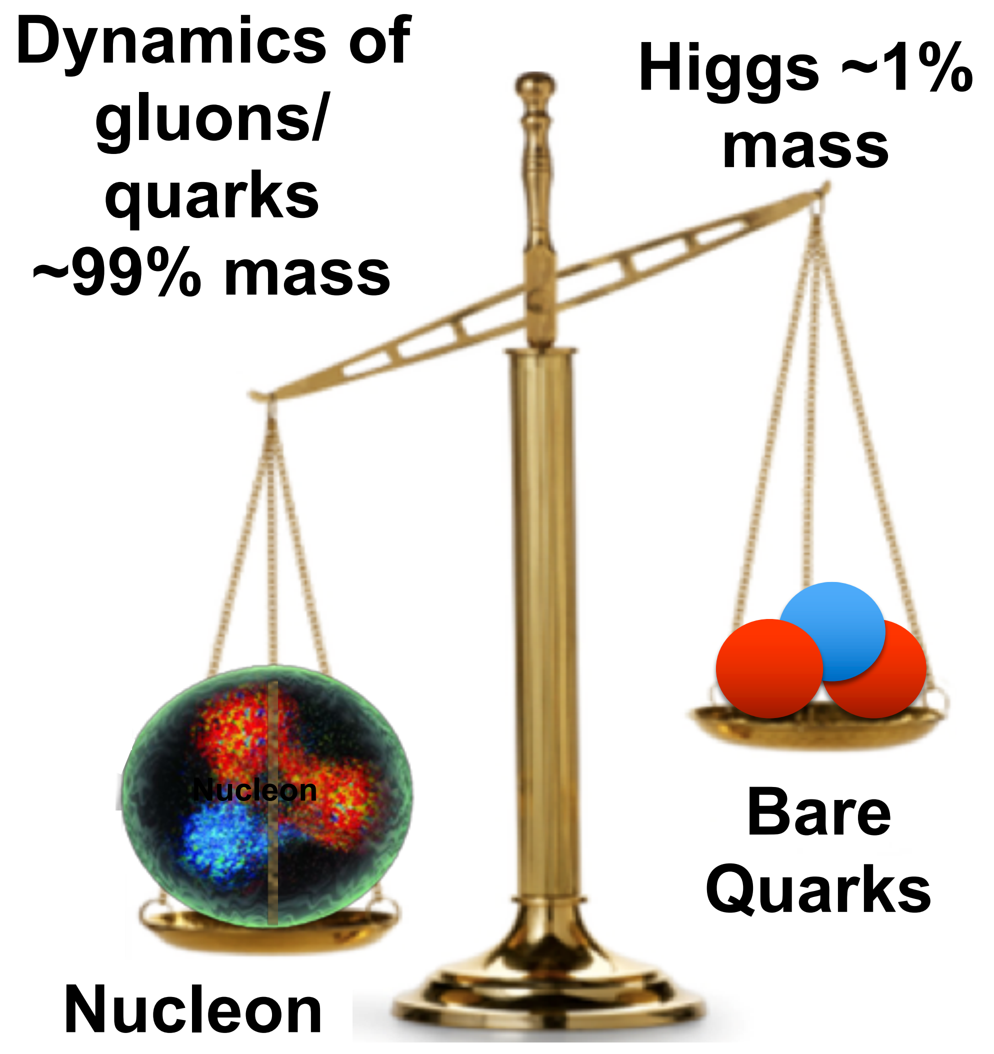
Rapid increase in mass due to gluon cloud (gluons are self-interacting)

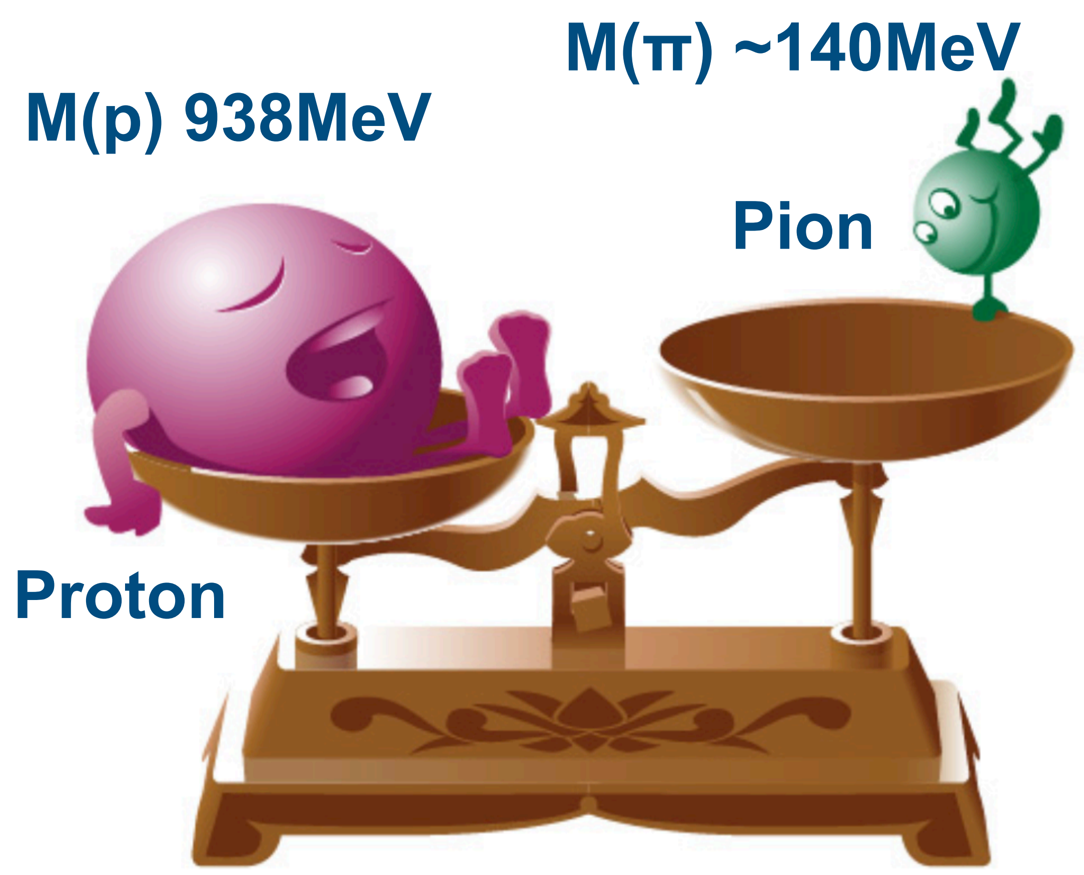


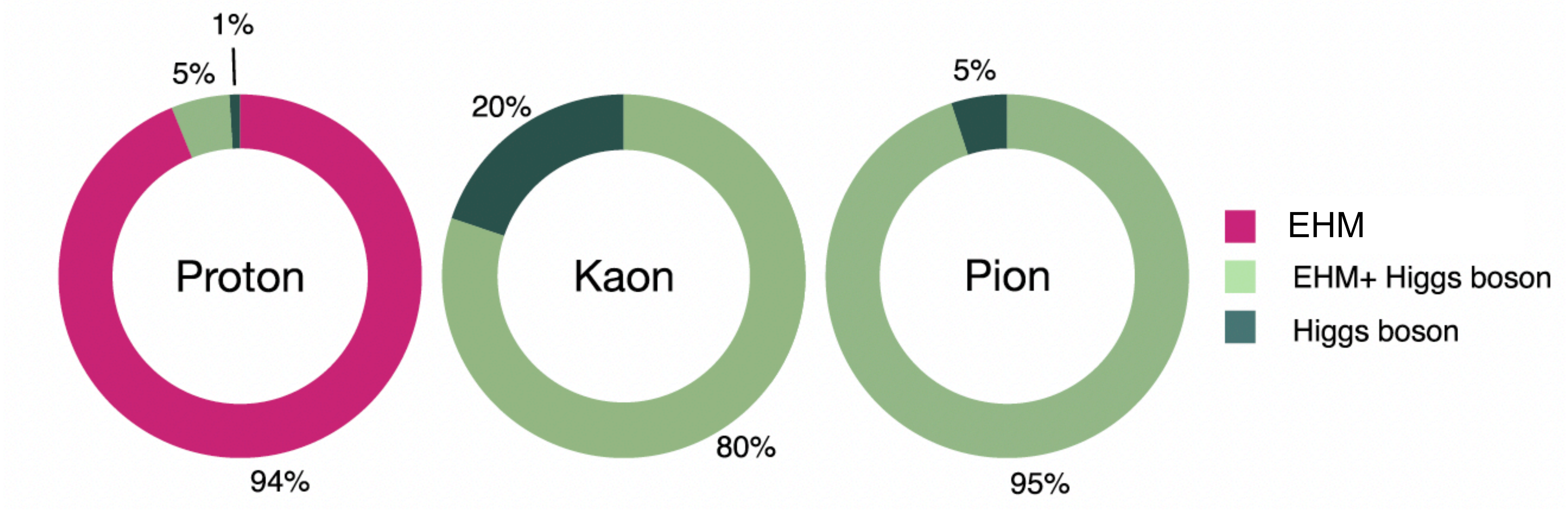
- *Numerous* motivations to study light π/K meson structure
- Critically, TDIS will offer unique information for unravelling nucleon mass enigma

- Dynamics of strong interaction in QCD → ~99% nucleon mass
- π/K are Nambu-Goldstone bosons on QCD
- Theoretical mass budgets for π/K different from nucleon and each other
- Different gluon contents?

- Comparing distributions of light quarks versus strange quarks within mesons → measurable signals of EHM → TDIS



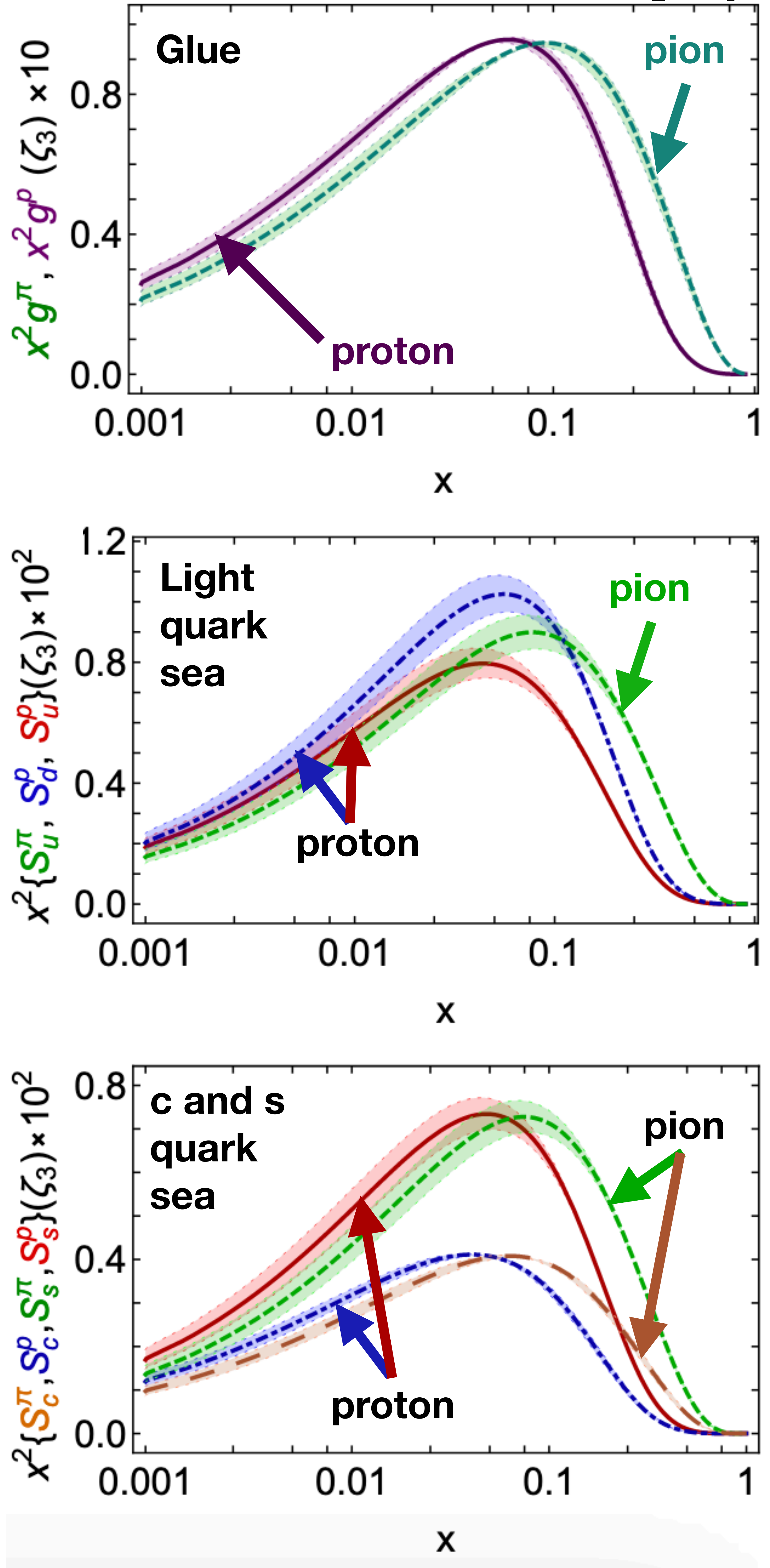


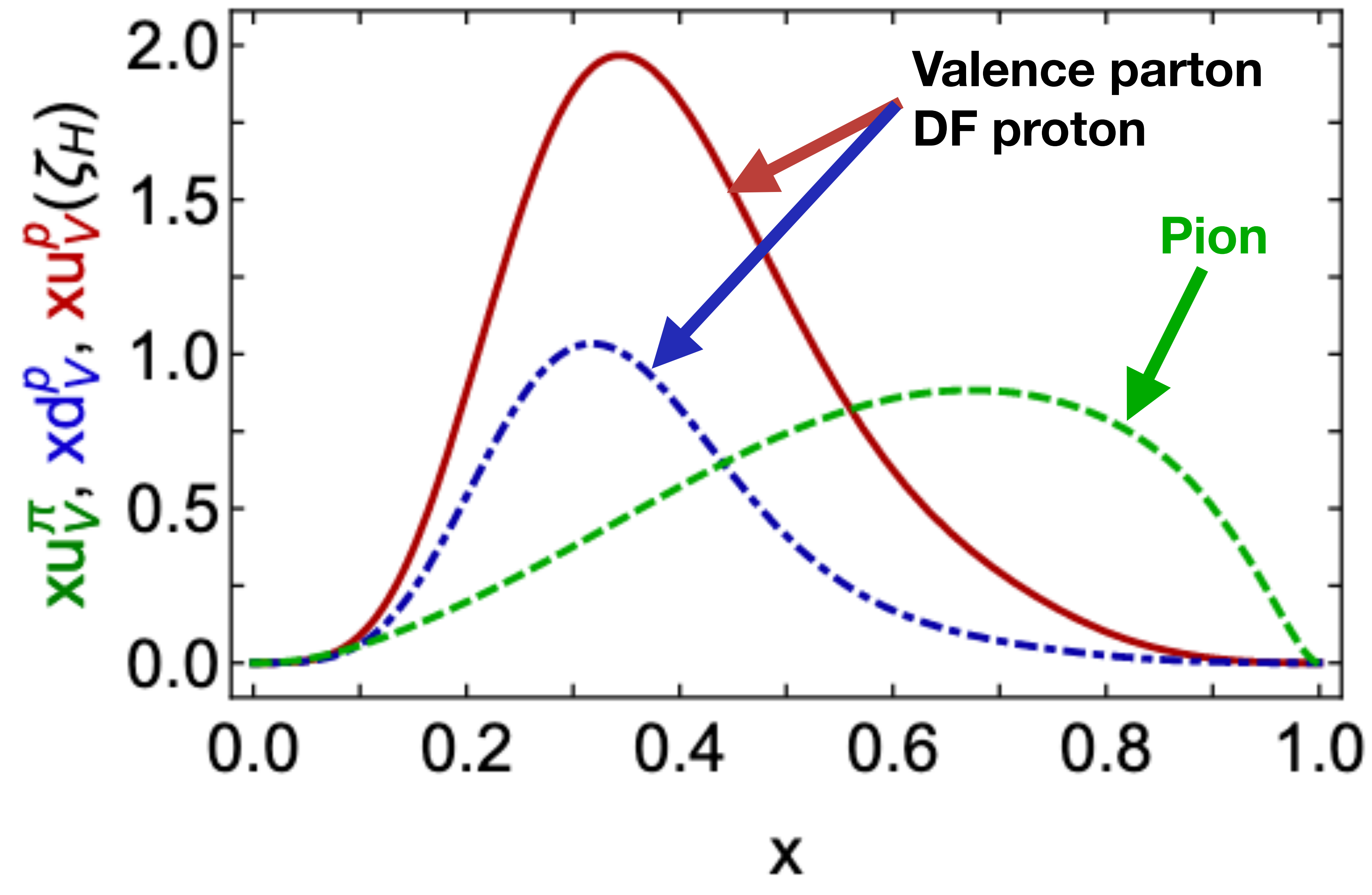


D. Binosi, DOI: 10.1007/s00601-022-01740-6

Pion vs Proton Valence PDF

A **From arxiv: 2203.00753 [hep-ph]**





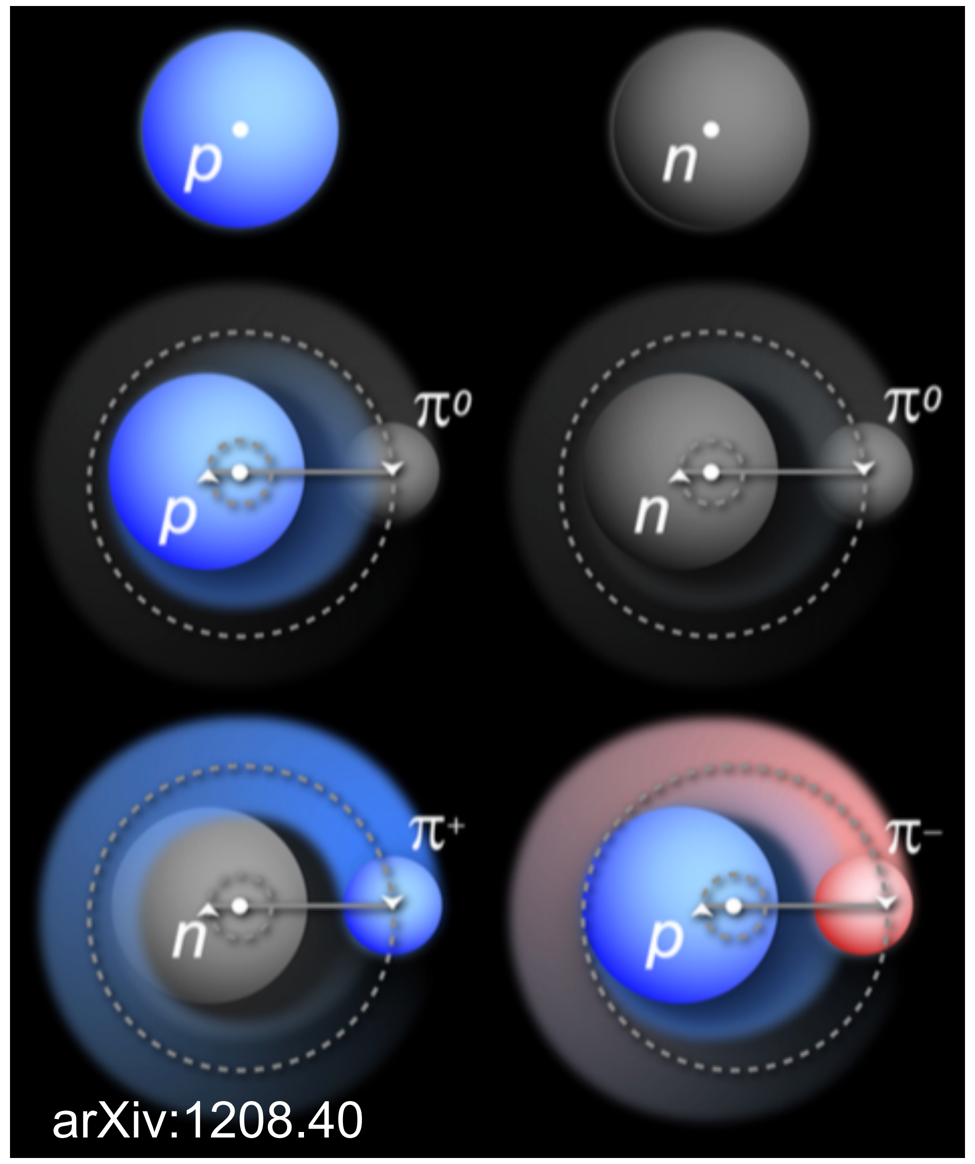
Continuum Schwinger function methods (DSE)

Ya Lu, Lei Chang, Khépani Raya, Craig Roberts, José Rodriguez-Quintero, 2203.00753 [hep-ph], Phys Lett B 830 (2022) 137130/1-7

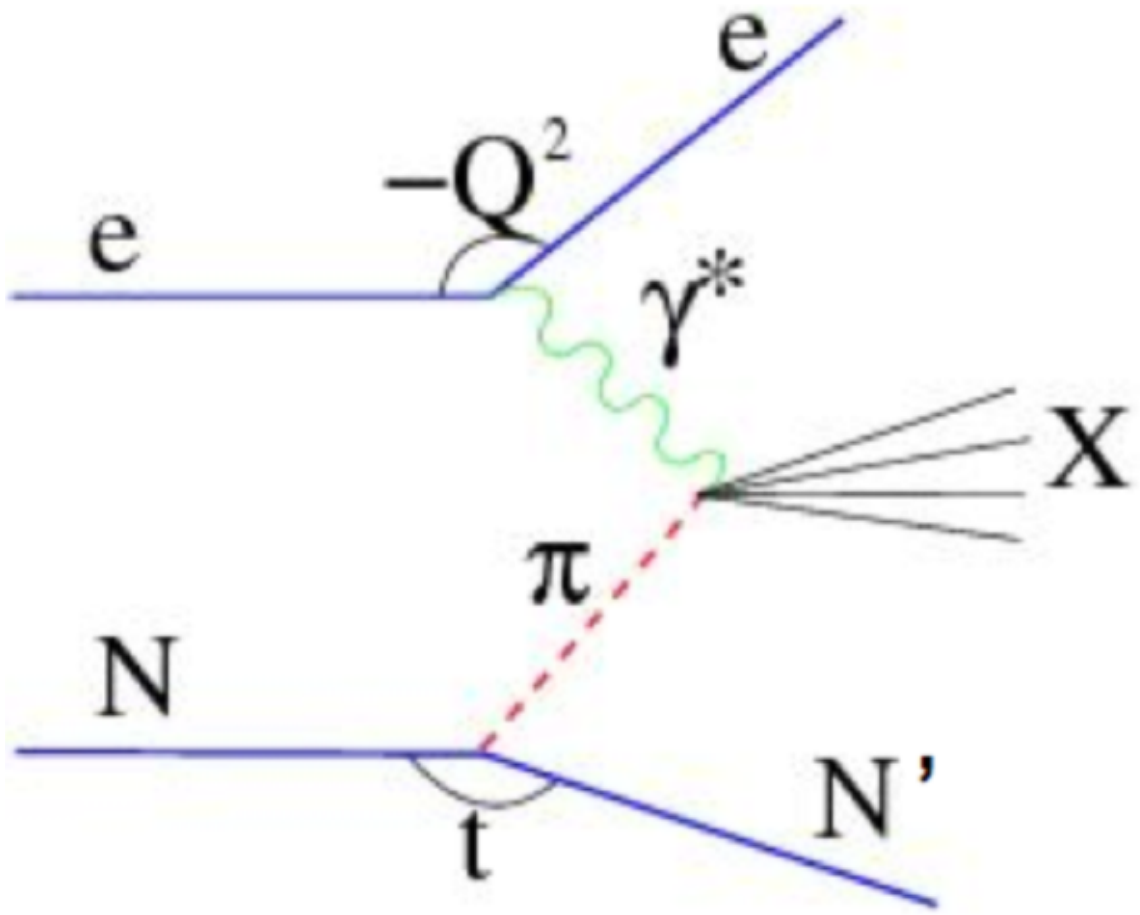
- EHM → interesting differences between pion/proton valence PDF
- π/K structure not well known experimentally - new data vital to help explain EHM
- JLab TDIS anticipated in community
- Significant number of recent publications advocating for new tagged meson SF measurements
  - e.g. as of last year >50 publications with >1200 citations (including 2023 LRP white paper and EIC YR)

Accessing Pions/Kaons?

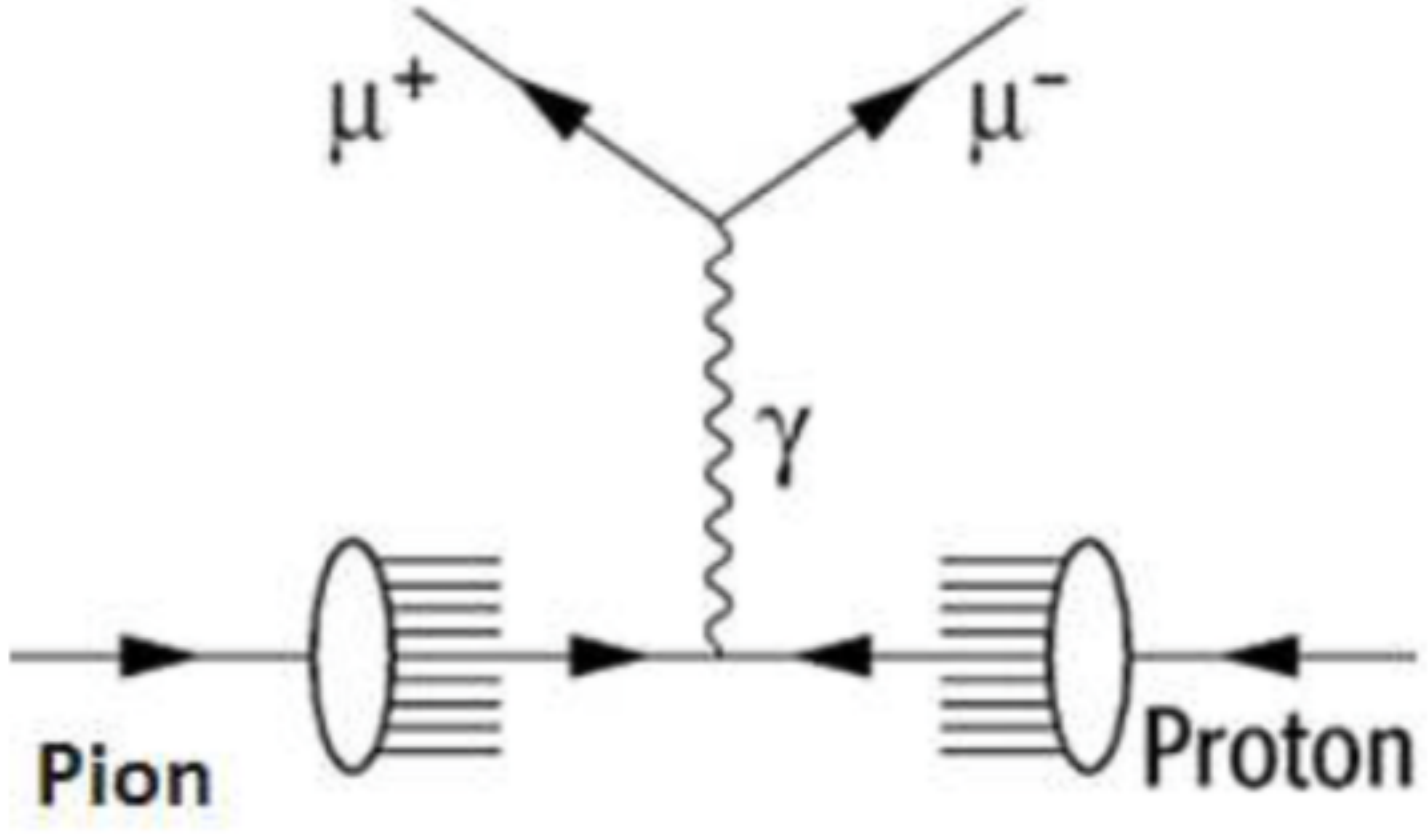
Sullivan Process



Hard scattering from virtual meson cloud of nucleon



Drell-Yan

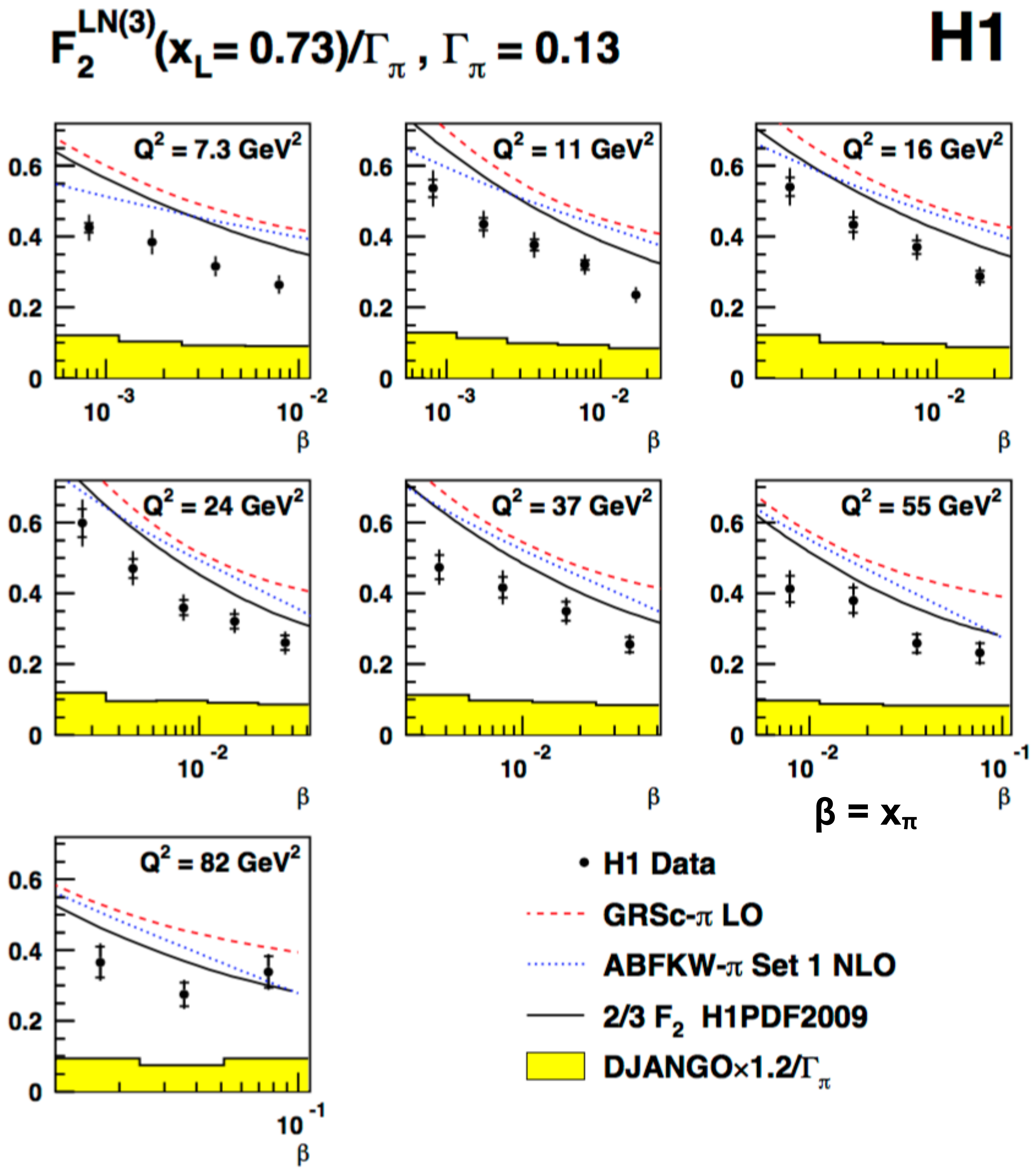


- TDIS
  - DIS with spectator tagging
  - Well established technique (e.g. BoNUS)
  - Effective free targets not readily found in nature
- Aims:
  - Directly tag elusive mesonic content of nucleon
  - Pion and kaon F_2 structure functions (SF) in valence regime

Inclusive DIS cross-section

$$\frac{d^2\sigma}{d\Omega dE'} = \frac{\alpha^2}{4E_0^2 \sin^4\frac{\theta}{2}} \cos^2\frac{\theta}{2}\left[\frac{1}{\nu}F_2(x,Q^2) + \frac{2}{M}F_1(x,Q^2)\tan^2\frac{\theta}{2}\right]$$

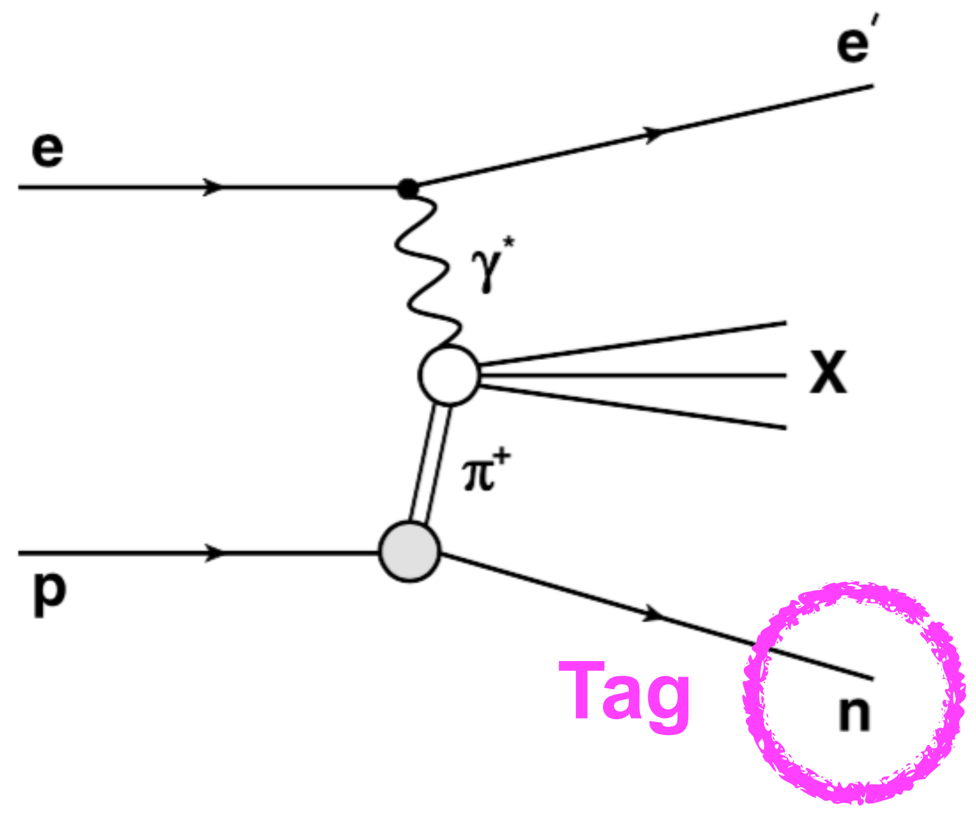
Sullivan Process has been Demonstrated



Eur. Phys. J. C (2010) 68: 381-399

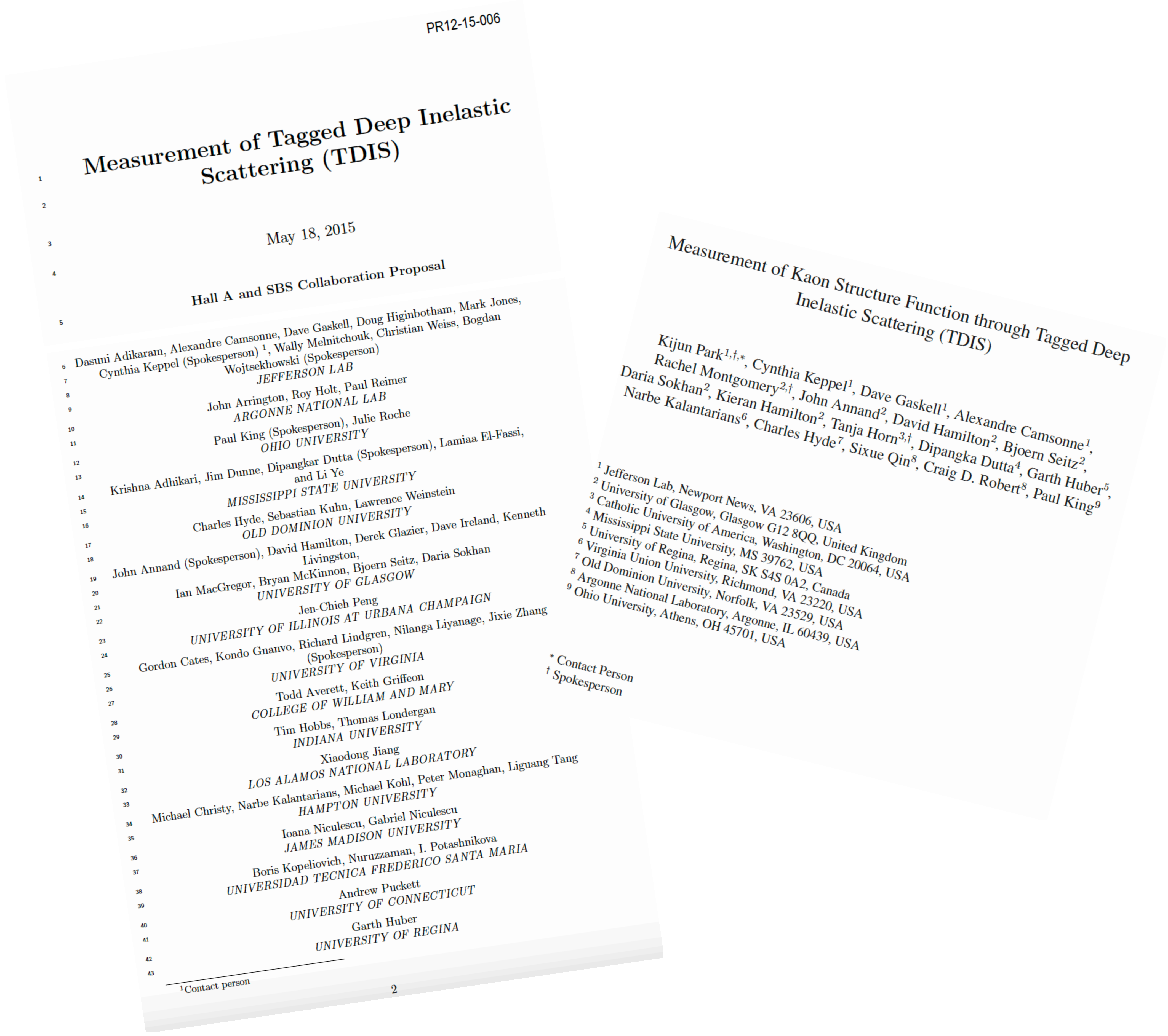
- •HERA tagged DIS
- Leading neutron tagged in ep → e'Xn
- Pion sea region, very low x and high Q^2
- Charged pion SF extracted

Diffractive scattering and forward detectors



- •TDIS: Valence regime - higher x, lower Q^2
- Evolution between kinematics

TDIS Program


PR12-15-006

Measurement of Tagged Deep Inelastic Scattering (TDIS)

May 18, 2015

Hall A and SBS Collaboration Proposal

Dasuni Adikaram, Alexandre Camsonne, Dave Gaskell, Doug Higinbotham, Mark Jones, Cynthia Keppel (Spokesperson) [1], Wally Melnitchouk, Christian Weiss, Bogdan Wojtsekhowski (Spokesperson)
JEFFERSON LAB
John Arrington, Roy Holt, Paul Reimer
ARGONNE NATIONAL LAB
Paul King (Spokesperson), Julie Roche
OHIO UNIVERSITY
Krishna Adhikari, Jim Dunne, Dipangkar Dutta (Spokesperson), Lamiaa El-Fassi, and Li Ye
MISSISSIPPI STATE UNIVERSITY
Charles Hyde, Sebastian Kuhn, Lawrence Weinstein
OLD DOMINION UNIVERSITY
John Annand (Spokesperson), David Hamilton, Derek Glazier, Dave Ireland, Kenneth Livingston,
Ian MacGregor, Bryan McKinnon, Bjoern Seitz, Daria Sokhan
UNIVERSITY OF GLASGOW
Jen-Chieh Peng
UNIVERSITY OF ILLINOIS AT URBANA CHAMPAIGN
Gordon Cates, Kondo Gnanvo, Richard Lindgren, Nilanga Liyanage, Jixie Zhang (Spokesperson)
UNIVERSITY OF VIRGINIA
Todd Averett, Keith Griffeon
COLLEGE OF WILLIAM AND MARY
Tim Hobbs, Thomas Londergan
INDIANA UNIVERSITY
Xiaodong Jiang
LOS ALAMOS NATIONAL LABORATORY
Michael Christy, Narbe Kalantarians, Michael Kohl, Peter Monaghan, Liguang Tang
HAMPTON UNIVERSITY
Ioana Niculescu, Gabriel Niculescu
JAMES MADISON UNIVERSITY
Boris Kopeliovich, Nuruzzaman, I. Potashnikova
UNIVERSIDAD TECNICA FREDERICO SANTA MARIA
Andrew Puckett
UNIVERSITY OF CONNECTICUT
Garth Huber
UNIVERSITY OF REGINA

[1] Contact person

2

Measurement of Kaon Structure Function through Tagged Deep Inelastic Scattering (TDIS)

Kijun Park[1,†,*], Cynthia Keppel[1], Dave Gaskell[1], Alexandre Camsonne[1], Rachel Montgomery[2,†], John Annand[2], David Hamilton[2], Bjoern Seitz[2], Daria Sokhan[2], Kieran Hamilton[2], Tanja Horn[3,†], Dipangka Dutta[4], Garth Huber[5], Narbe Kalantarians[6], Charles Hyde[7], Sixue Qin[8], Craig D. Robert[8], Paul King[9]

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[9] Ohio University, Athens, OH 45701, USA

* Contact Person
† Spokesperson

Pion TDIS

- C12-15-006, PAC43 approved
- C1 → subject to technical review
- A- rating - exciting physics: first time pion Sullivan process with both proton/neutron targets to extract charged and neutral pion SF

Kaon TDIS

- Run group C12-15-006A, PAC45 approved
- First Sullivan process extraction of kaon SF

nTDIS

- Run Group C12-15-006B, PAC49 approved
- Neutron SF, plus other topics
- See back up slide if interested

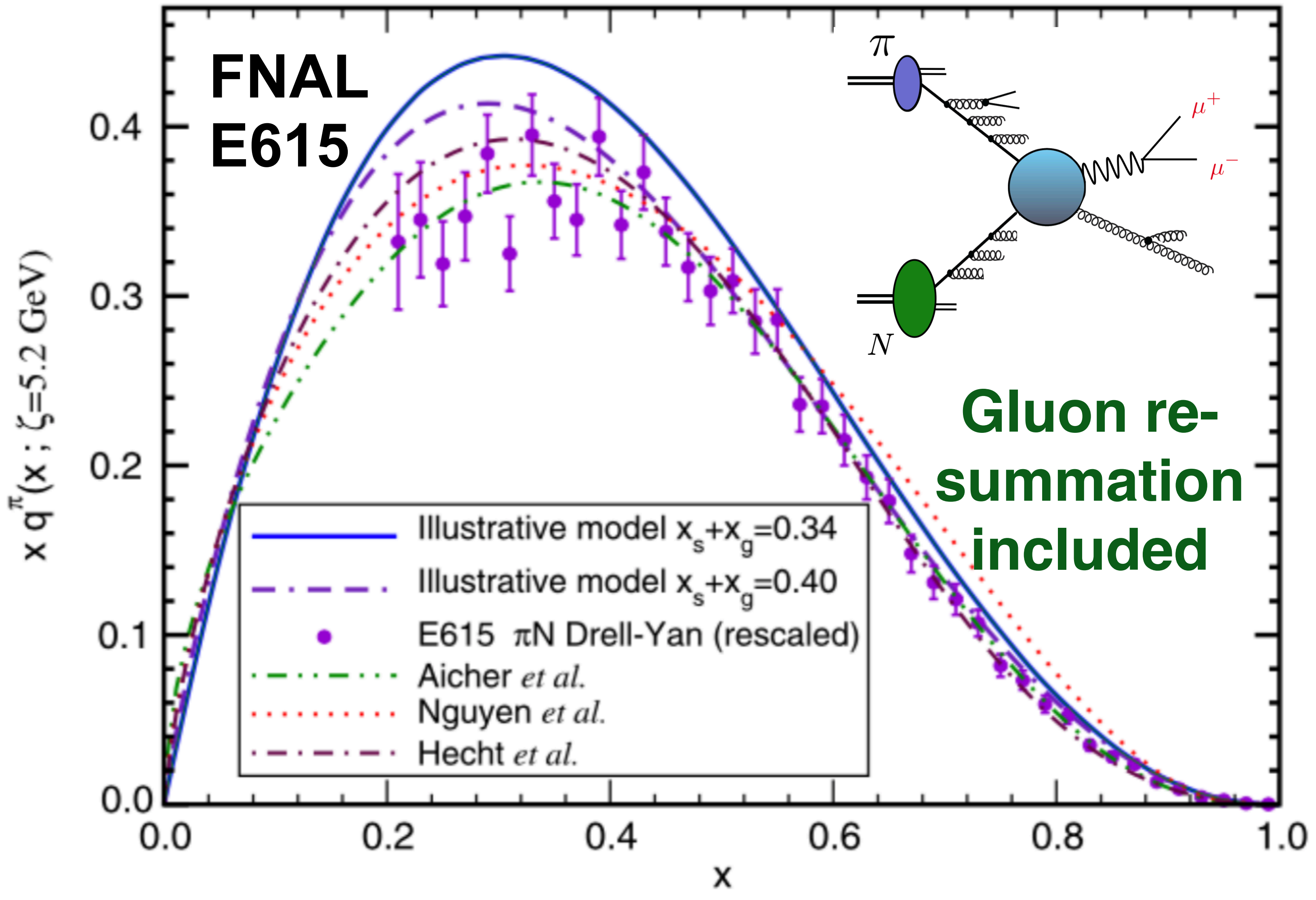
TDIS C12-15-006 passed jeopardy July 2023 (PAC51)

Summary: The physics case for measuring meson structure in TDIS is strong, and there is substantial community interest in this topic. The PAC also recognizes that substantial progress has been made towards the TDIS detector design. This commendably includes the adoption of a full GEANT4-based simulation including digitization, development of multiple prototypes, planning of test beam data to vet technical design choices, and incorporation of lessons learned from the experience of other experiments. The PAC encourages the proponents to finalize work towards a technical review of their final detector design to remove the C1 condition.

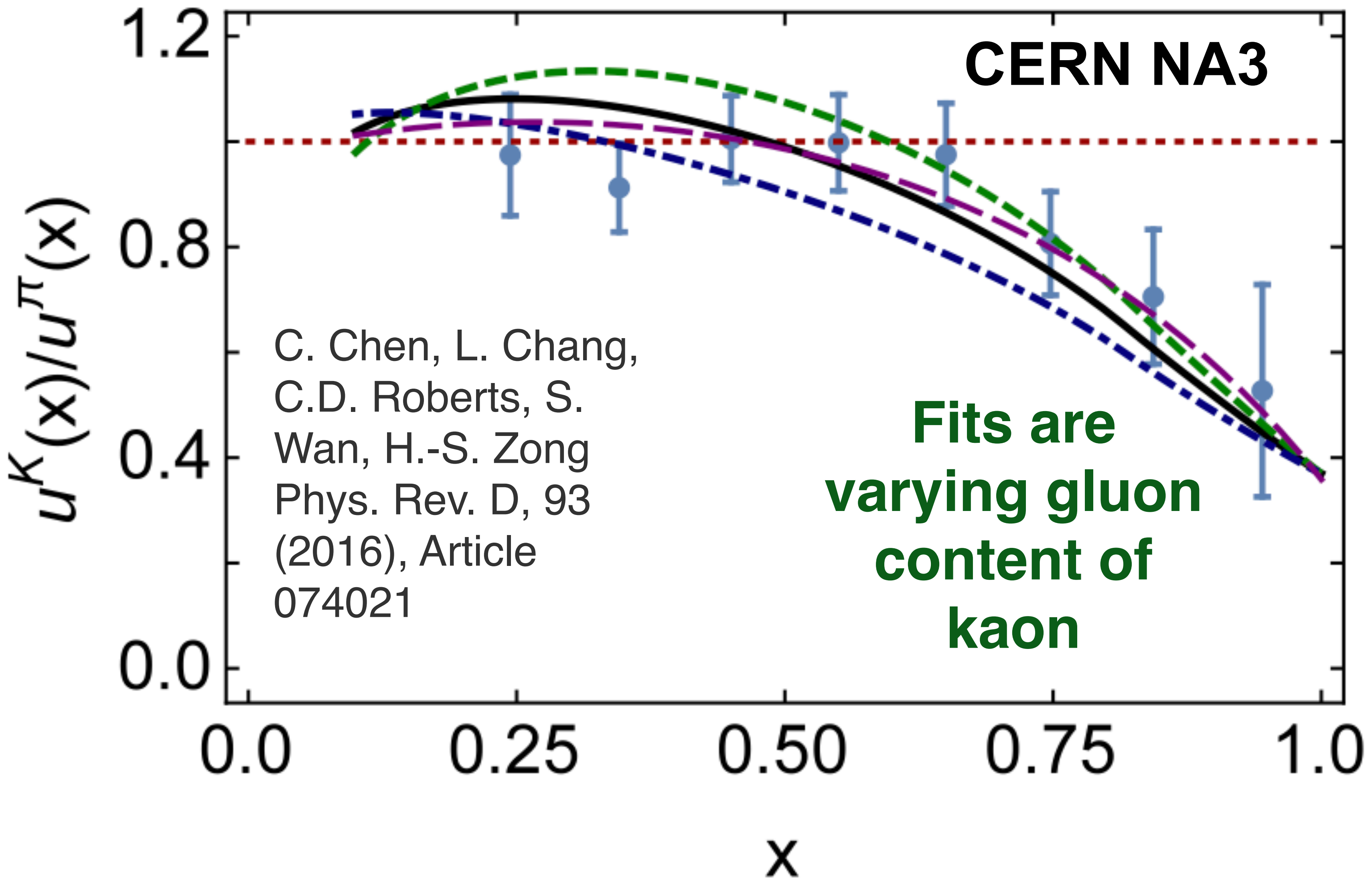
Where will TDIS lie amongst existing data?

Pion valence quark distribution function

L. Chang et al., Physics Letters B 737 (2014) 23–29

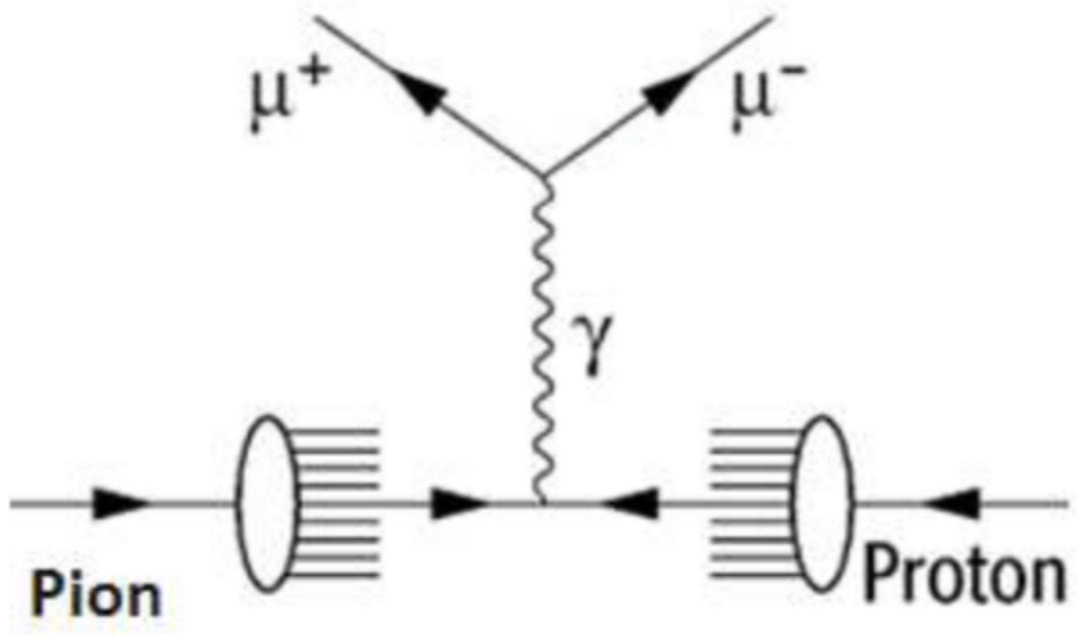


Ratio K/pi u-quark distributions



Valence region - Drell Yan

- Limited CERN/Fermilab data



- Large-x interesting - substantial theory
  - pQCD, DSE, light-front, …, NLO, gluon re-summation

- Practically non-existent data for kaon

TDIS

- *Direct* probe
- Independent cross-check
  - gluon re-summation, and PDF universality
- Extend to neutral pions - check for isospin dependence

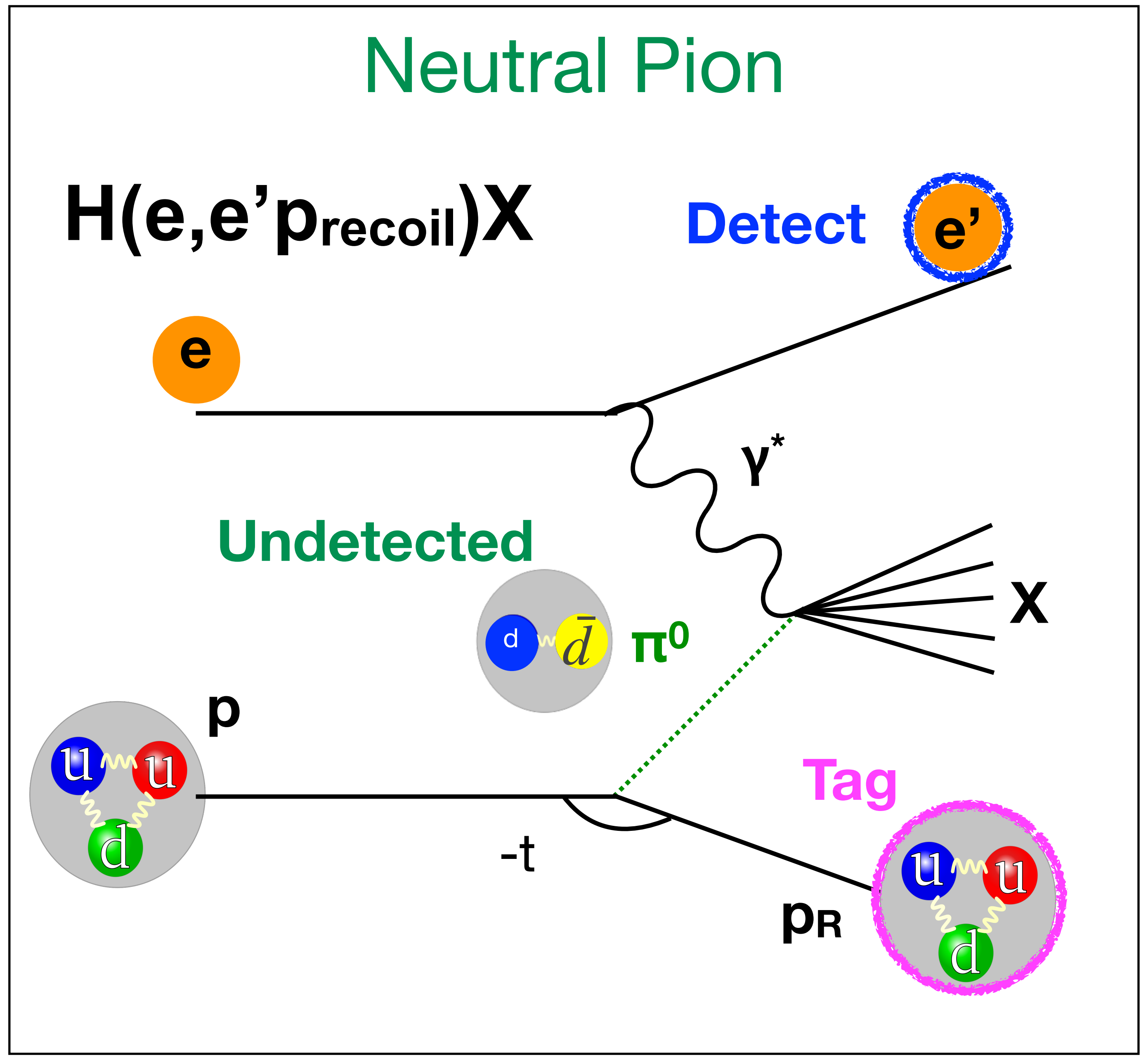
- More data essential to reduce uncertainties in global PDF

TDIS Measurements - Unique to JLab

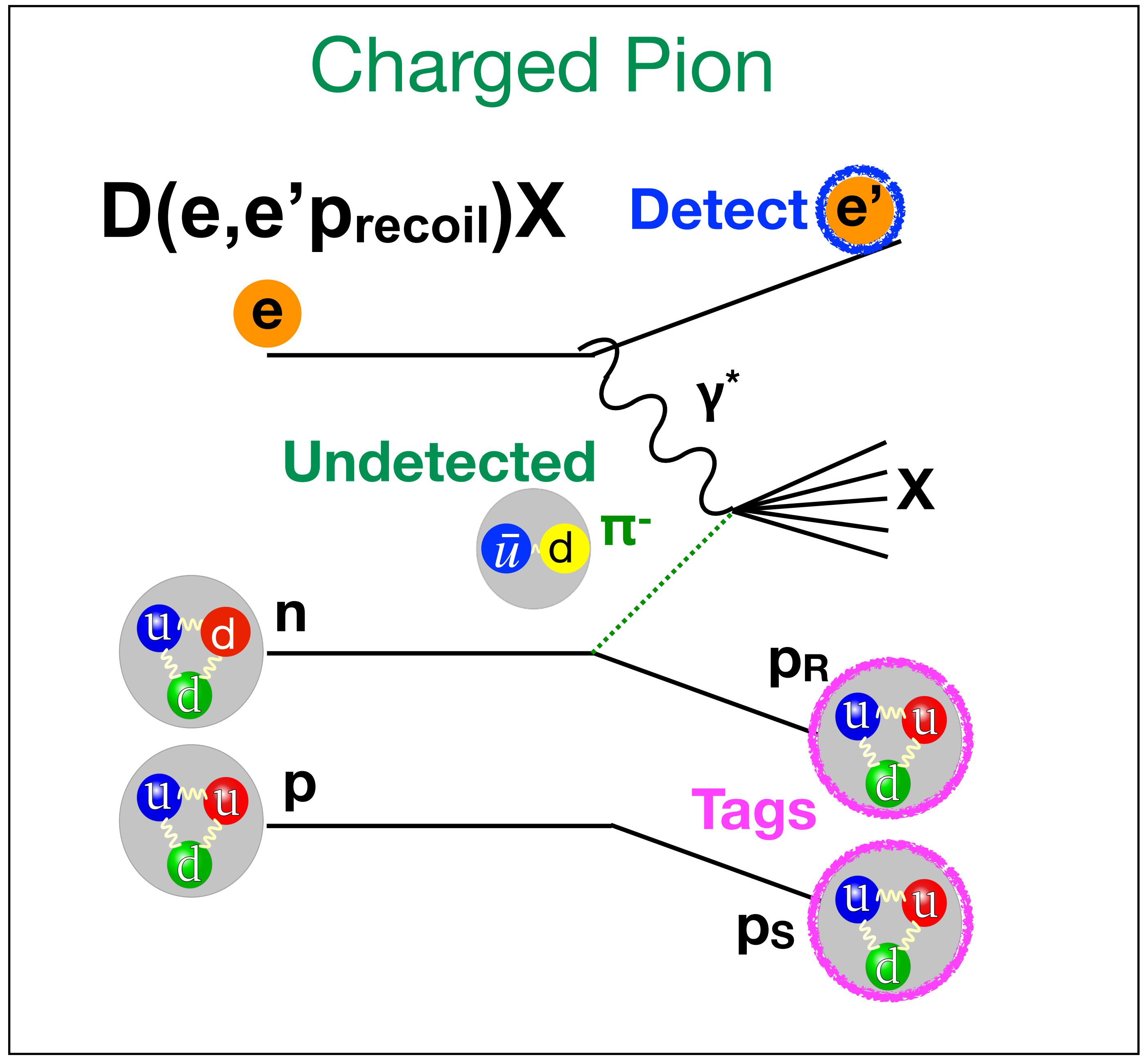
$8 < W^2 < 18$ GeV^2
$1 < Q^2 < 3$ GeV^2
$0.05 < x < 0.2$

Need small -t to extrapolate to pion pole

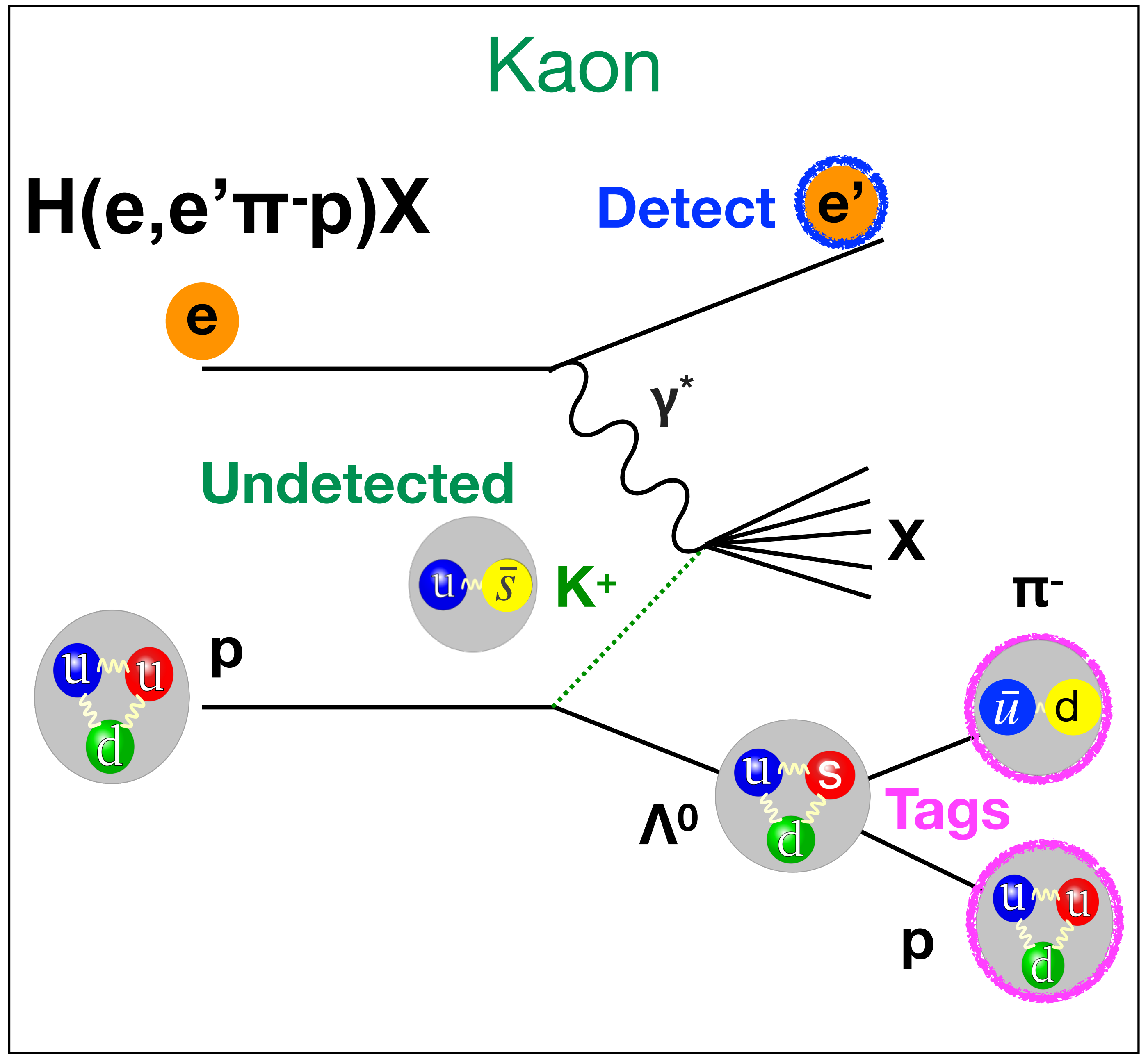
Very low momentum recoiling hadrons (60 - 400 MeV/c)



Independent Check, add to sparse data



Expected world first



Expected world first

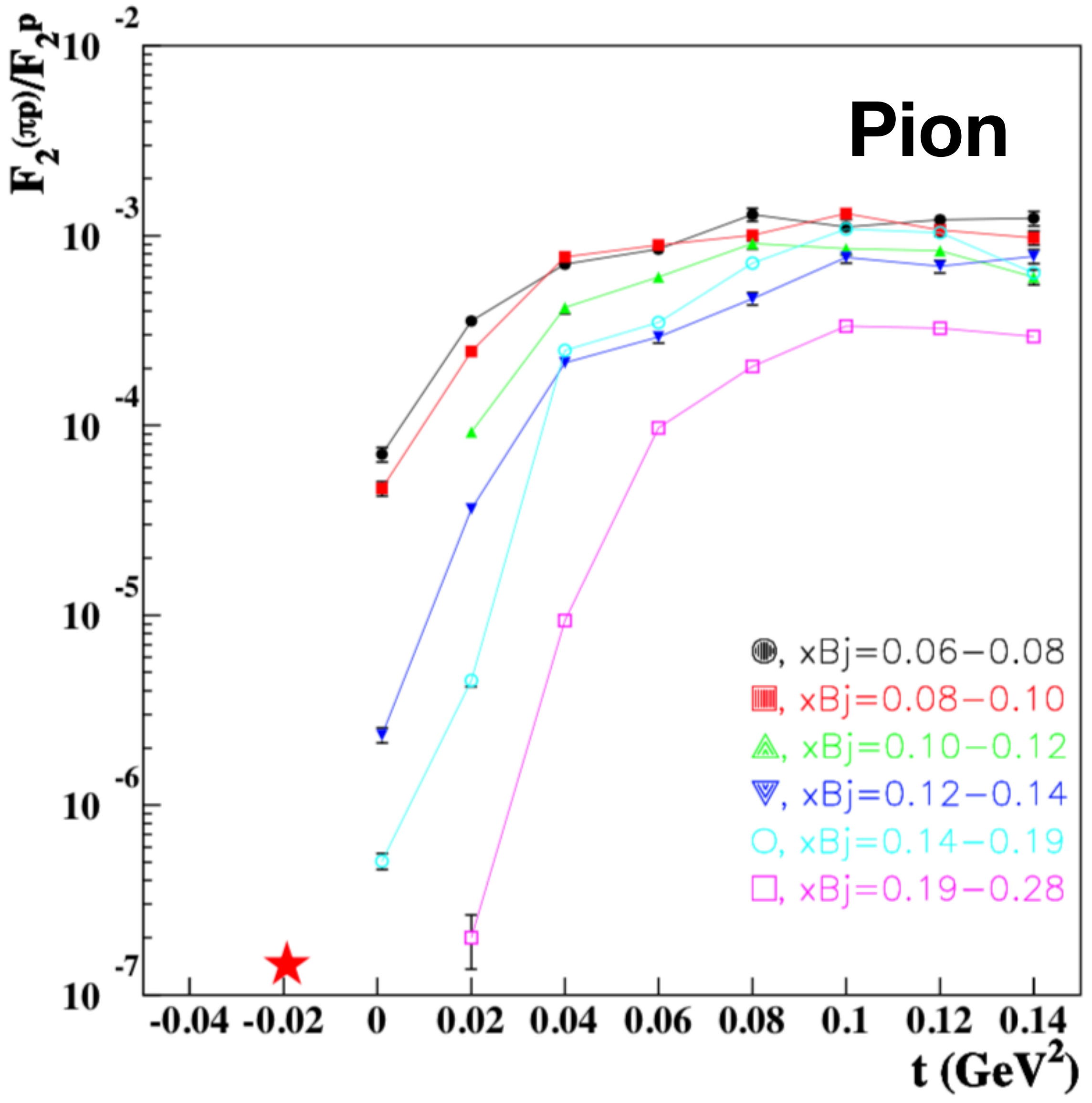
$$R^T = \frac{d^4\sigma(ep \to e'Xp')}{dxdQ^2dzdt} \Big/ \frac{d^2\sigma(ep \to e'X)}{dxdQ^2} \Delta z \Delta t \sim \frac{F_2^T(x,Q^2,z,t)}{F_2^p(x,Q^2)} \Delta z \Delta t$$

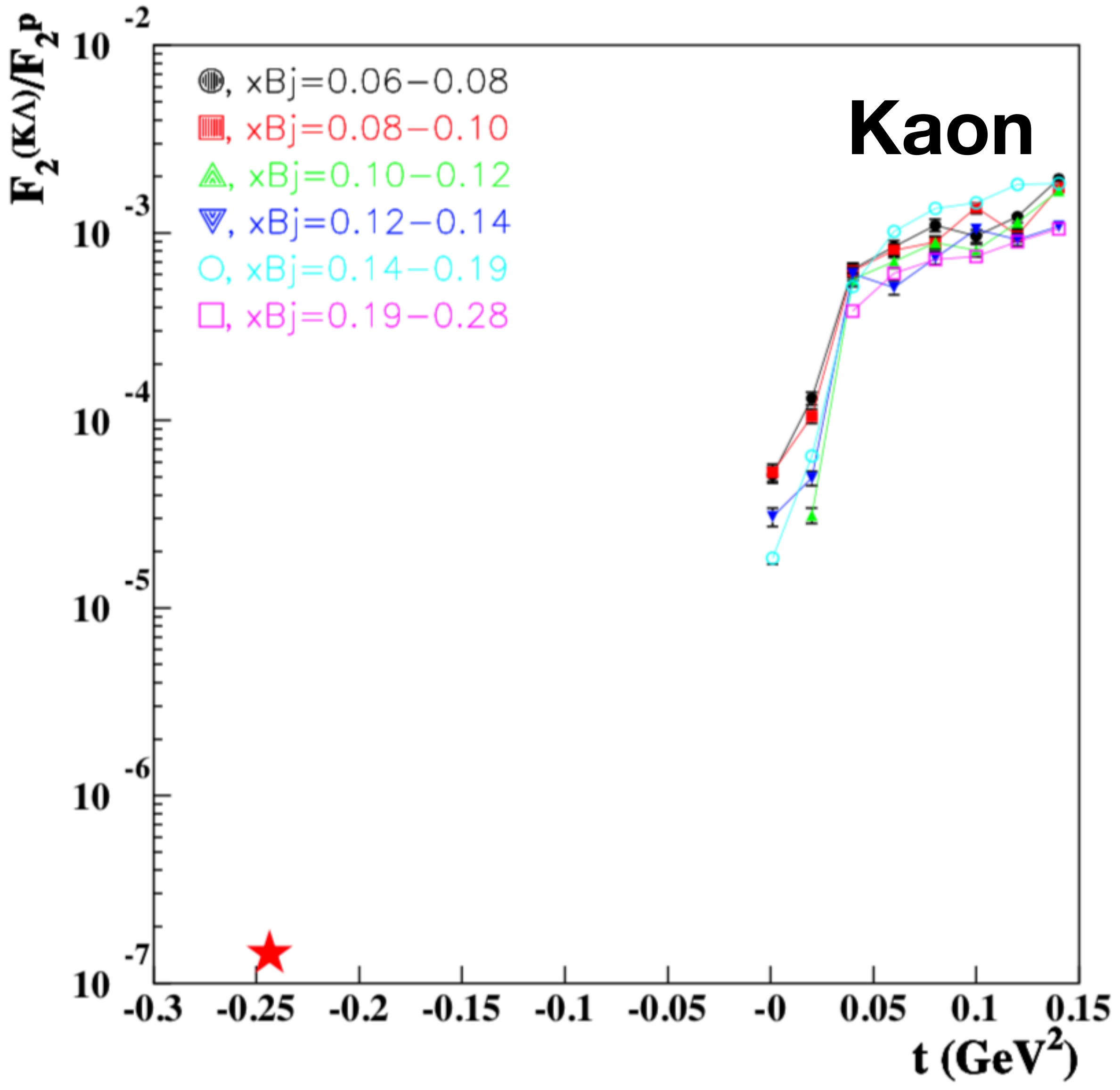
$$F_2^T(x,Q^2,z,t) = \frac{R^T}{\Delta z \Delta t} F_2^p(x,Q^2)$$

- Measure ratio of tagged to total inclusive DIS x-sec
- Tagged signal is orders of magnitude smaller than DIS signal → need high luminosity!

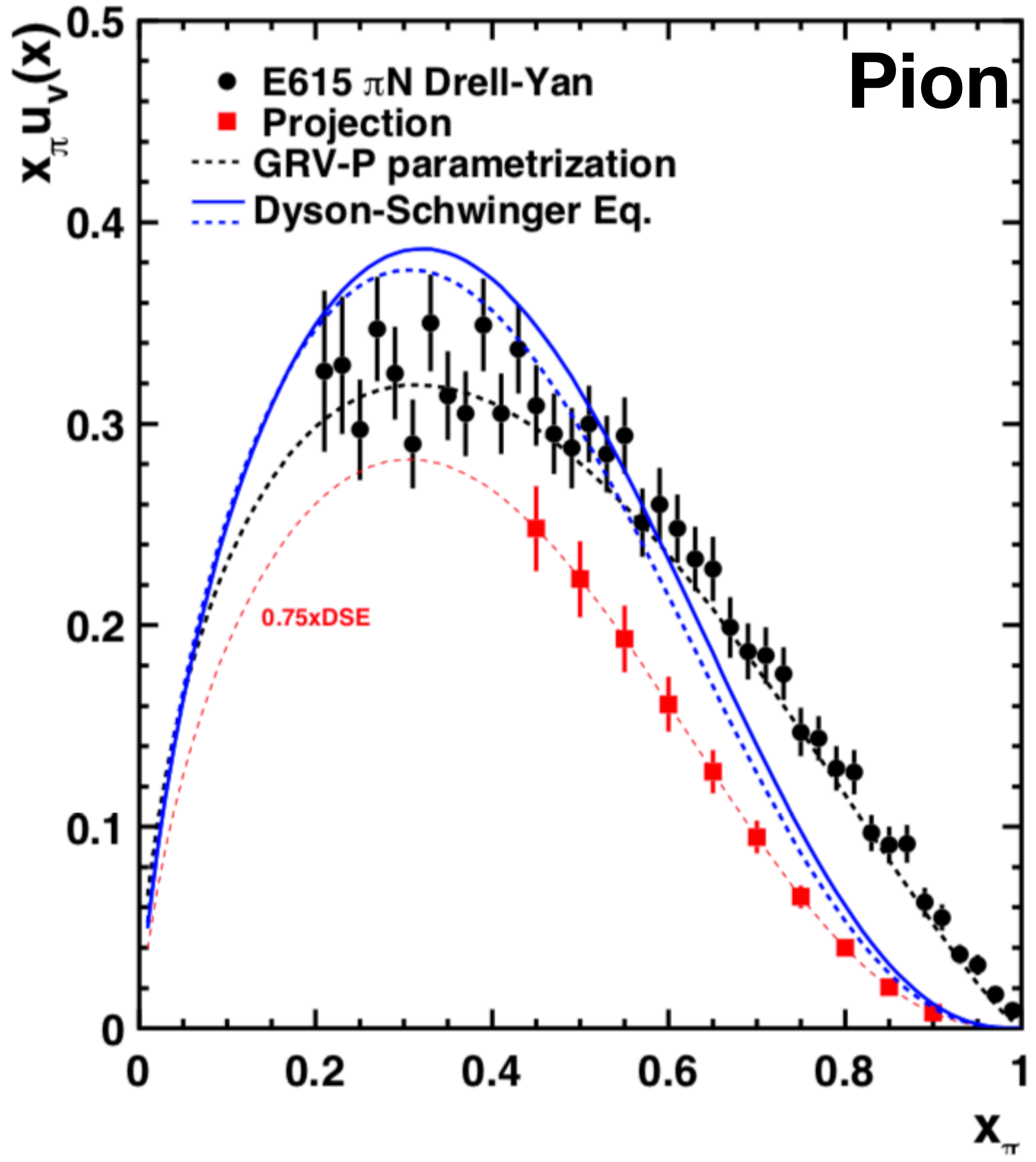
- JLab is **the** unique place to perform these measurements
- Pion flux contribution also dominant at JLab kinematics

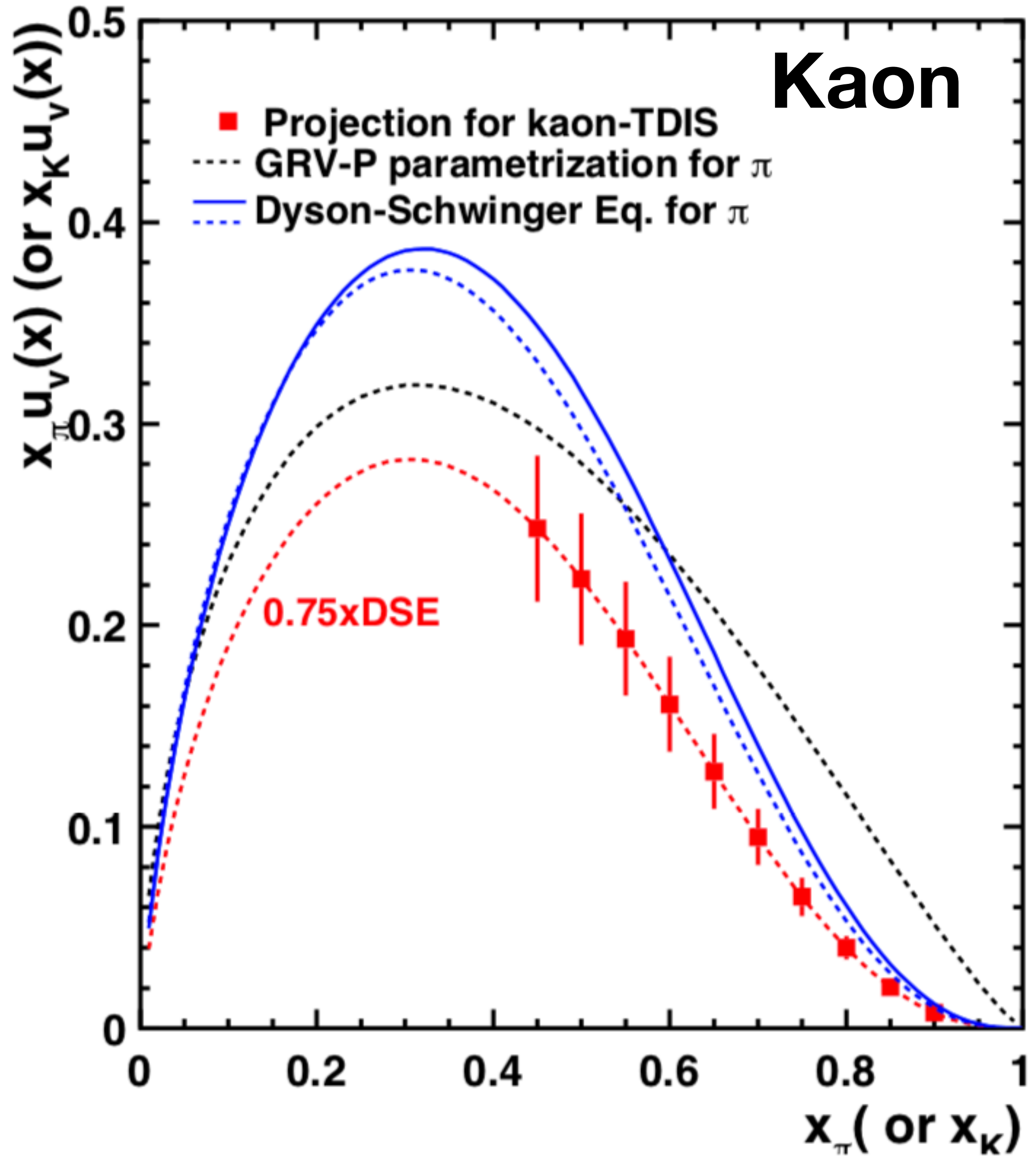
Example Projections





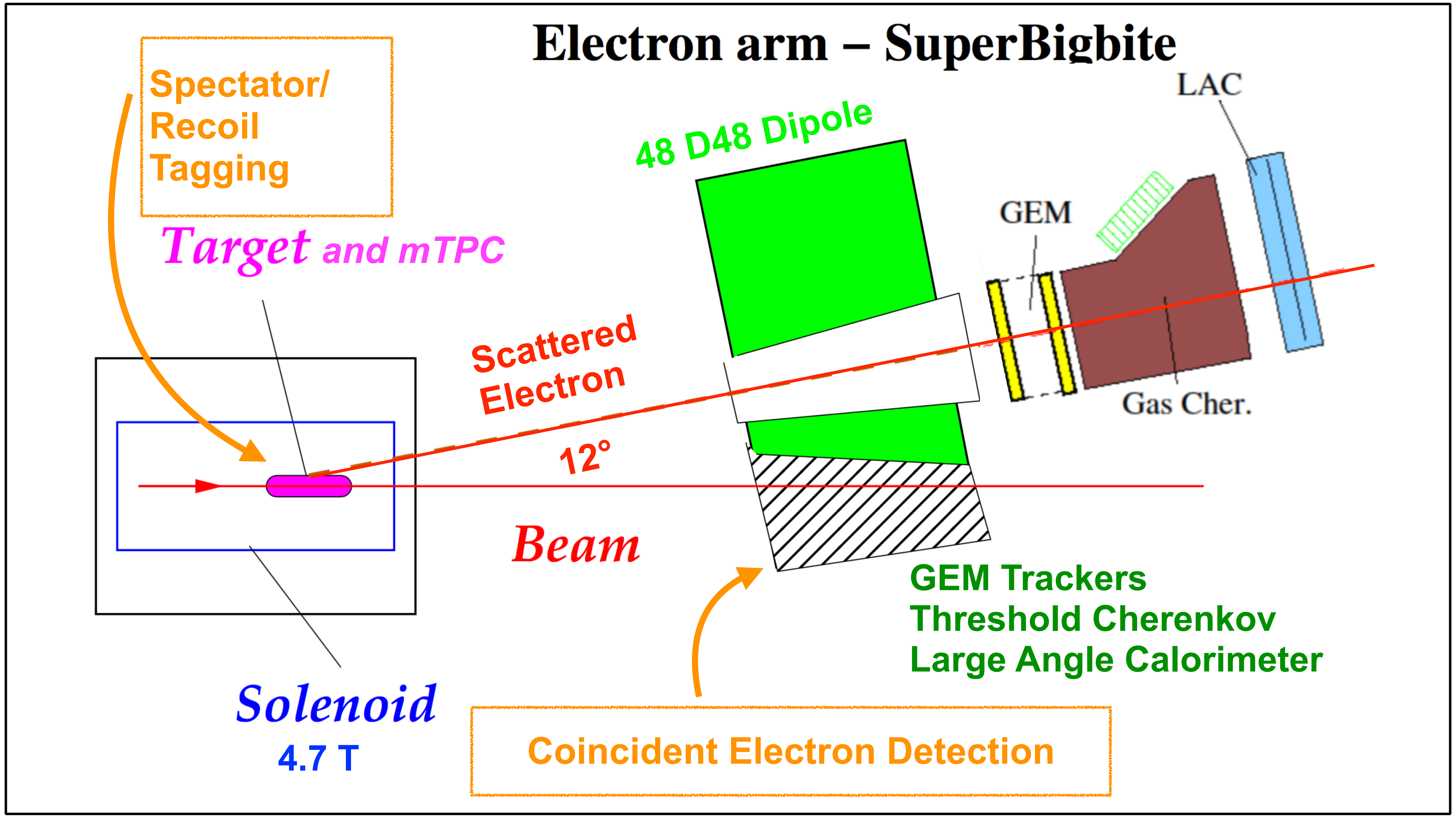
- Based on phenomenological pion cloud model
  - T.J. Hobbs, Few Body Syst. 56 (2015) no.6-9
  - J.R. McKenney et al., Phys. Rev. D93 (2016), 05011
- Kinematical mapping of F_2
- Low momentum reach of recoil detector essential to obtain shapes of curves





- Projected range of coverage for relevance to valence quark distribution analyses

TDIS Set-Up

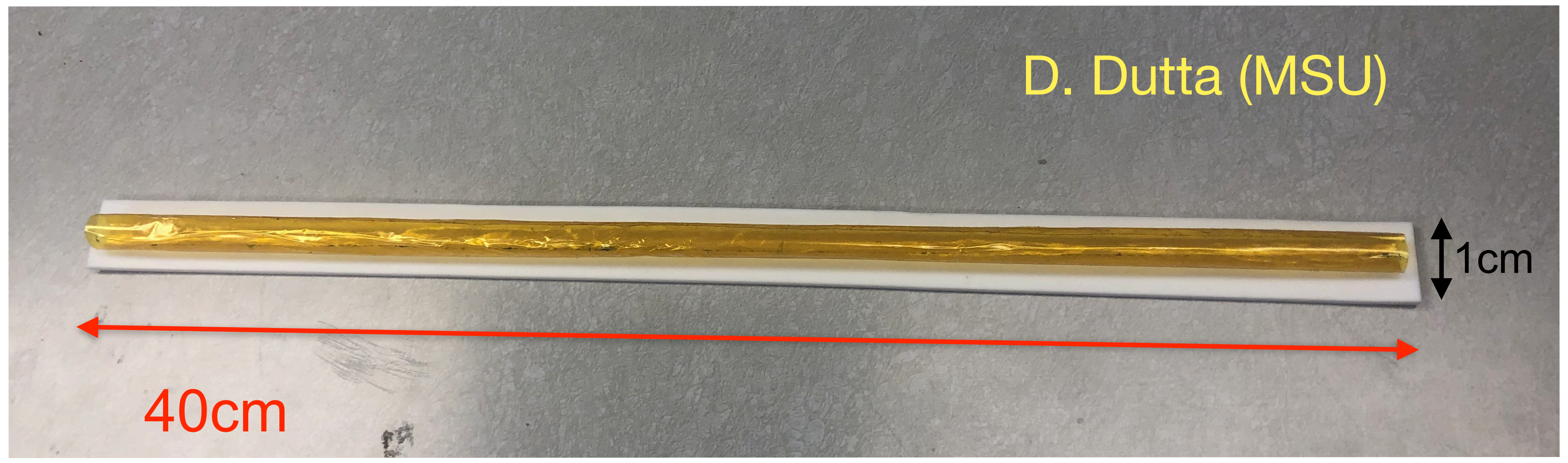


- 50μA 11 GeV beam
- H/D gas target
- → high luminosity 3 x 10^{36} $cm^{-2}s^{-1}$

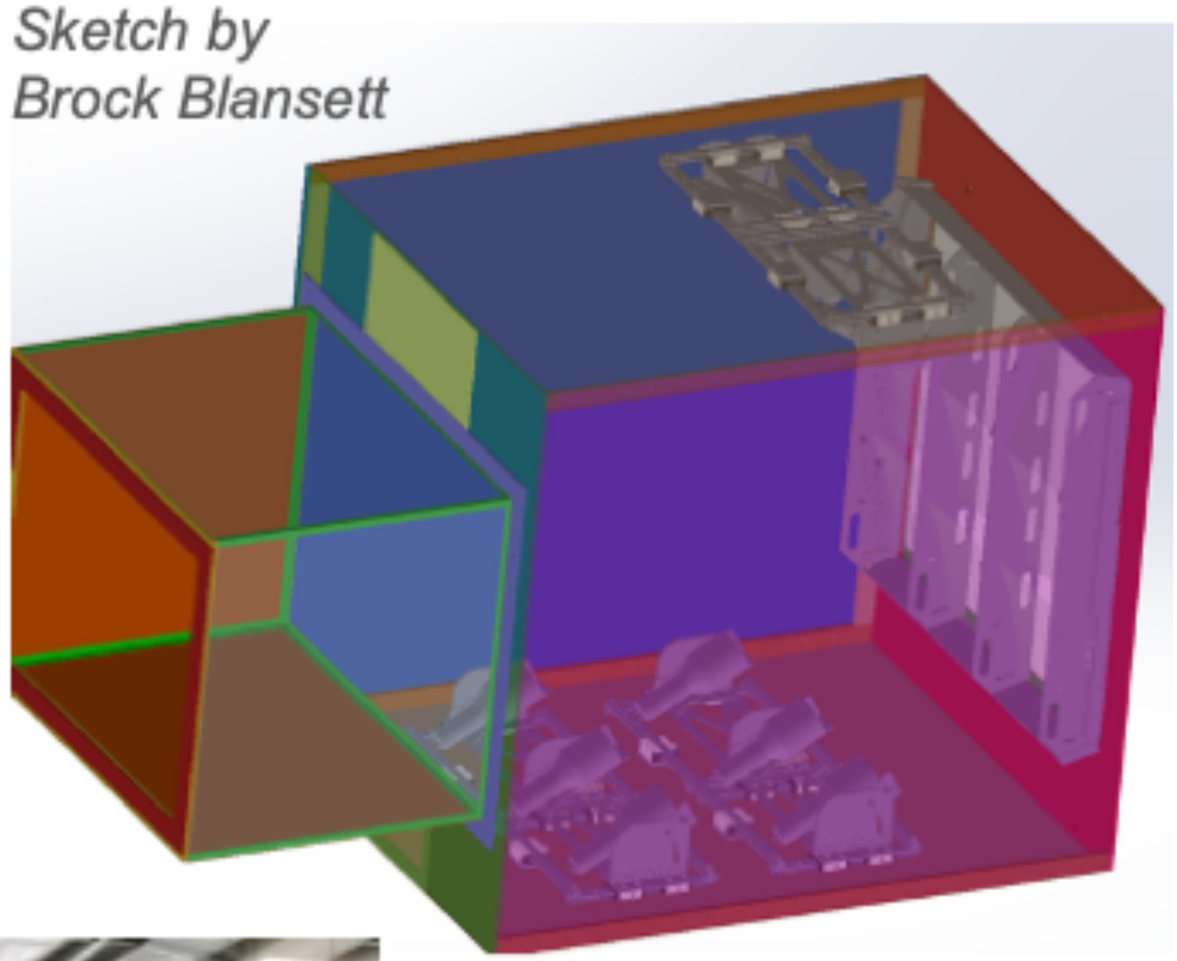
- e' detection in reconfigured SBS
  - GEMs (from SBS);
  - Cherenkov;
  - Calorimeter (CLAS LAC)
  - Electron PID and (L2) trigger, tracking and π rejection (~10^{-4})

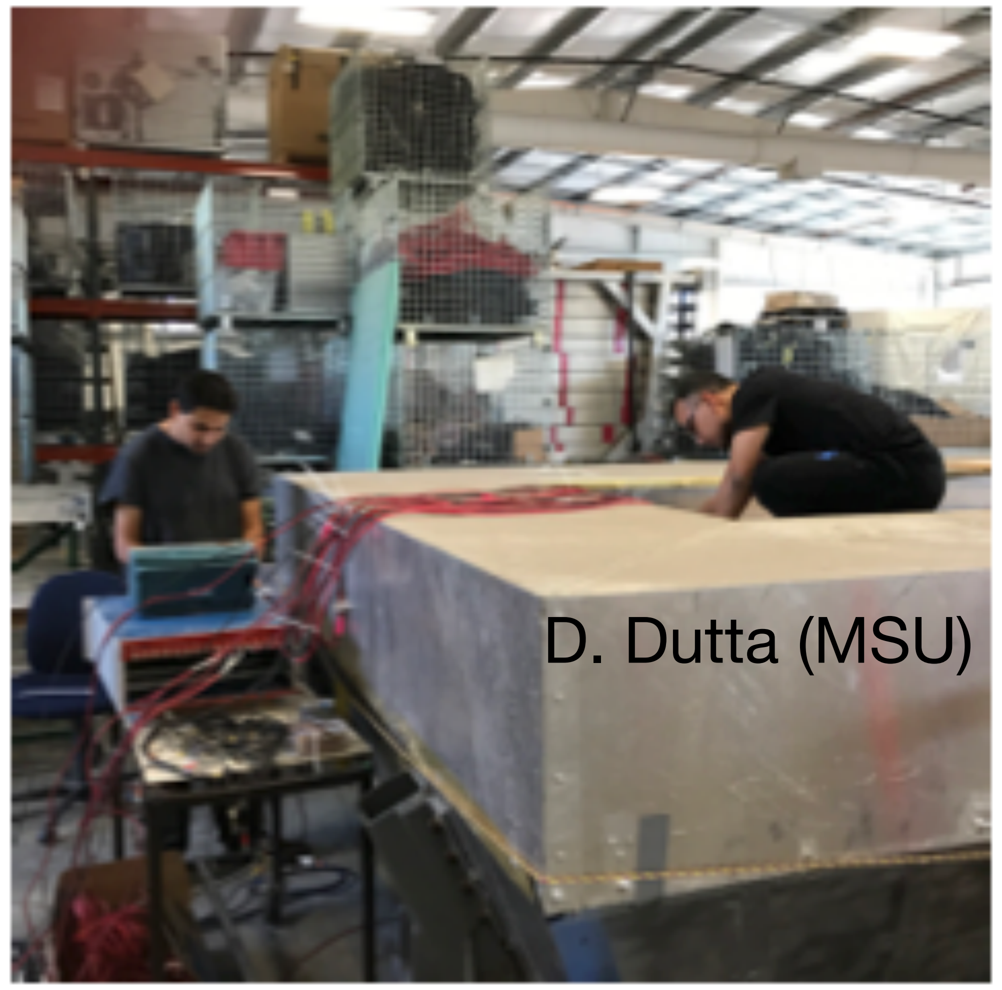
- High rate multiple time projection chamber (mTPC) for tagging
- Solenoid

TDIS Set Up - On-going Developments



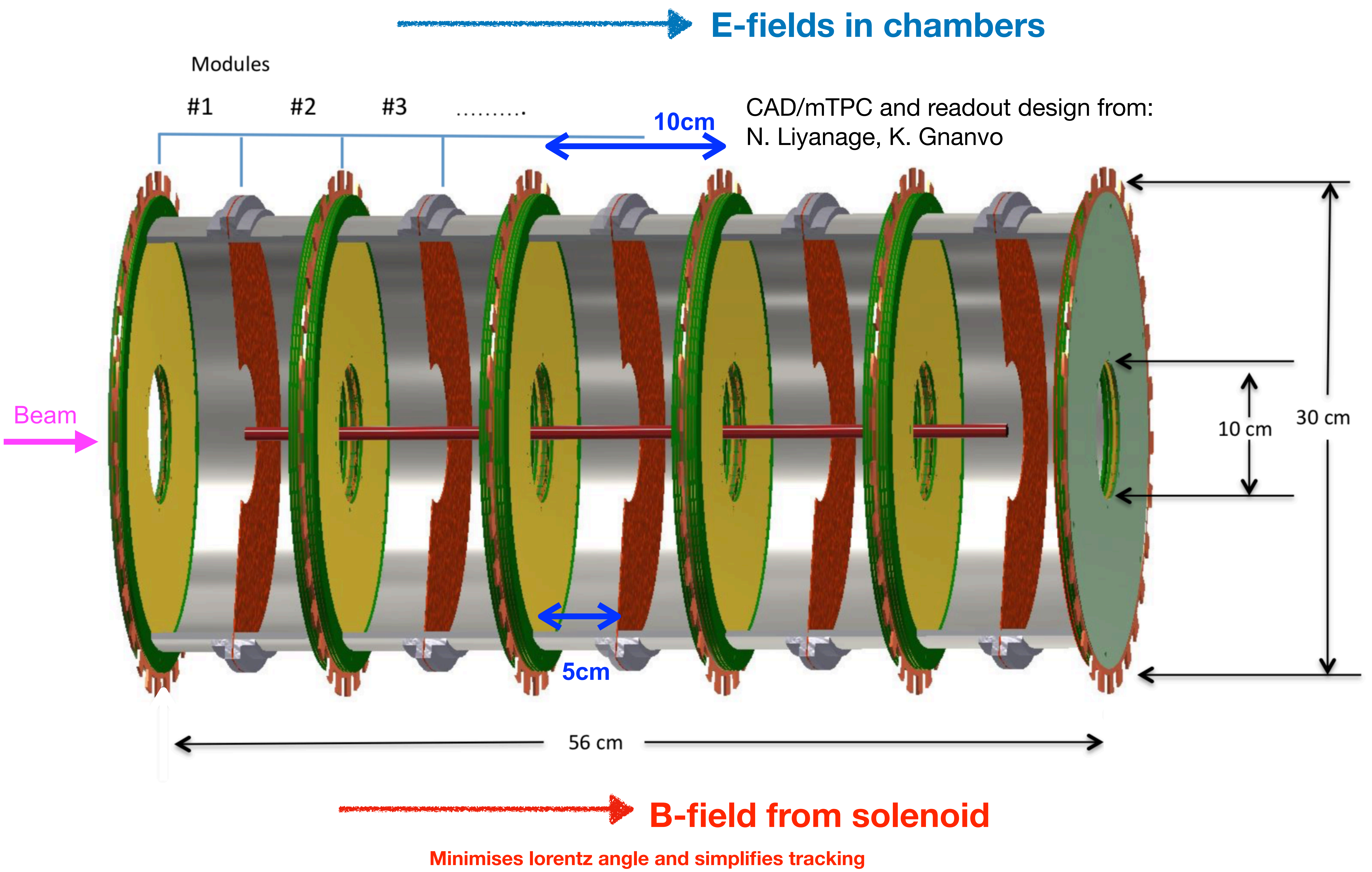
Sketch by
Brock Blansett





- Straw target prototyping (MSU)
  - 25μm Kapton walls; spiral wound; 3atm; room temp
- Recent theory suggests TDIS signal ~30% larger and less sensitive to pion flux factor than expected
  - J. R. McKenney et al. Phys. Rev. D 93, 054011 (2016) and P. Barry (JLab)
  - Potential to run at lower beam current
- New hadron blind gas Cherenkov under design (UT)
  - 4m Neon or Ne/Ar, 1atm
  - Distinguish e/π over 2-11GeV
- LAC refurbished and under test (MSU, JLab)
  - Plans to develop FPGA electron trigger
- mTPC prototyping (UVa, JLab)
- Front-end electronics development and prototyping at JLab (JLab, Univ. Sao Paolo)

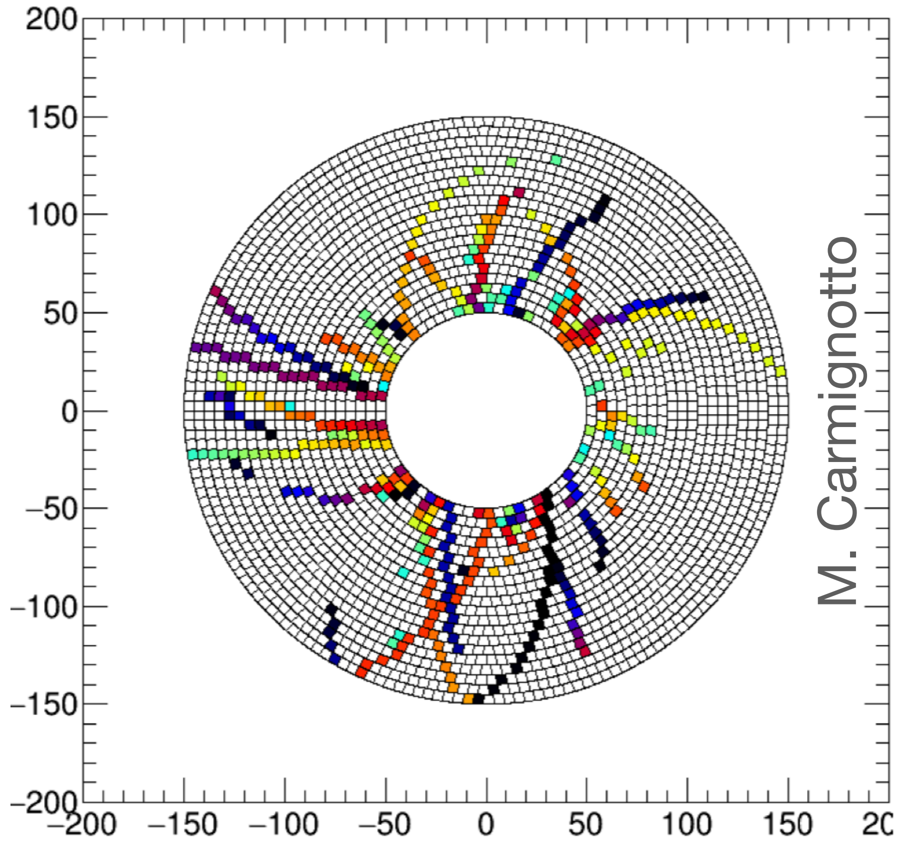
High Rate mTPC



- Division into chambers
- Reduced background rates

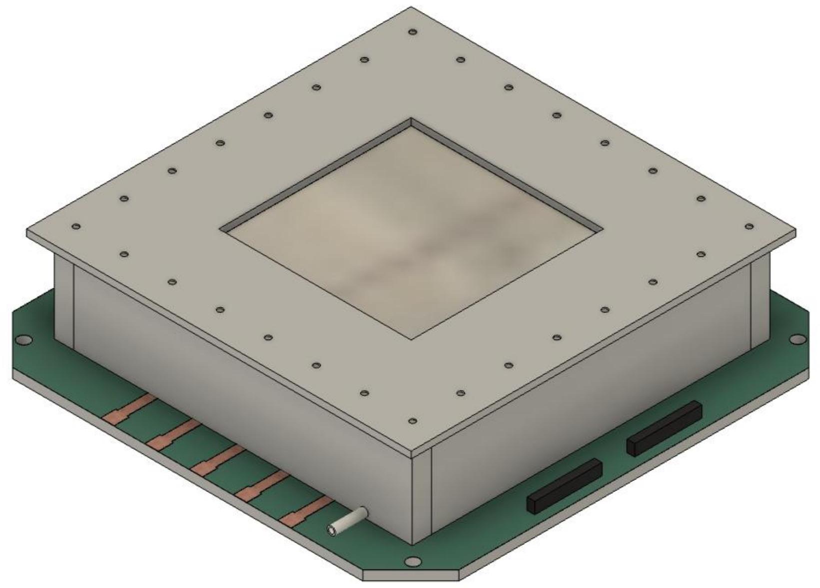
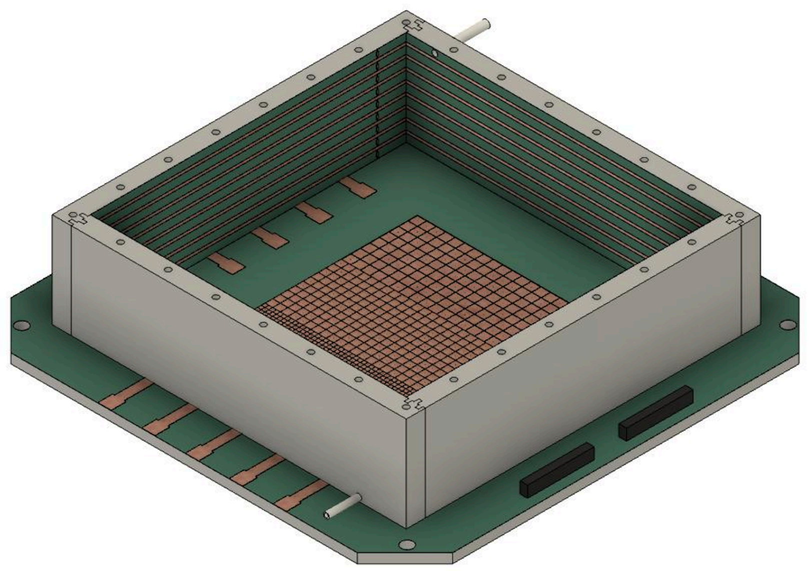
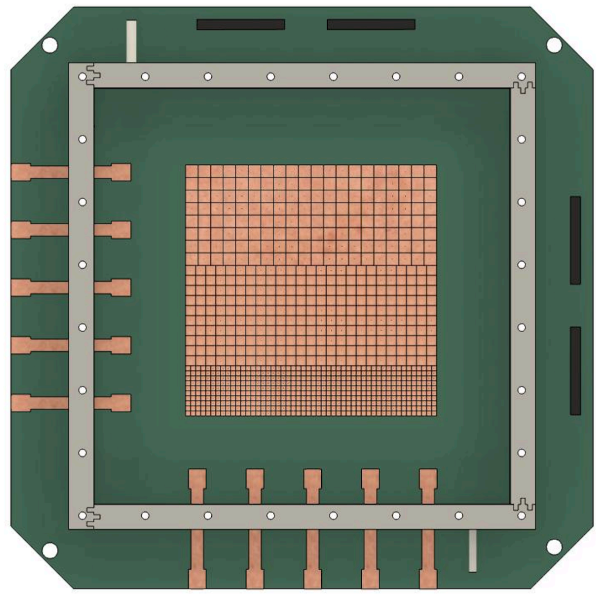
- Low density gas at STP
- Fast drift times (~2-3μs)

- Multi layer GEM foil readout
- Segmented readout pads



- Tag recoils/spectators
  - Vertex tracking
  - Momentum reconstruction (inside solenoid)
  - PID by dE/dx

mTPC Prototyping

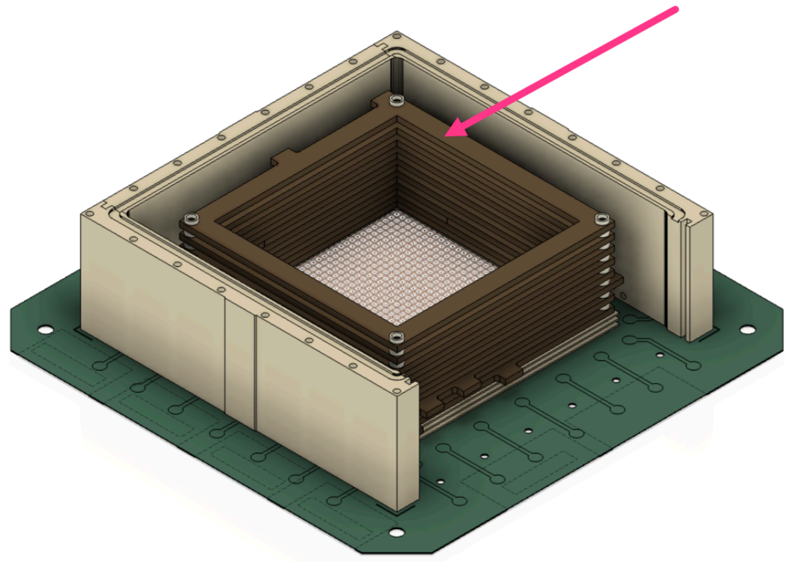




CAD model: S. Ali

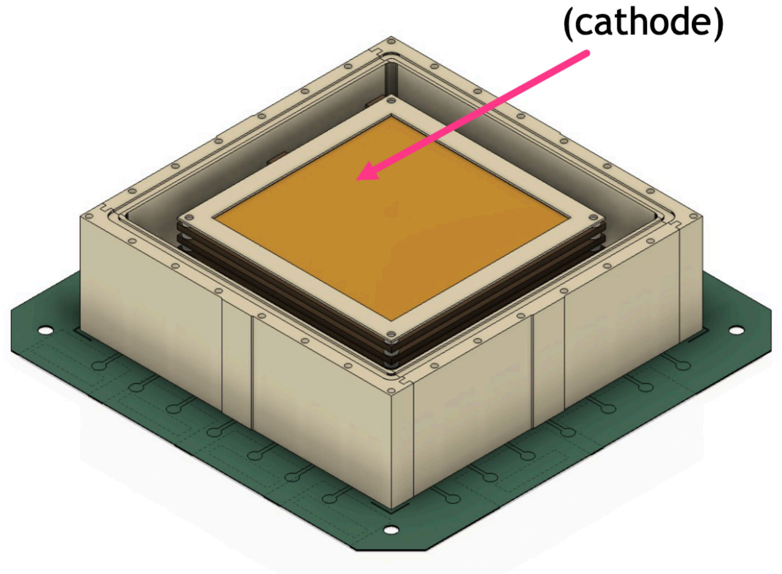
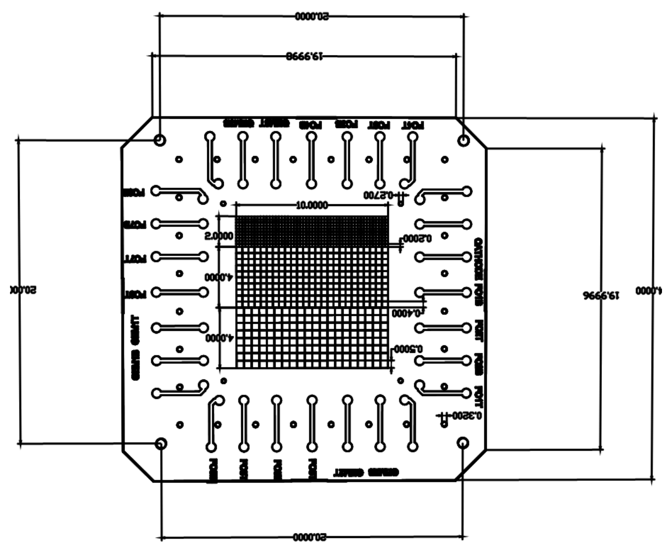
Field set up by electrode strips

Different sized readout pads

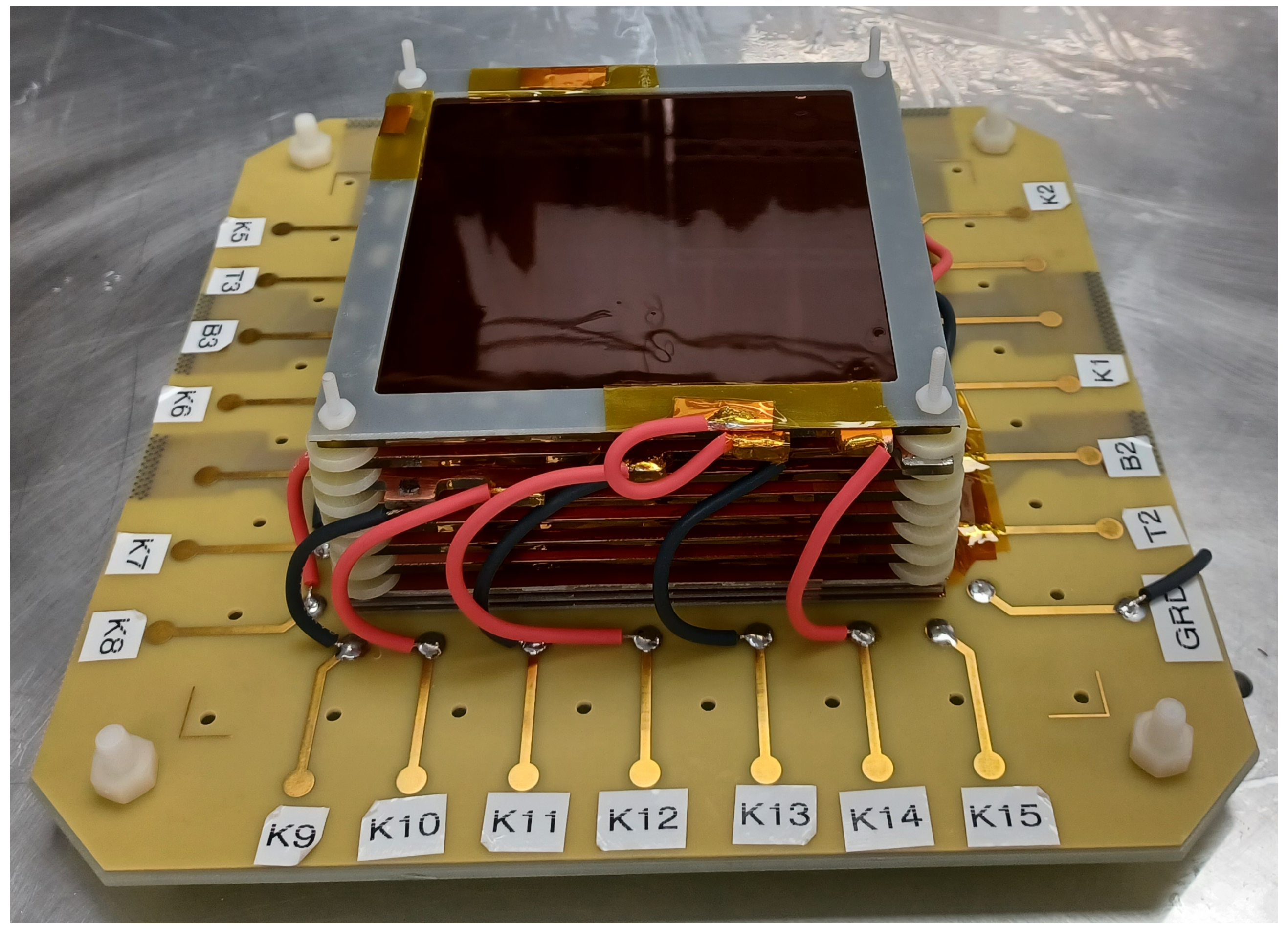
Field Cage

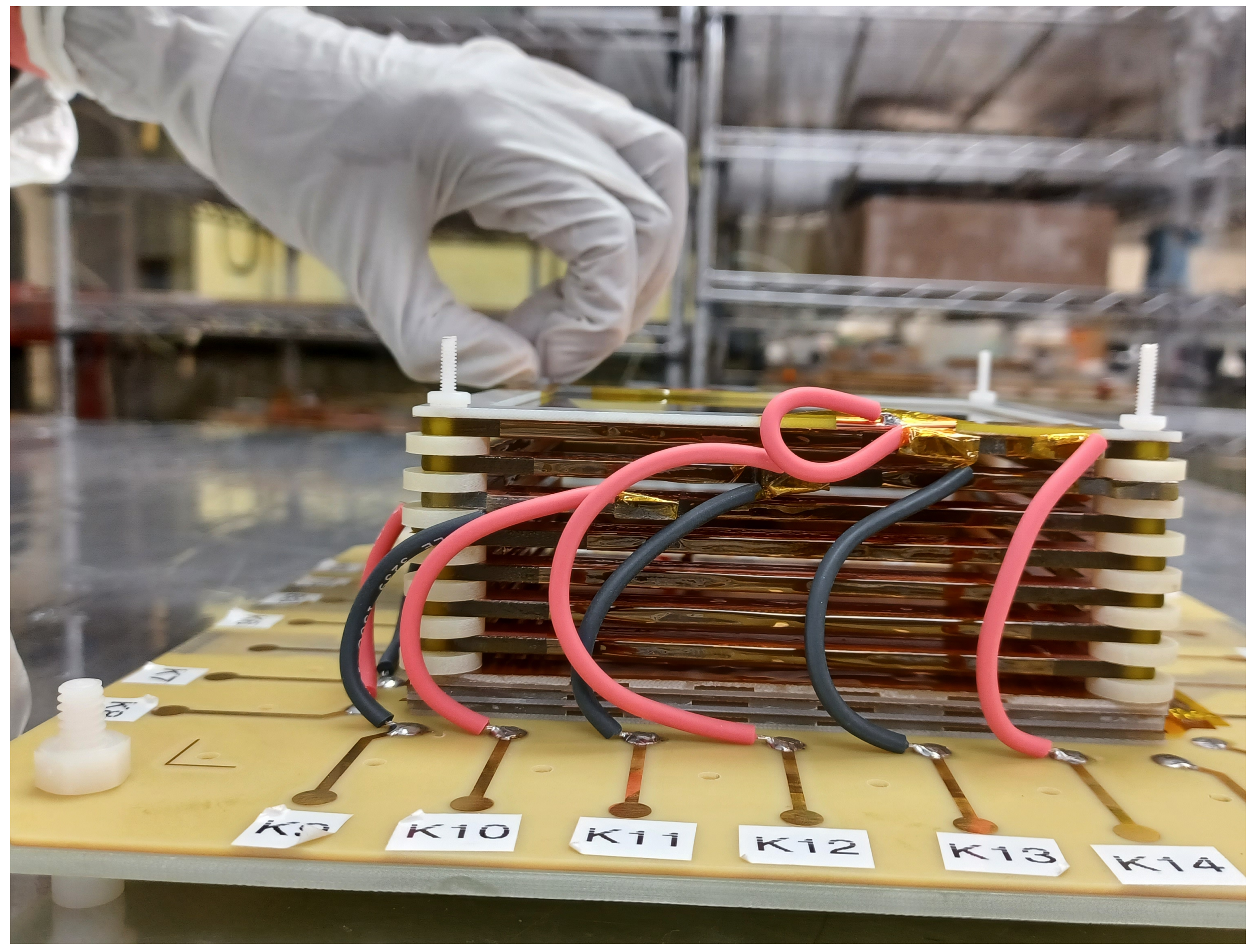


Alumnized Kapton (cathode)

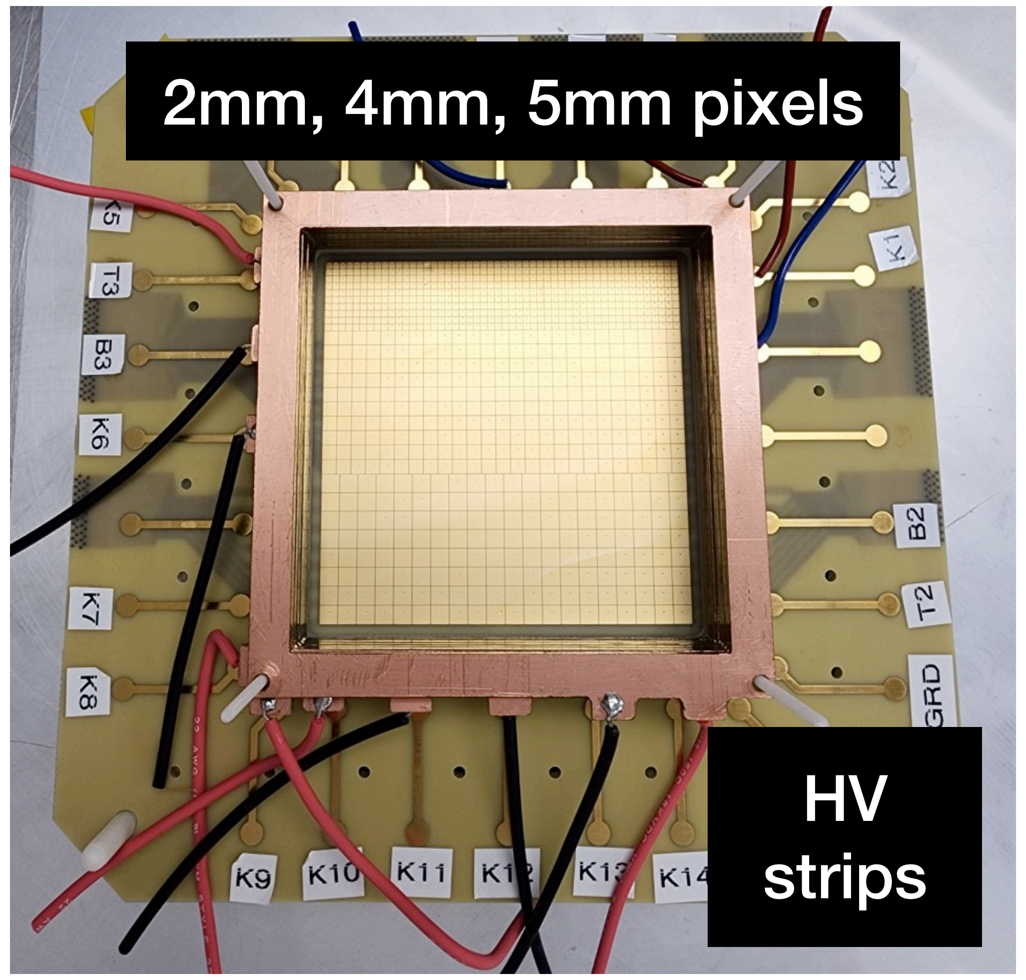



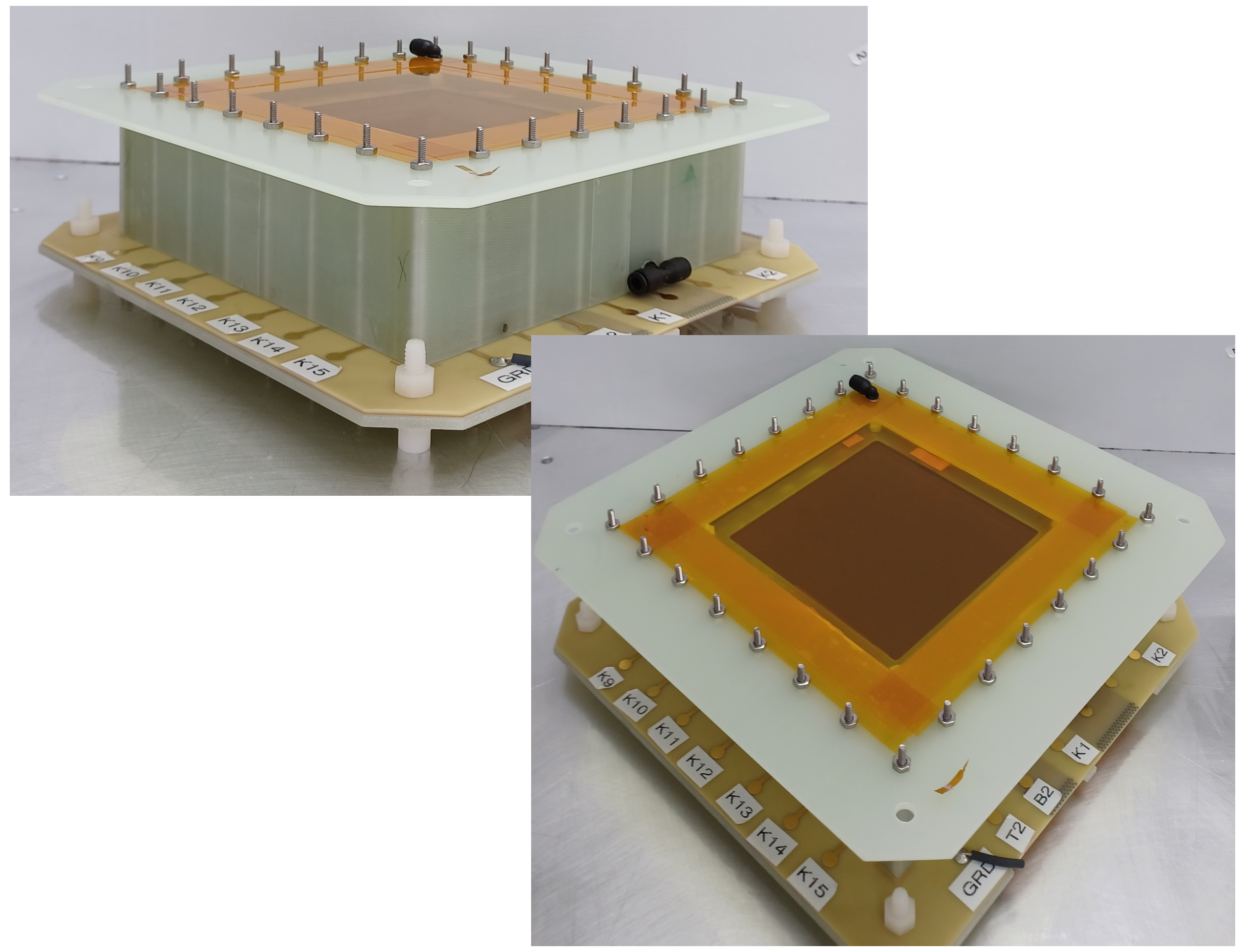
- UVa completed 1st square prototype
  - (H. Nguyen, N. Liyanage, et al.)
  - 10 x 10 cm^2 active area, 5cm drift in field cage, triple GEM foils, segmented anode with different pixel sizes
- JLab currently testing prototype (E. Christy et al.):
  - Validate field cage, readout
  - Test tracking algorithms
  - Study track resolution vs pad sizes
  - Study drift gases
- After tests of square prototype, a cylindrical one will be built at JLab
  - Design currently underway, needs R&D





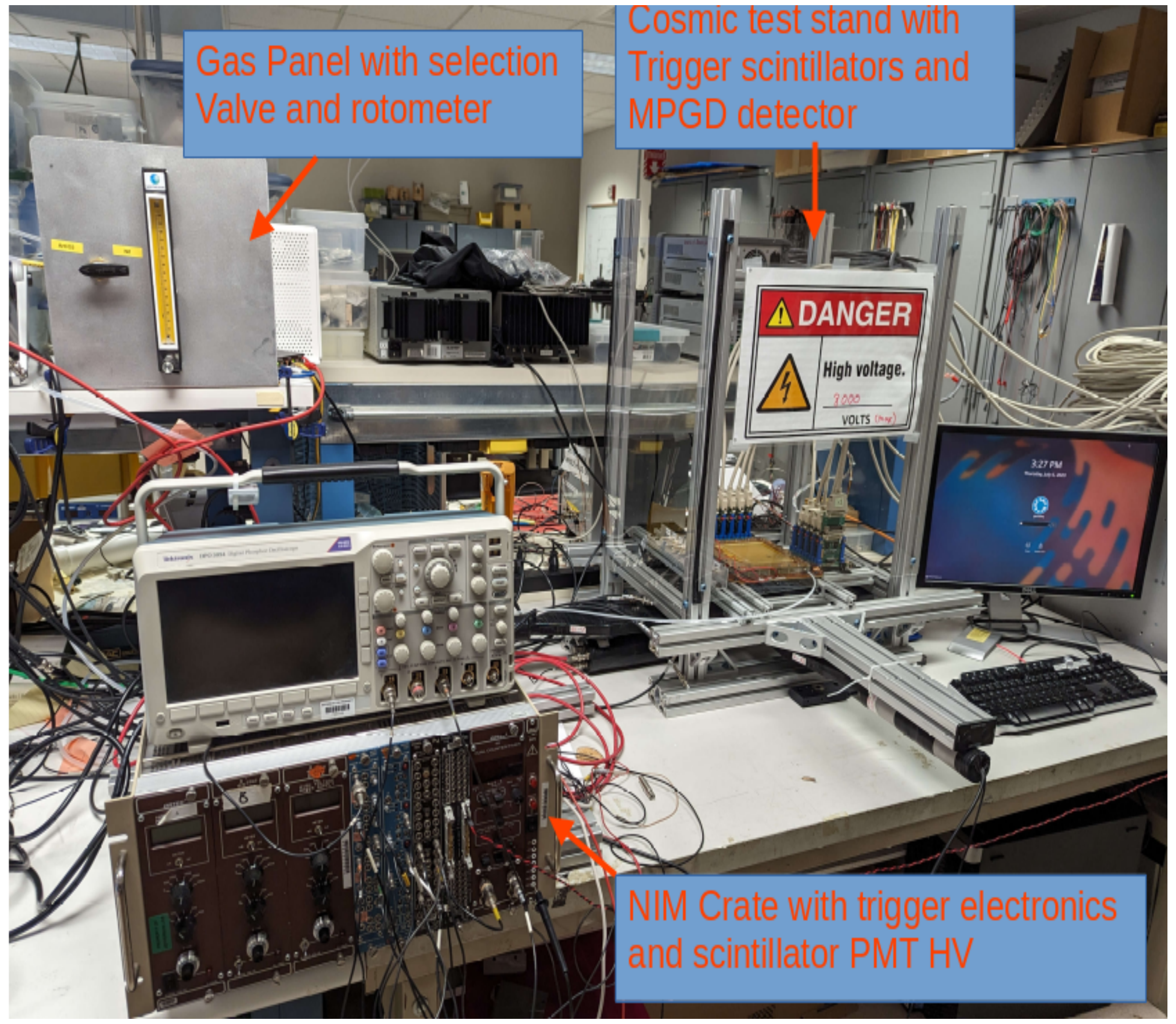
Construction images: Aruni Nadeeshani (MSU), Huong Nguyen (UVa)



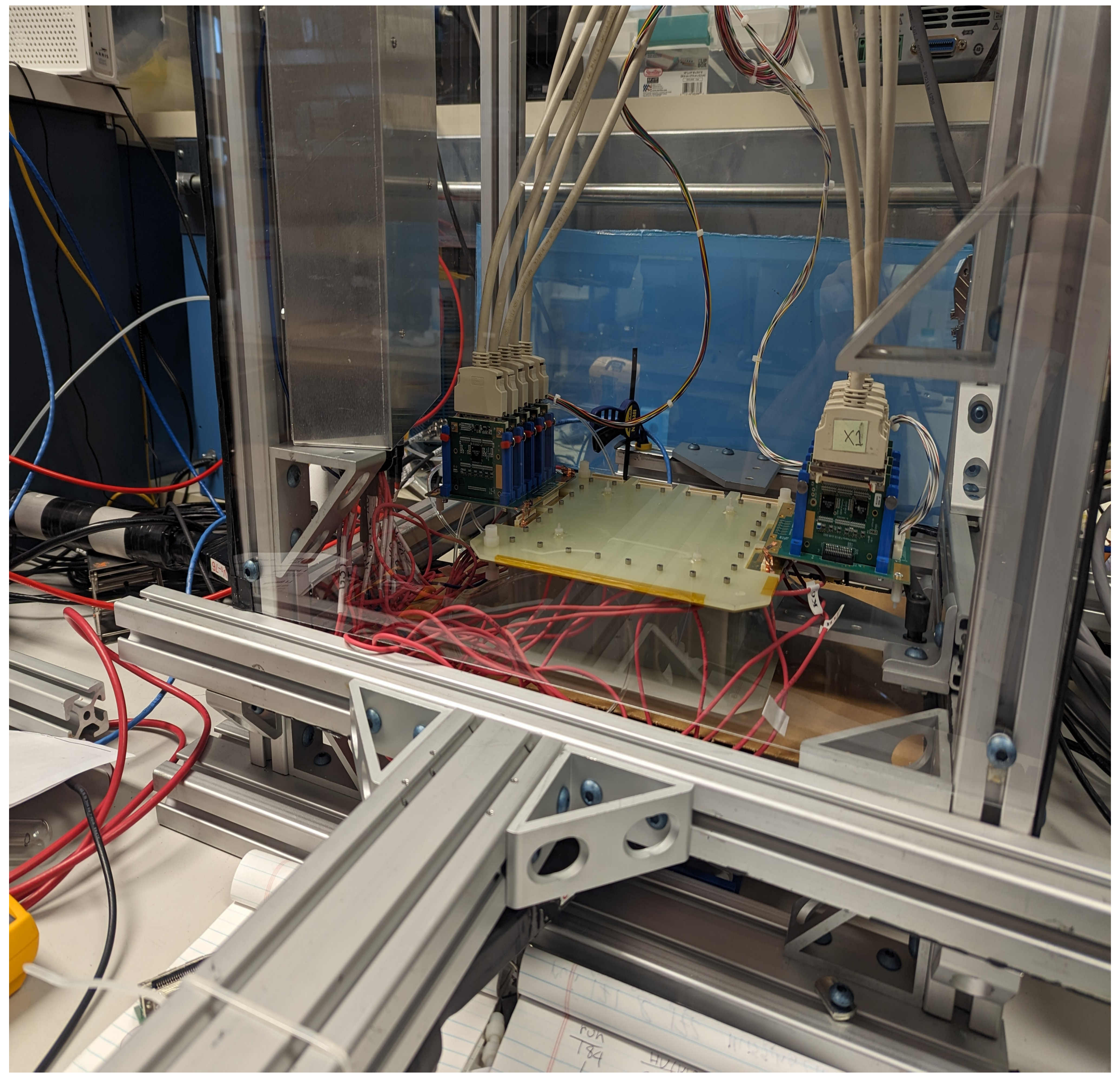


mTPC Prototyping Tests at JLab

From E. Christy (JLab)

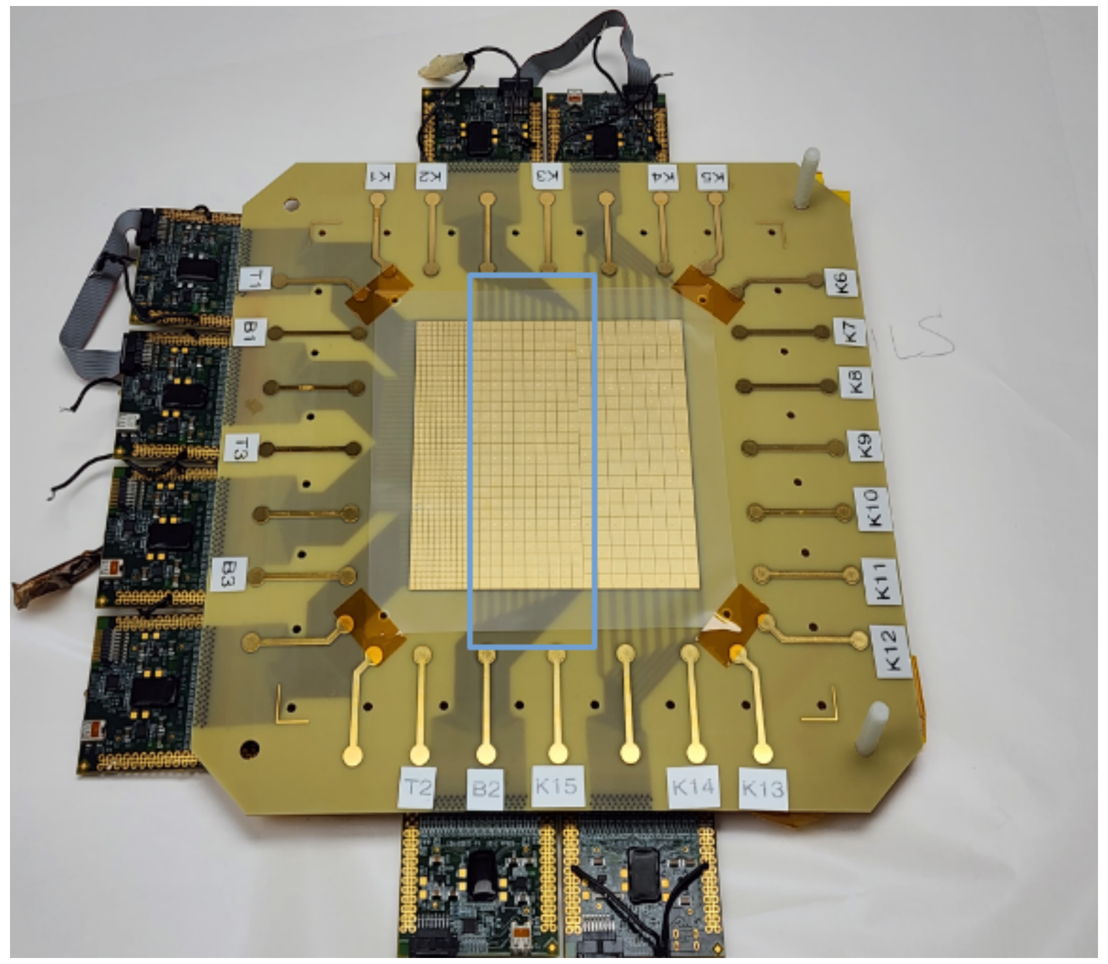


Preamp cards with shaper
24 channels per card / 5 cards per baseboard

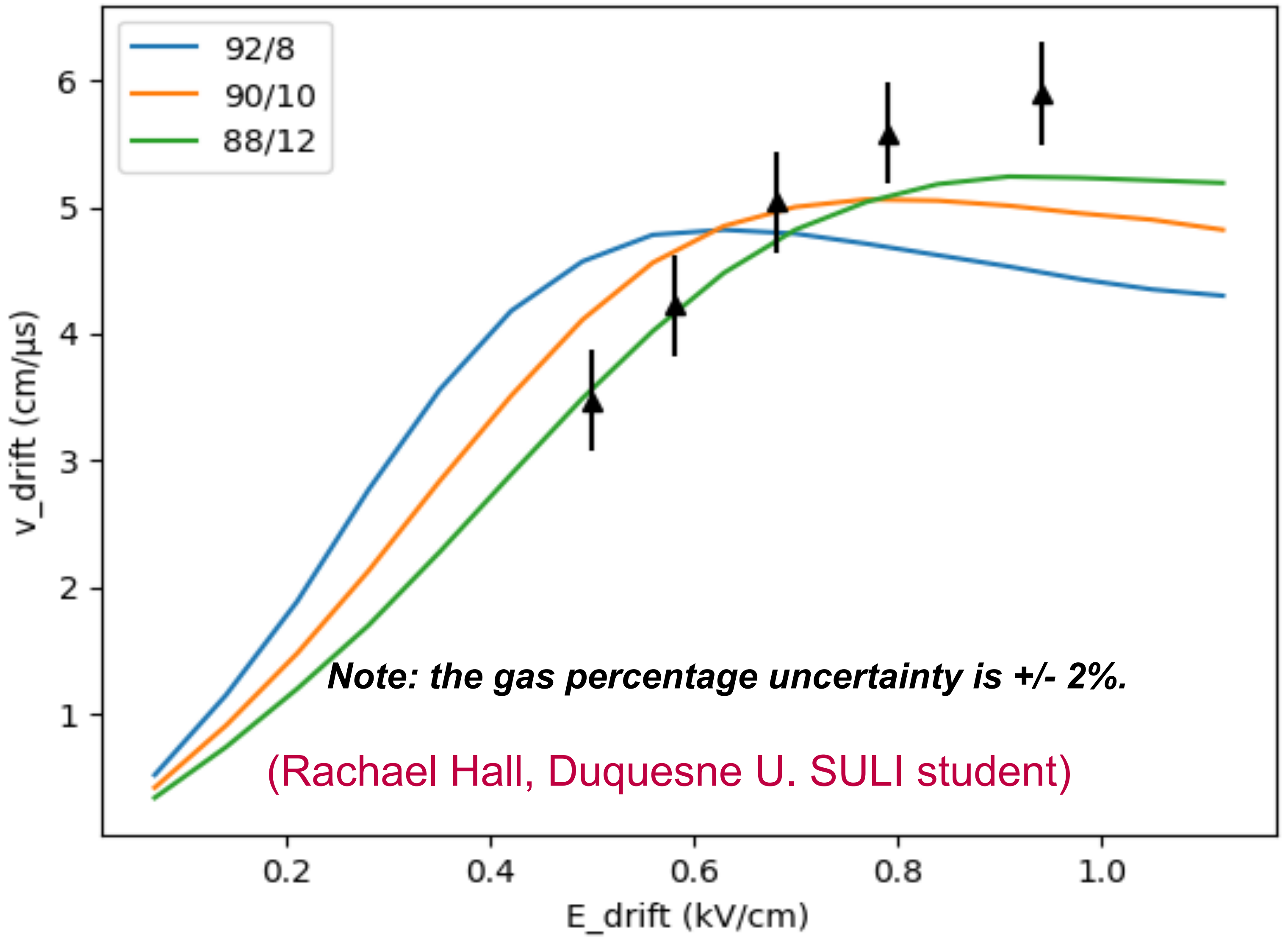


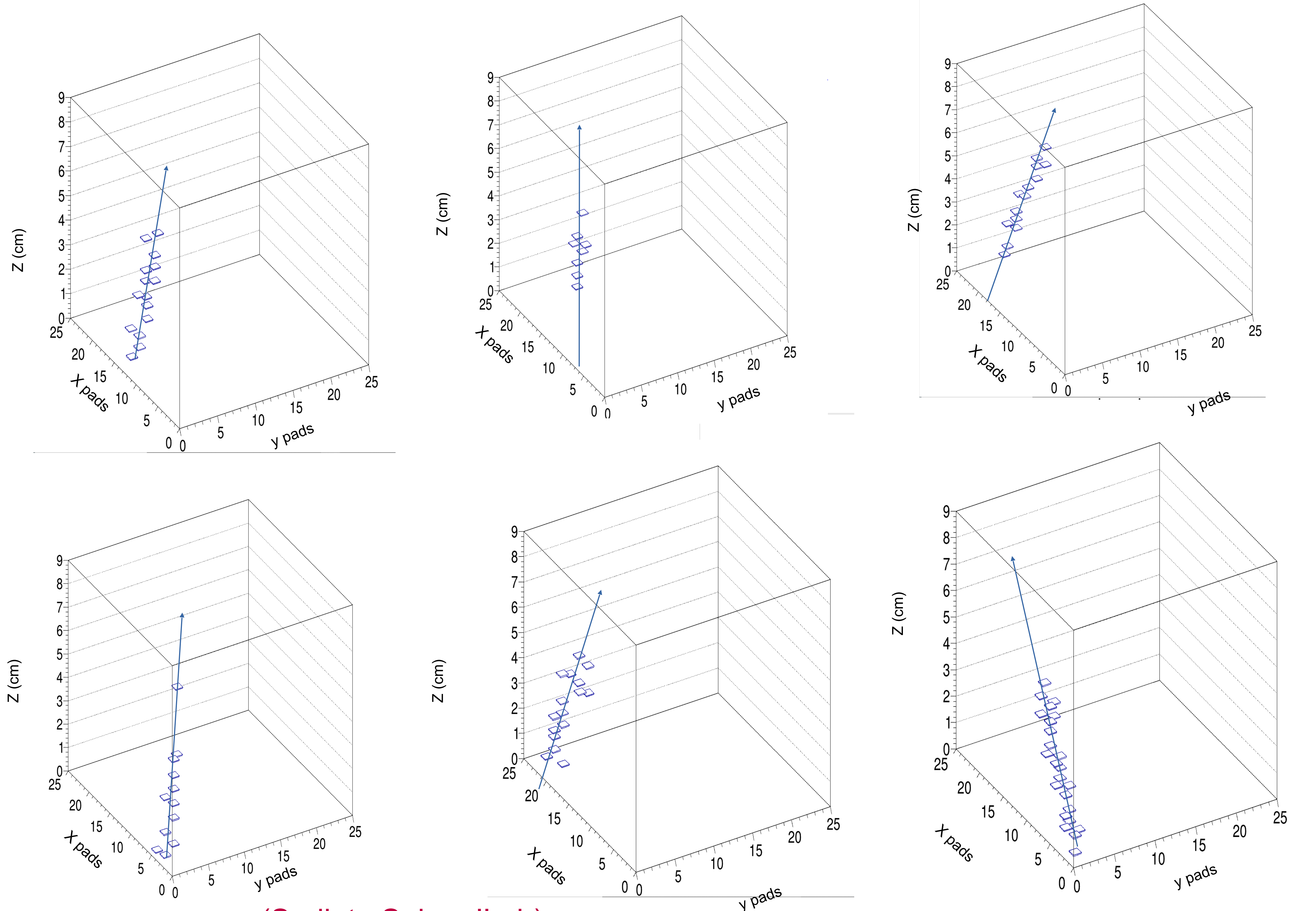
- Tests on-going with JLab FA125 VME system
- Will move to TDIS electronics in future

- Cosmics triggers of orthogonal directions:
  - Testing drift times of charge in field cage
  - Recording tracks
  - (Horizontal orientation shown, as in left pic, 5cm drift)
- Reported some HV discharges in initial testing



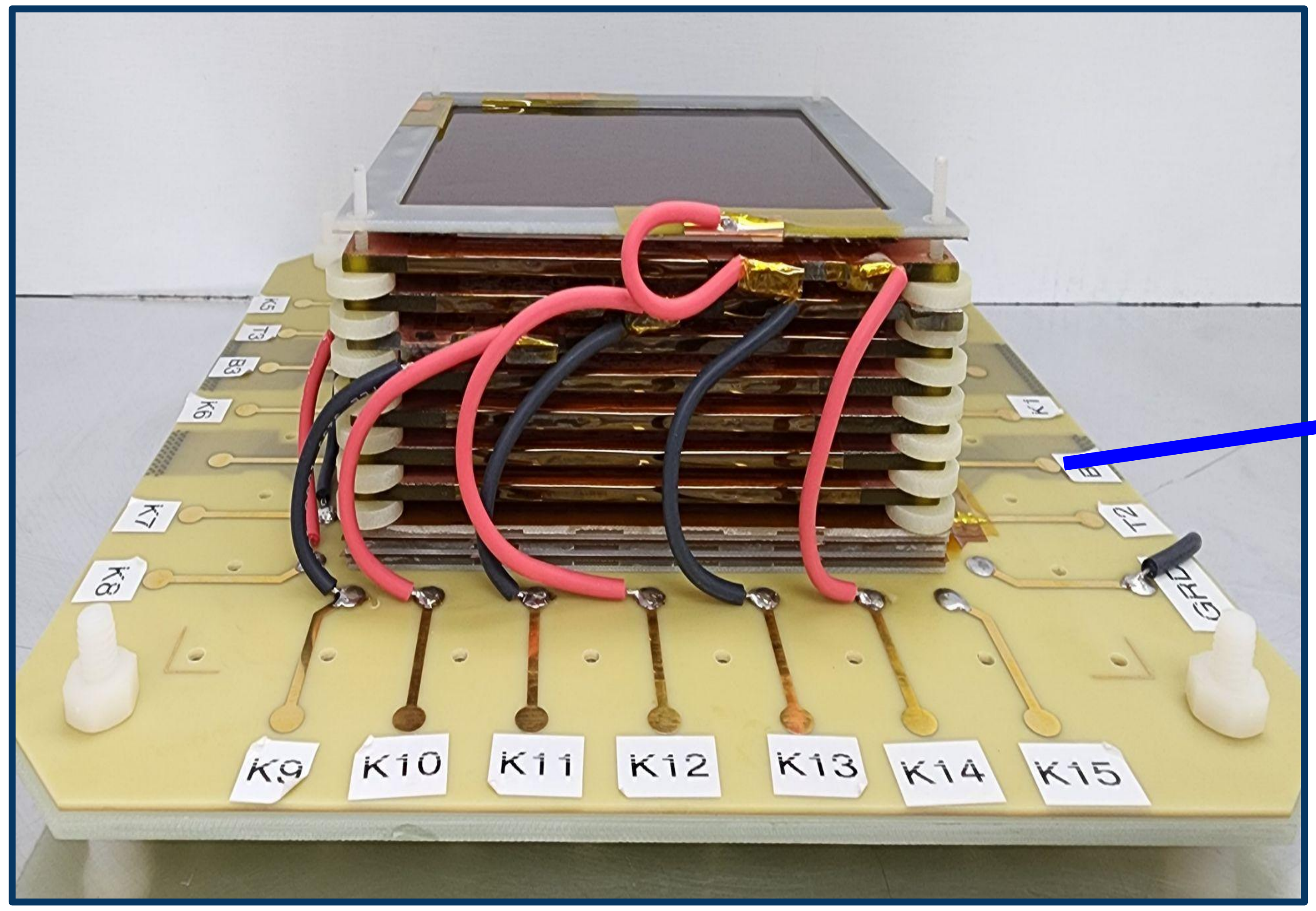
Data shown taken with medium sized pads

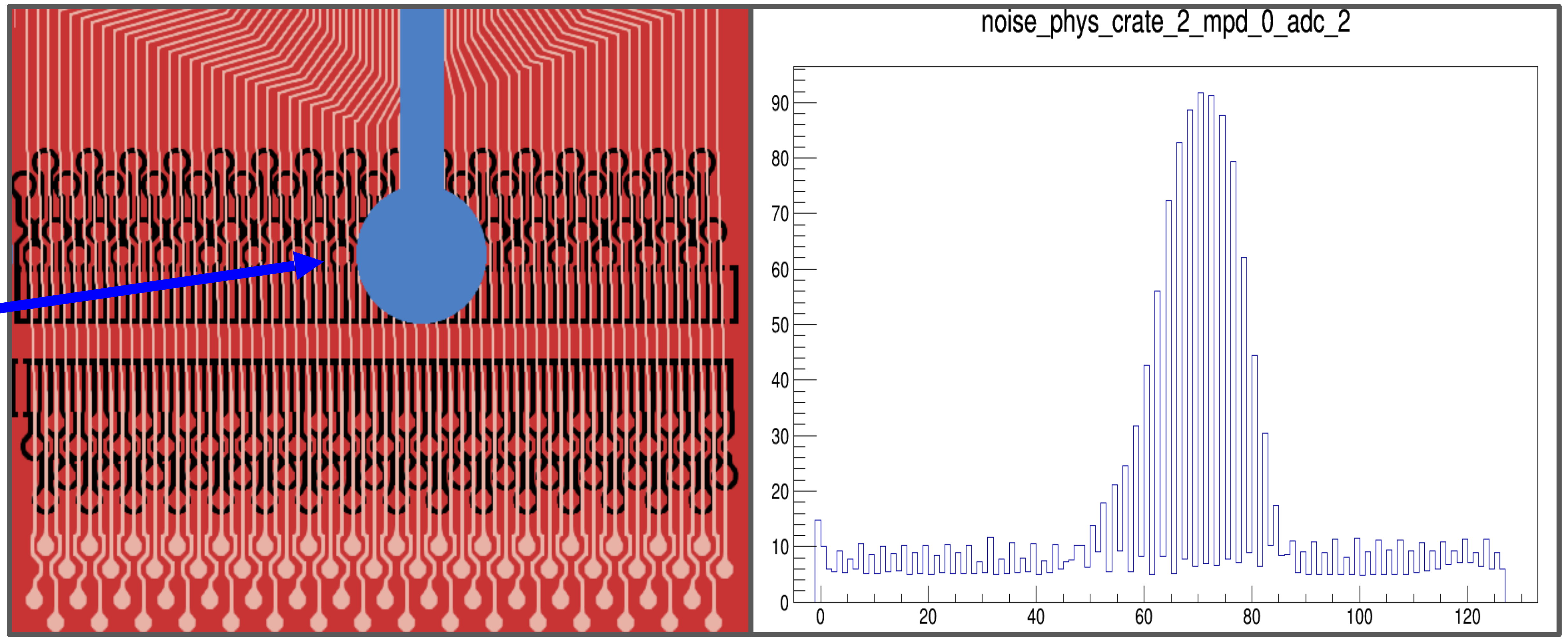




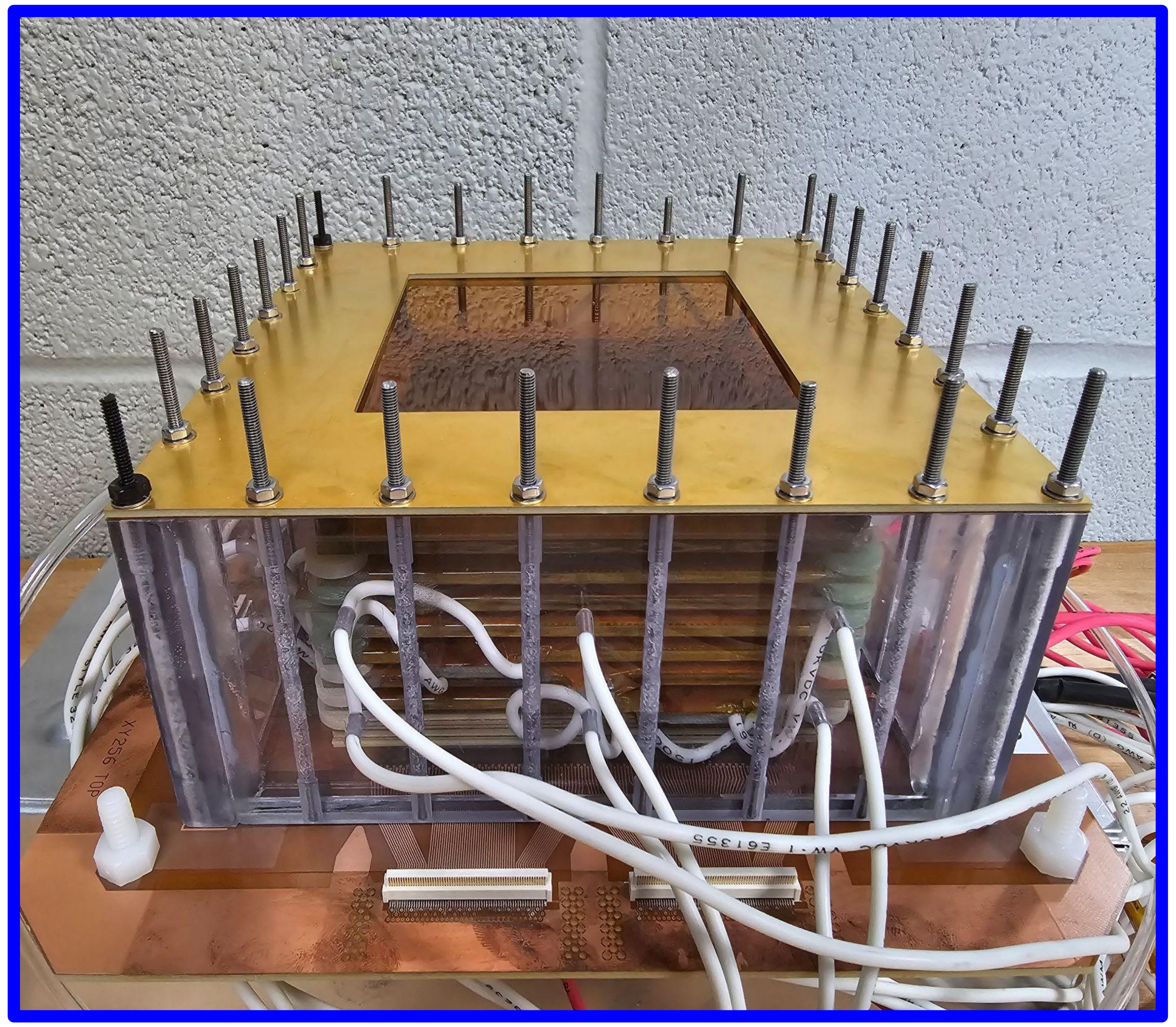
(Sudipta Saha, JLab)

Fixing Issues with HV Connections





Slide from H. Nguyen (UVa)



- Significant noise due to the active use of HV electrodes etched on top of RO channels
- Serious discharged due to routing HV electrodes for the field cage through RO plate

➔ **Solution from Huong:** *Allowing the wires from the HV dividers to connect directly to the field cage through the wall*

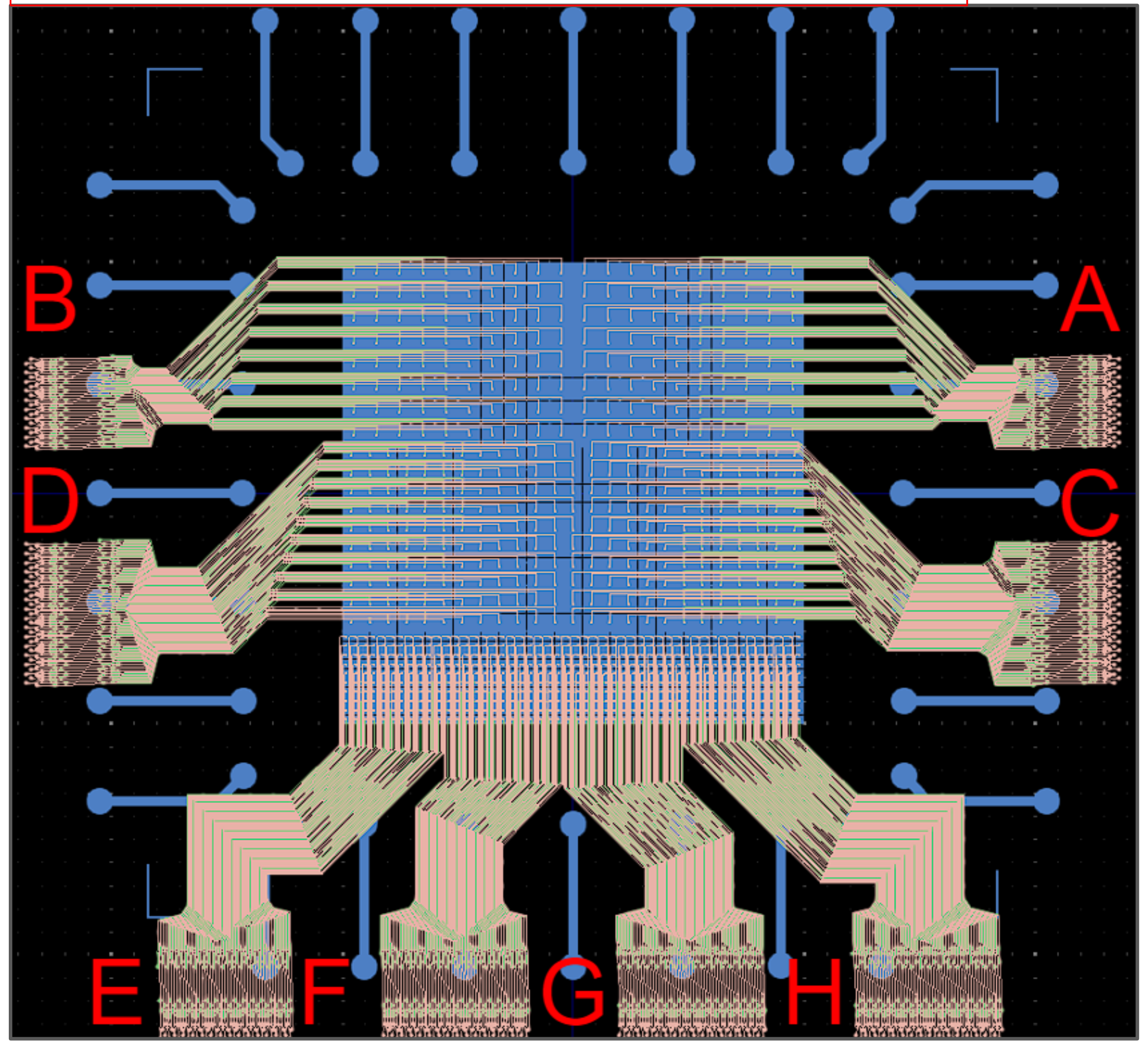
- JLab can now put 8kV on cathode without discharge events ✔
- More info on HV in back up (e.g. want >1.5kV/cm in drift region → >10kV required!)
- Next steps: modify HV box to accommodate LEVO HV connectors and test with CAEN R1570ET up to at least 10 kV (there would be one R1570ET per chamber)

Finalising Pixel Pad Mapping

Slide from H. Nguyen (UVa)

Readout GUI Visualization

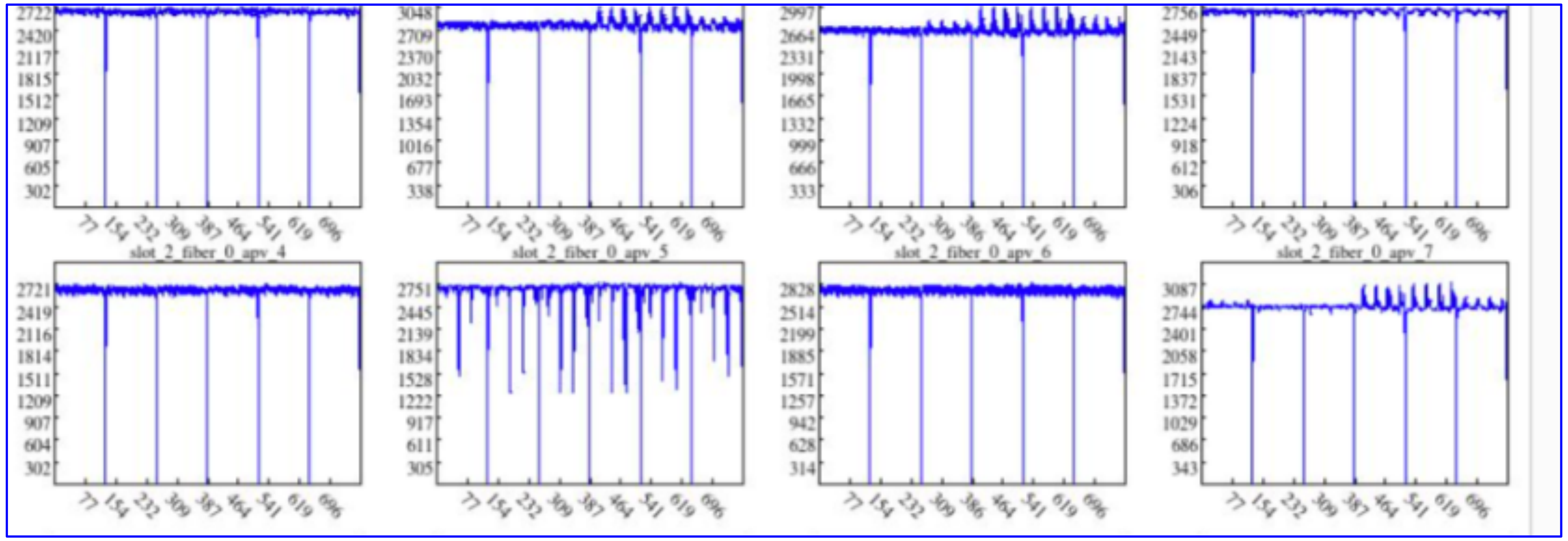
APV PCB/Gerber Layout



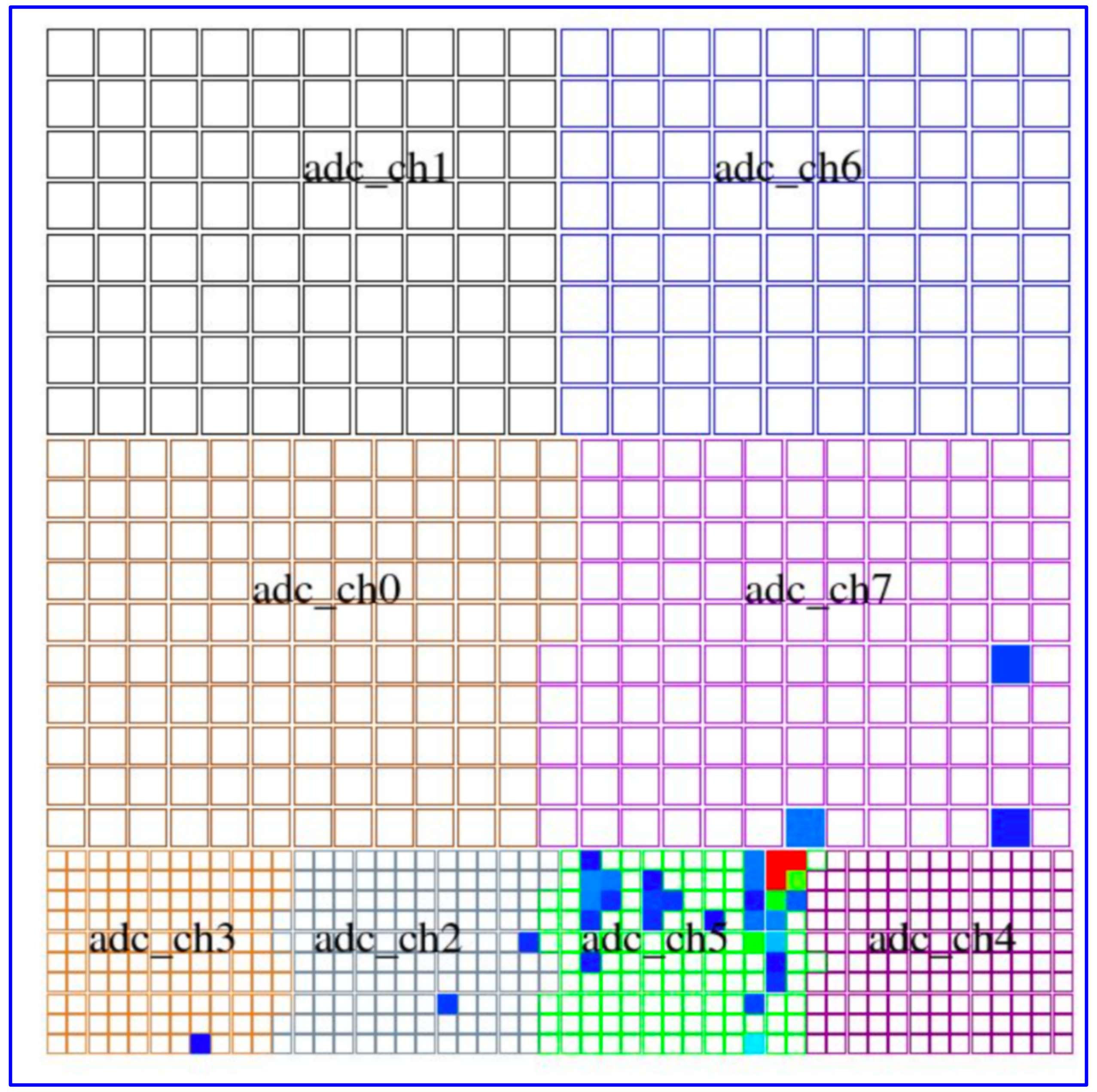
- ❖ Mapping:

  Pixel Pad => APV channels
- ❖ Verifying mapping:

  Take data with APV & SRS

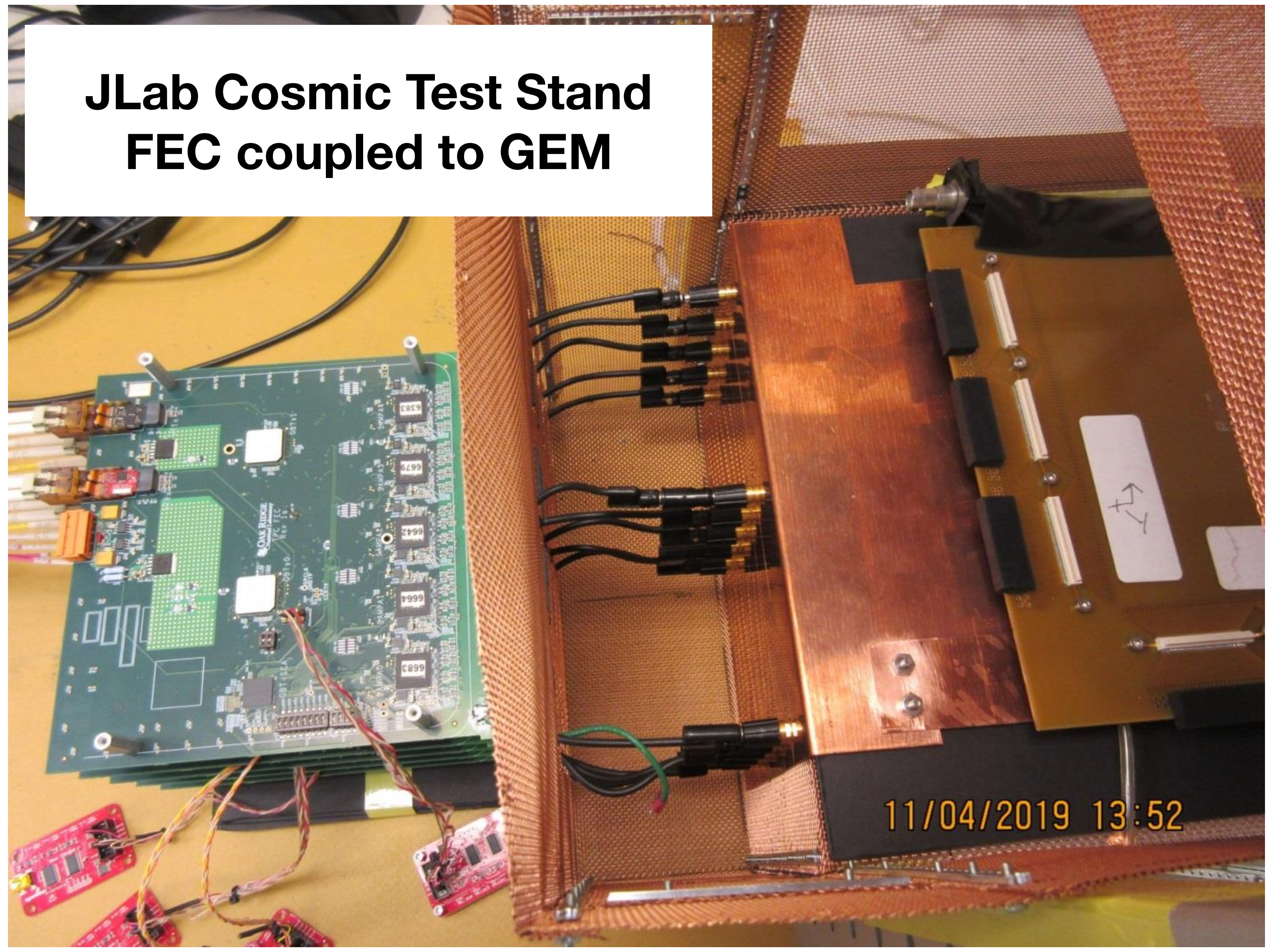


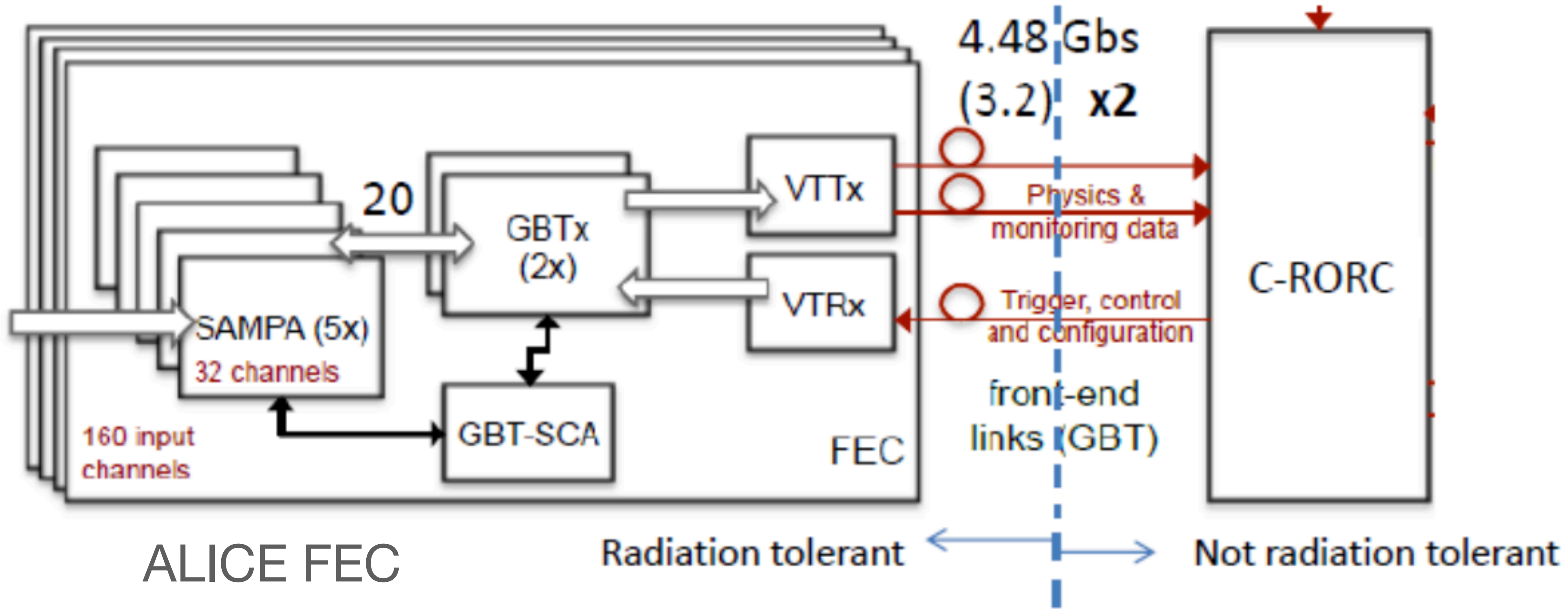
❖ ***Correct mapping was confirmed***



Front-End Readout

All pics: E. Jastrzembski (JLab)





FEC – Front End Card (160 ch / FEC) (5 FEC = 800 ch)
C-RORC – Common Read Out Receiver Card (PCIe)
GBTx – Giga Bit Transceivers
GBT-SCA – GBTx Slow Controls Adapter
VTTx, VTRx – Fiber optic transceivers

- SAMPA ASIC:
  - Pre-amp, ADC, zero-suppression…
  - (M. Bregant, Sao Paolo)

- Prototyping stand at JLab (E. Jastrzembski et al.) - originally stand used Oak Ridge SAMPA FEC for ALICE TPC
- mTPC prototype will use sPHENIX TPC FEC and SAMPA v5 (80ns shaping time)

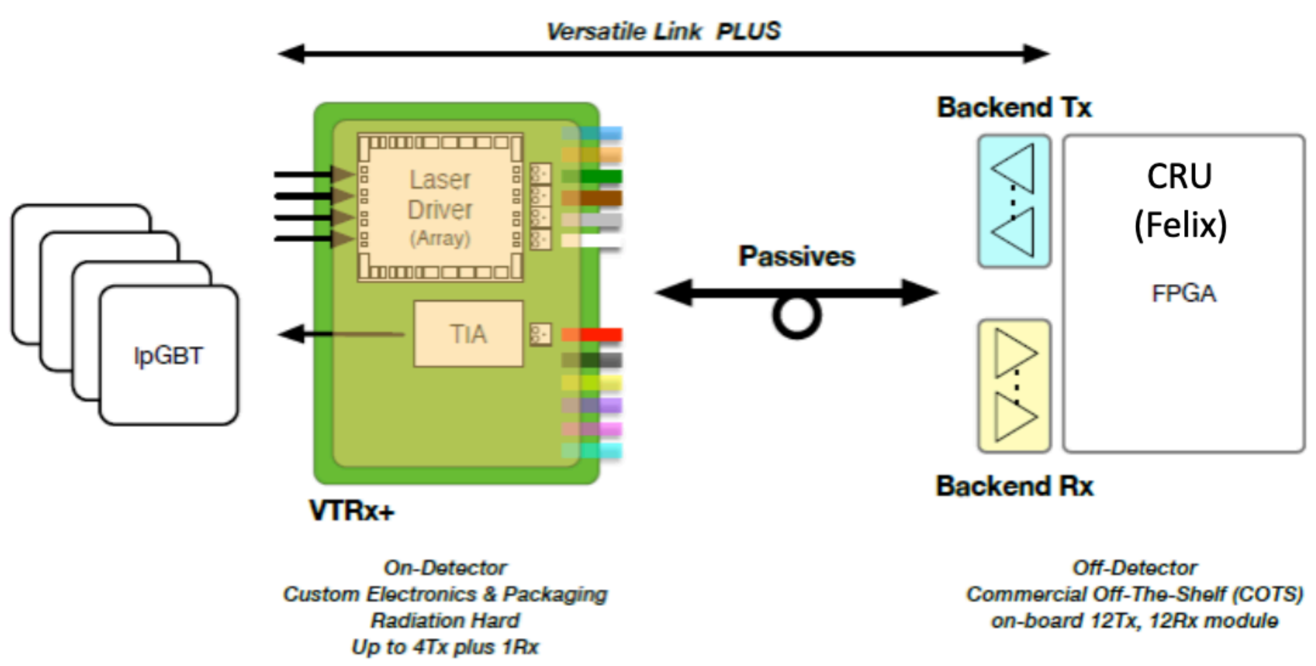
- SAMPA FECs can be operated in triggered or continuous mode
- TDIS has been a driver for streaming readout at JLab

Updated Components Procured for TDIS FEC

From E. Jastrzembski JLab

- 2nd generation CERN rad hard data transmission components
- Developed for high luminosity LHC
- **lpGBT**
  - > 2x higher data rates than GBT
  - Includes some of GBT-SCA functionality (I2C, GPIO) so no extra ASIC required
- **VTRx+**
  - Supports higher data rates of lpGBT
  - Higher integration - 4 Tx and 1 Rx (1 Tx and 1 Rx for VTRx)
  - Rx (downlink) for configuration of FEC

Versatile Link+ (lpGBT)



uplink (**x4**)
5.12 or 10.24 Gb/s

downlink
2.56 Gb/s

lpGBT uplink modes

5.12 FEC5 – 4.48 Gb/s user data
5.12 FEC12 – 3.84 Gb/s user data

10.24 FEC5 – 8.96 Gb/s user data
10.24 FEC12 – 7.68 Gb/s user data

FEC = Forward error correction
(FEC12 more robust than FEC5)

(10.24 FEC12 uplink 2.4x higher data rate than **GBT-VTRx**)

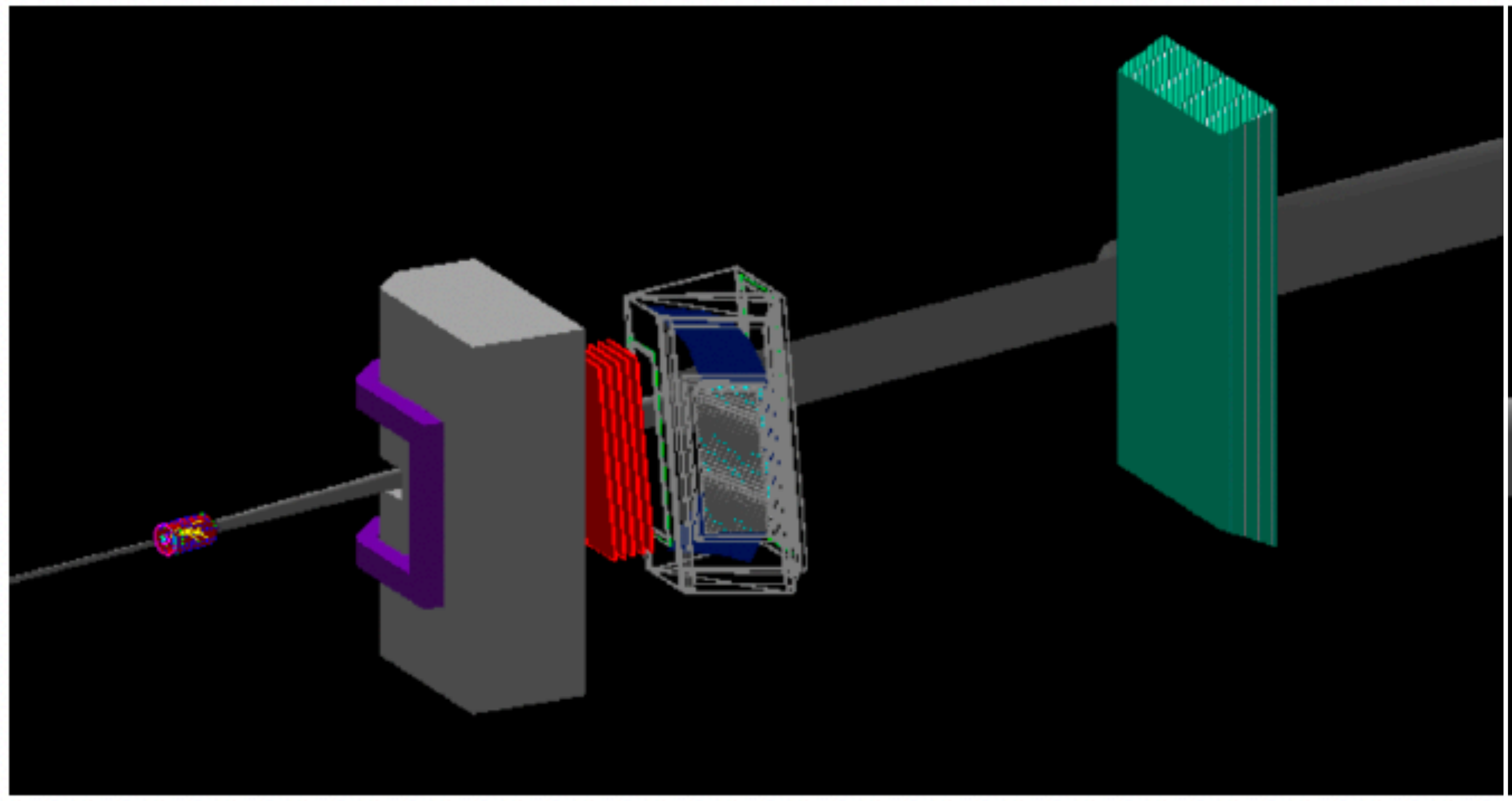
(CRU = Common Readout Unit)

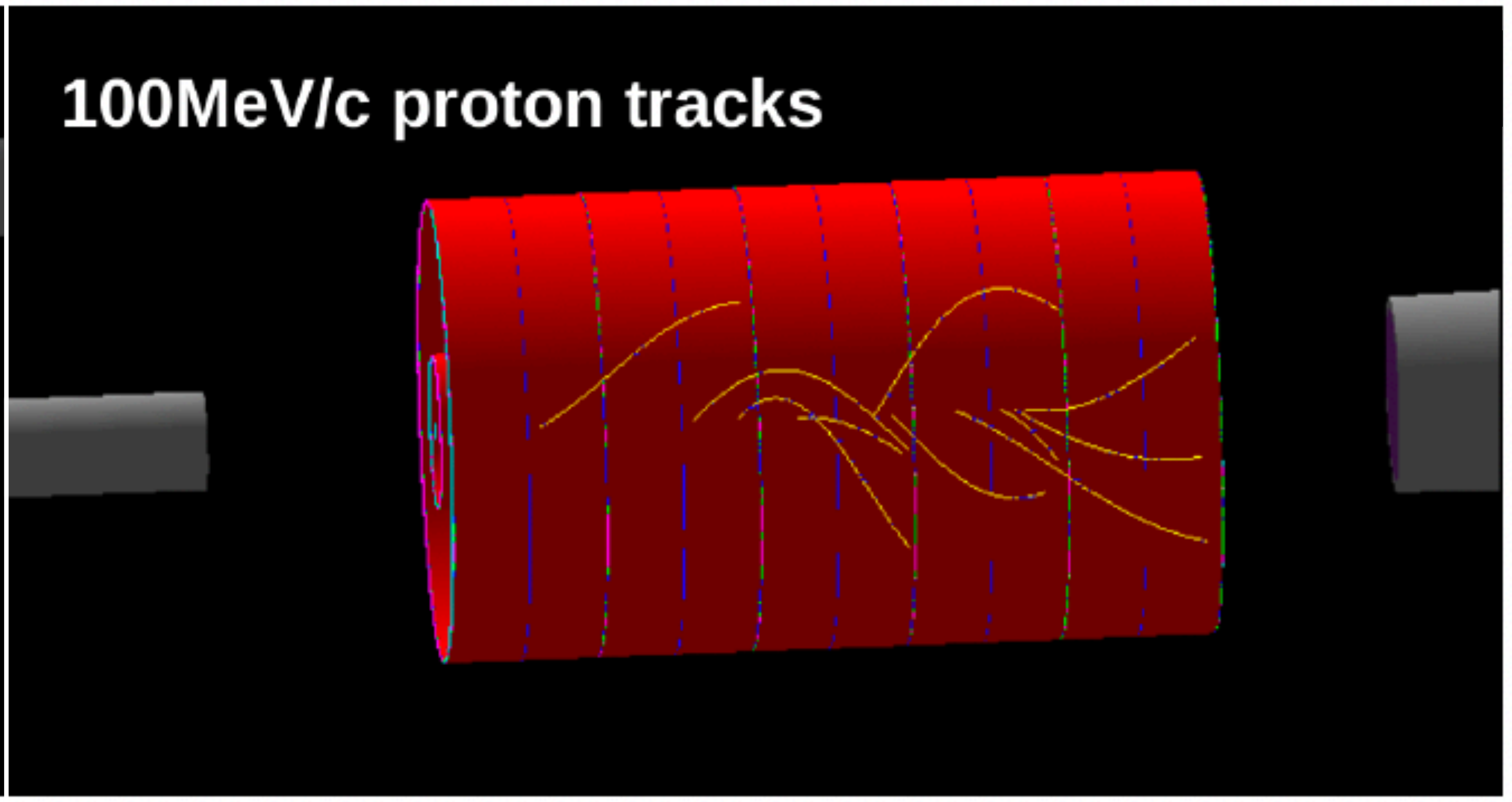
- 2nd generation CERN rad hard power DC-DC convertors
- **bPOL12V** (5.5-12V input, 0.63-5V output @4A)
  - +12V to FEC
  - Steps down voltage for input to bPOL2V5
- **bPOL2V5** (for HL LHC) (2.1-2.5V input, 0.6-1.5V output @3A
  - Generates SAMPA analogue and digital voltage rails
  - Generates lpGBT, VTRx+ digital rails

- All of the following components are in hand at JLab for a 50K channel TPC system:
  - SAMPA V5
  - lpGBT
  - bPOL12V
  - bPOL2V5
- VTRx+ for a 50K channel system is expected in early 2025

More info in back up slides if interested, including comparison between triggered, streaming or streaming plus DSP SAMPA modes

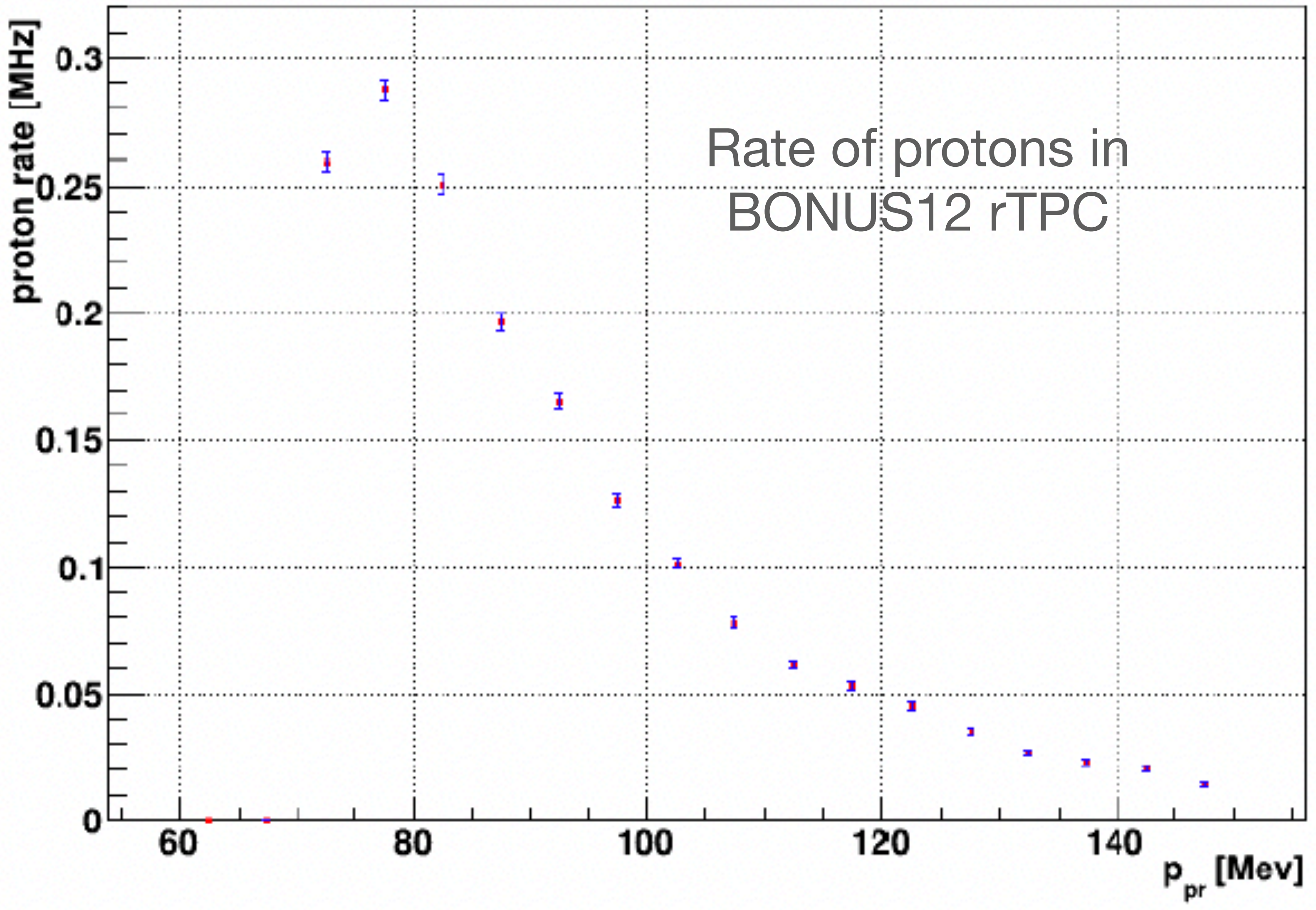
Simulated Fully in g4sbs



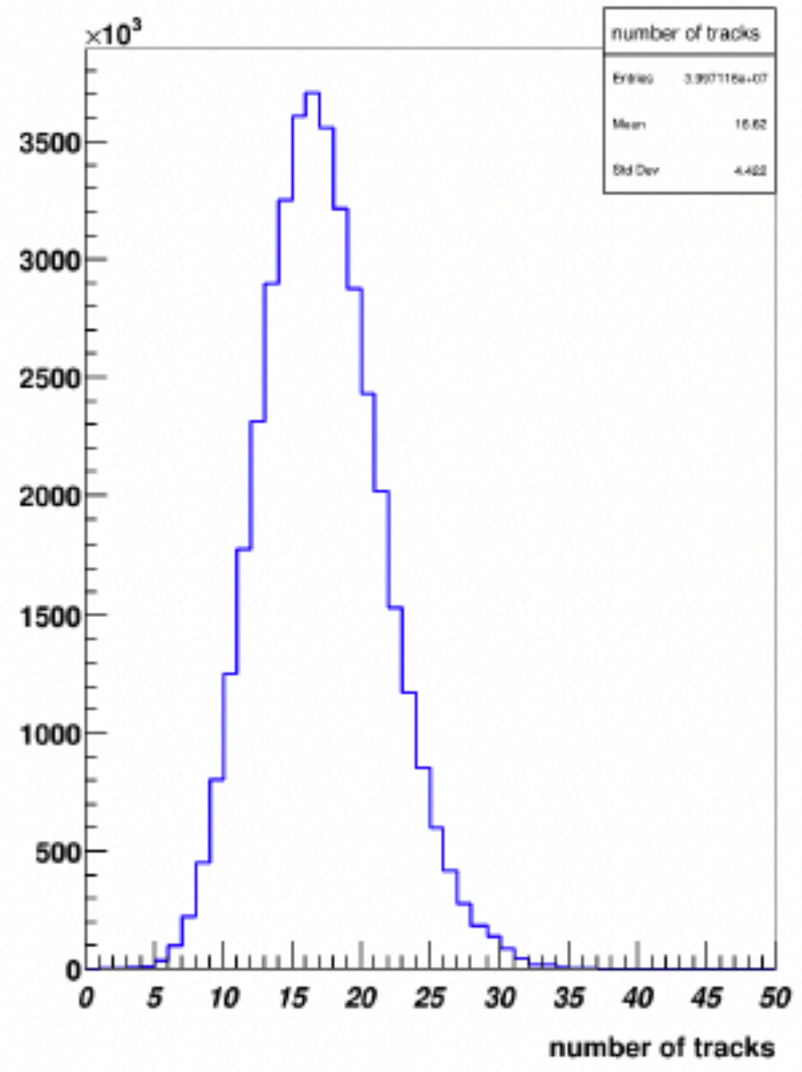


- *Team* of contributors (e.g. E. Fuchey, C. Ayerbe, R. Montgomery, A. Nadeeshani, A. Puckett, M. Carmignotto… …)
- Digitisation implemented

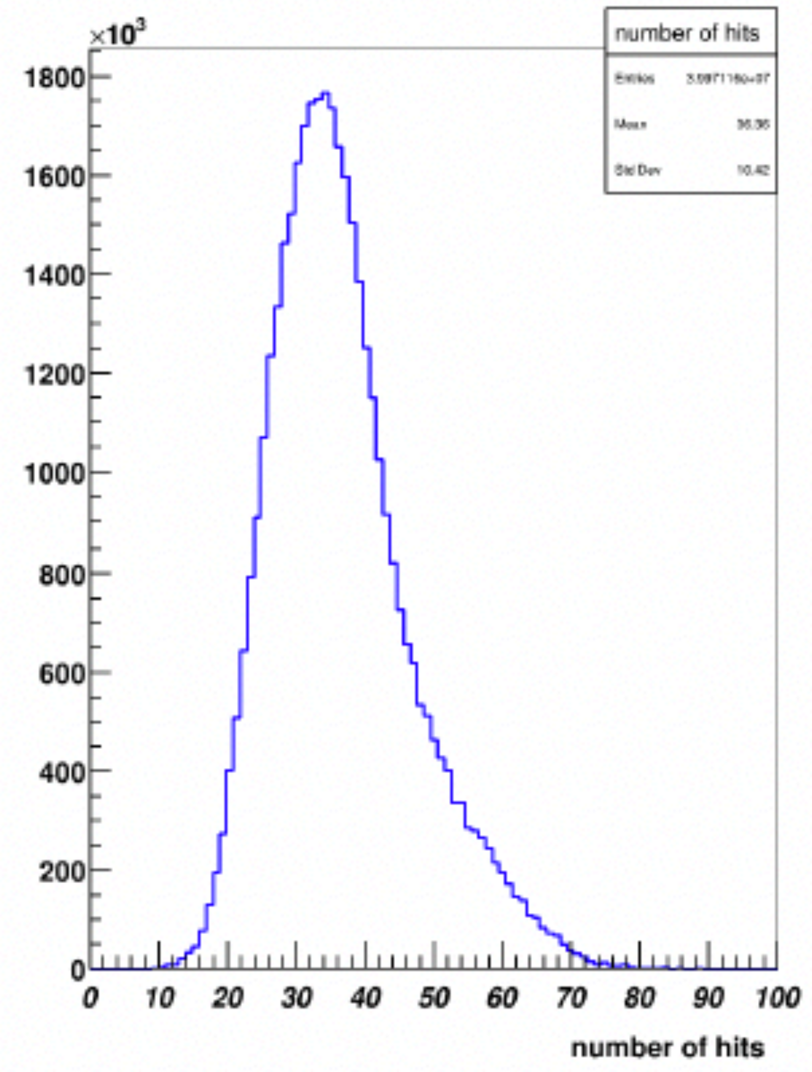
- mTPC also simulated using CERN's magboltz/garfield
  - Gas mixtures…



BONUS12 proton tracks per event



BONUS12 proton hits per event



Plots from A. Nadeeshani (MSU)

- Simulation benchmarked with BONUS12 data

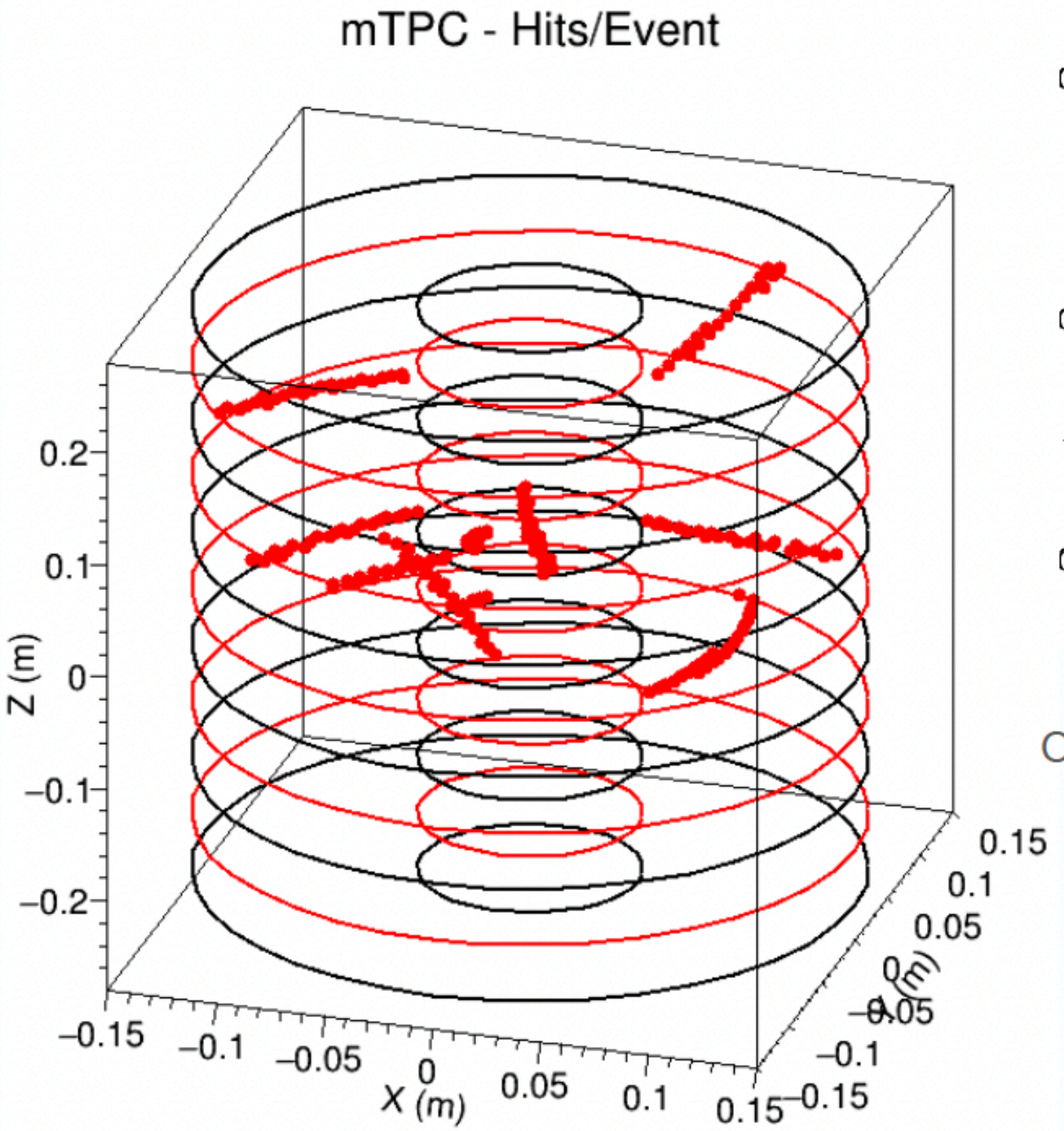
- TDIS simulated rates match observed BONUS12 rates
  - e.g. expected ~2k tracks per event in TDIS for tracking goal

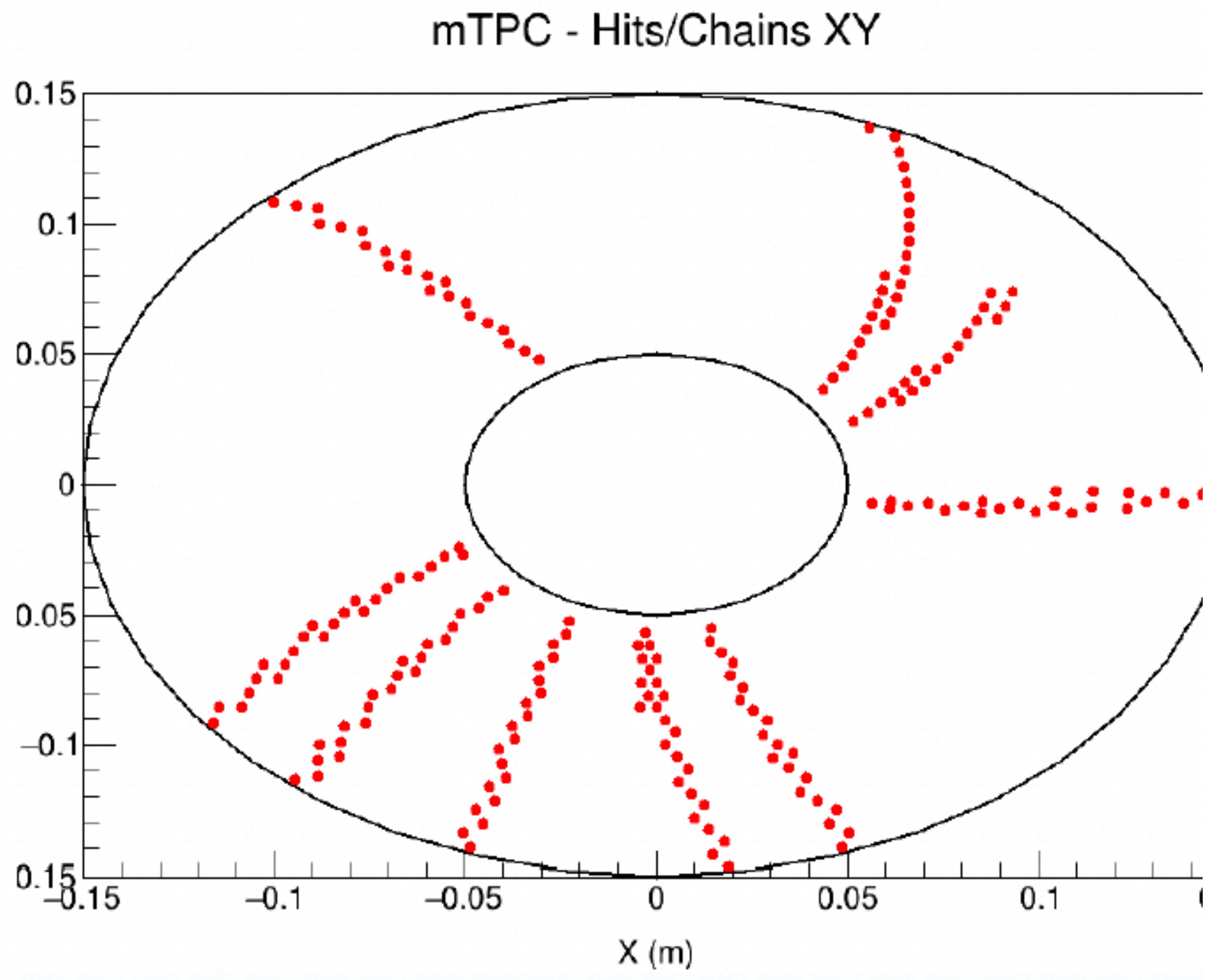
mTPC Tracking Algorithms

Demonstration of tracking capability is currently a key activity to enable us to remove the C1 status

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

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





Outputs from Python based toy model using Event Display

Slide from A. Nadeeshani (MSU)

Track Reconstruction

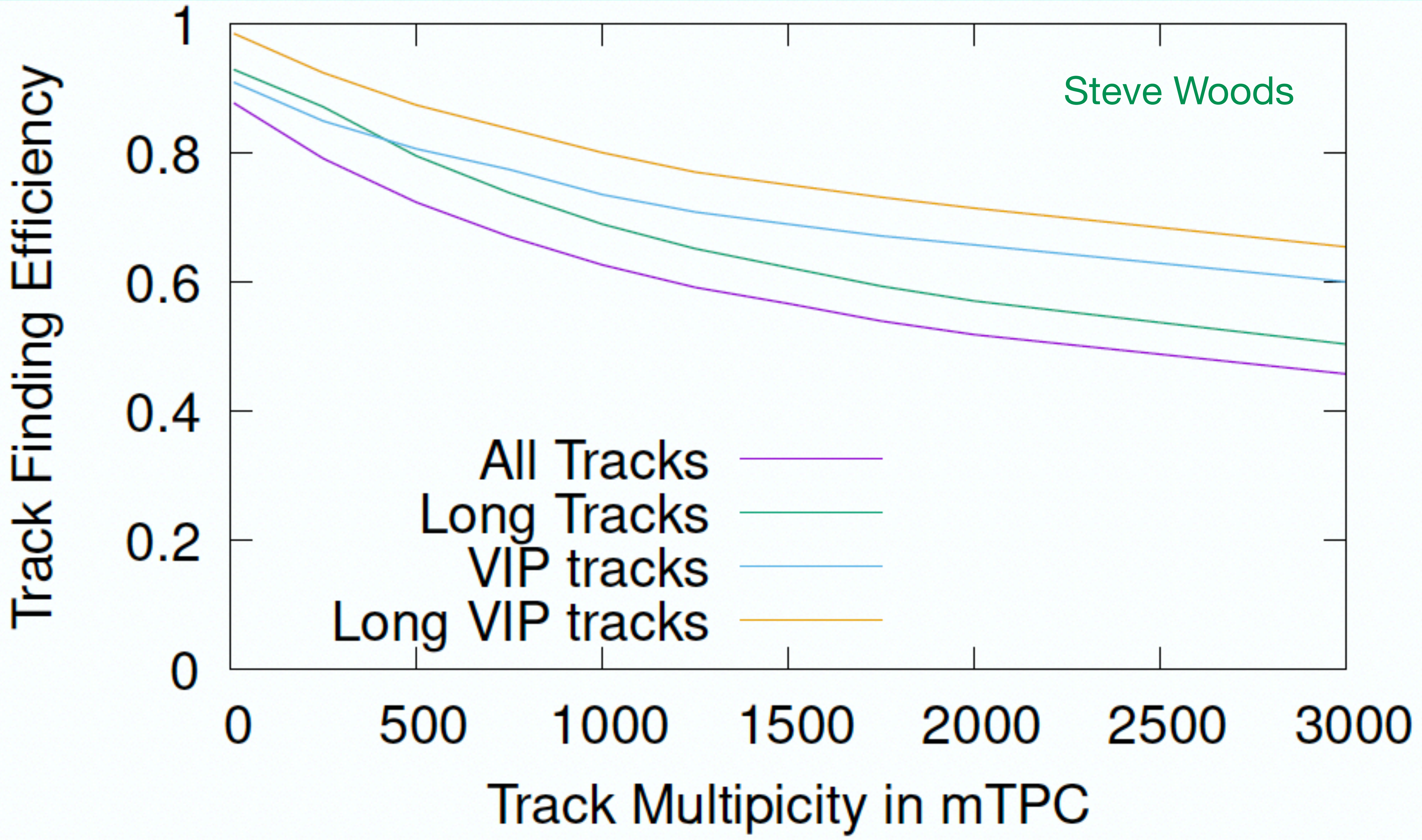
Using A Common Tracking Software

1. The Translate the tracking detector geometry in to analogous ACTS geometry:ACTS takes many formats of geometry input eg: GEANT4, DD4hep. For TDIS experiment we used the existing geometry in the GEANT4 and make gdml files.

2. ACTS has available ROOT Geometry plugin that can take relevant active TGeo objects and covert them into Acts: Surfaces. TGeo plugging developments are still ongoing.

Using Python based toy model

- Steve developed a chain finder method using a Python-based toy model simulation of the mTPC (multiple Time Projection Chamber).
- Subsequently, this method was applied to digitized hits derived from proton events in the G4SBS based TDIS Geant4 simulation.
- The toy model serves as a valuable tool for swiftly grasping the mTPC's angle and momentum acceptance, which is determined by its geometry.
- Additionally, it aids in testing tracking algorithms.
- The chain finder method demonstrates track finding efficiencies exceeding 50% for multiplicities of up to 3000.



Slide from A. Nadeeshani (MSU)

At multiplicity of 2000 tracks per event (~1GHz in entire mTPC volume) shows efficiency of 68% for clean tracks

Summary

- Meson structure → crucial component of nucleon structure
- Comparing π/K → direct experimental insights into EHM
- Experimental data for π/K SF → **extremely sparse**

✓ TDIS at JLab → **unique** opportunity

- Understand nucleon & meson structure on deeper level
- **EHM community awaiting JLab TDIS experiment**
  - increased demand for JLab TDIS data wrt theory and future experiments…

✓ TDIS 11GeV → very important gateway for future programs

- Future EIC, proposed EicC, 20+GeV JLab
- TDIS @ 11GeV key for realising:
  - meson tagging techniques, challenging novel instrumentation, improving models/predictions…

✓TDIS at JLab status

- Passed jeopardy last year
- Numerous active developments on-going (eg front-end, prototyping, tracking …) with lots more to come

Thank you

And thank you to TDIS colleagues for input

Back Up

MTPC High Voltage

- **5 independently powered, double-sided TPC Modules**

  Each TPC module has:
  → 2 drift regions, GEM amplification layers, readout boards
  → shared Cathode

- **Single HV to GEMs with voltage divider chain**

  → 3 HV channels for each double-sided TPC
  → 15 channels total required.

- **Want capacity for over 1.5 kV /cm to shorten drift time window for reduced backgrounds – over 10 kV required.**

- **CAEN R1570ET to power each MTPC segment.**
  (4-channels, 15 kV max)

  - Tested two supplies so far, 3 more to be tested
  - 3 test cables made by Fast Electronics – Tested to operate to 11 kV

Standard Symbols PS

Rectangular prototype TPC not yet being powered with these supplies

Plan to modify HV box with it returns to JLab

Slide from E. Christy (JLab)

From E. Jastrzembski JLab

1 – SAMPA in Triggered Mode

- Modest experiment trigger rate (~6 KHz)
- High channel hit rate (~1 MHz)
- Small mTPC drift time (1.5 μs)
- More efficient to operate the SAMPA chips in triggered mode than in continuous mode

- Set channel thresholds below pedestal – all channels report samples for each trigger
- 2 μs capture window, 20 MHz ADC sampling (40 samples/window, 10 bits each = 400 bits/ch/trig)
- 50 bit header + 20 aux bits for each channel => 470 bits/ch/trig => 15,040 bits/chip/trig

- **25 KHz triggers** => 376 Mb/s/SAMPA
- Use 3 e-links @ 160 Mb/s each from SAMPA to lpGBT
- lpGBT: 5.12 Gb/s FEC12 supports 24 e-links @160 Mb/s each
- **8 SAMPA →   1 lpGBT   →   1 VTRx+** (single Tx used)

From E. Jastrzembski JLab

1 – SAMPA in Triggered Mode

Notes:

- Front-end card with 8 SAMPA + 1 lpGBT + 1 VTRx+ may not be the optimal solution for the geometry of the mTPC.
- 1 lpGBT can support 12 SAMPAs when operated at 10.24 Gb/s FEC12. Negatives: Front end card becomes more complex with additional SAMPAs.

From E. Jastrzembski JLab

2 – SAMPA in Streaming Mode (DAS)

- **ALICE card**: 2.5 SAMPA → 1 GBT (SAMPA V4 – 160 ns shaping time)
- Can stream **ALL** ADC samples at **5 MHz** sampling rate (FEC limitation) in DAS mode
- Also can stream at **20 MHz** sampling with zero suppression applied (DSP mode)

- For **SAMPA V5**, DAS mode must be at **10 MHz** sampling to be equivalent (80 ns shaping time)
- Can do: **2 SAMPA →** **1 lpGBT** at **10 MHz** sampling (DAS mode)
- lpGBT 10.24 Gb/s FEC12

- **8 SAMPA →** **4 lpGBT** **→** **1 VTRx+** (4 Tx used)

From E. Jastrzembski JLab

2 – SAMPA in Streaming Mode (DAS)

- **ALICE card**: 2.5 SAMPA → 1 GBT (SAMPA V4 – 160 ns shaping time)
- Can stream **ALL** ADC samples at **5 MHz** sampling rate (FEC limitation) in DAS mode
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- lpGBT 10.24 Gb/s FEC12

- **8 SAMPA →** **4 lpGBT** **→** **1 VTRx+** (4 Tx used)

From E. Jastrzembski JLab

3 – SAMPA in Streaming Mode (DSP- zero suppression)

- **1 MHz** average hit rate per channel, **20 MHz** ADC sampling
- Frame = 1000 samples = 50 µs => 50 hits/frame/ch
- Zero suppression: 1 hit ~ 9 samples (3 pre, 3 above threshold, 3 post) (**80 ns** shaping time)
- 1 hit = 100 bits (ADC = 90, TDC = 10)
- Bits/frame/ch = 5060 (100 bits/hit x 50 hits/frame + 50 (header) + 10 (counter))
- SAMPA bits/frame = 161,920 (5060 bits/frame/ch x 32 ch)
- **SAMPA bit rate = 3.24Gb/s** (161,920 / 50 µs)
- Use 11 e-links @ 320 Mb/s each

- **2 SAMPA →** **1 lpGBT** can handle **1 MHz** average hit rate per channel with **20 MHz** ADC sampling (zero suppression applied) - lpGBT 10.24 Gb/s FEC12

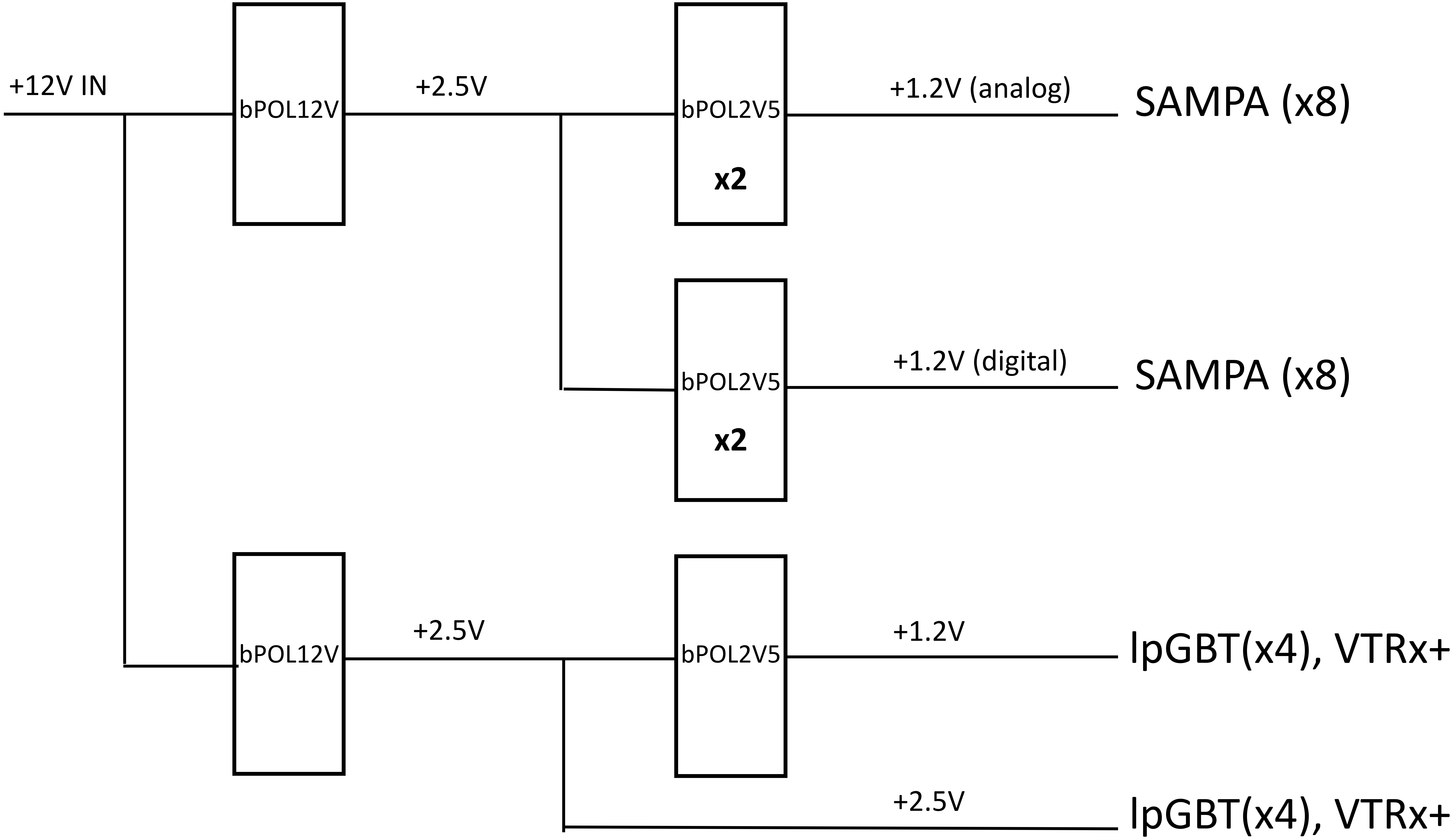
- **8 SAMPA →** **4 lpGBT** → **1 VTRx+** (4 Tx used)

From E. Jastrzembski JLab

Comments

- A streaming architecture will incur additional costs at the concentrating units (FELIX CRU) where **4x** the number of transmission links must be handled
- Streaming will also require **4x** the number of PCs to support the CRUs, as well as more network links to build events

Possible Front end Card Power Architecture (8 SAMPA → 4 lpGBT → 1 VTRx+)

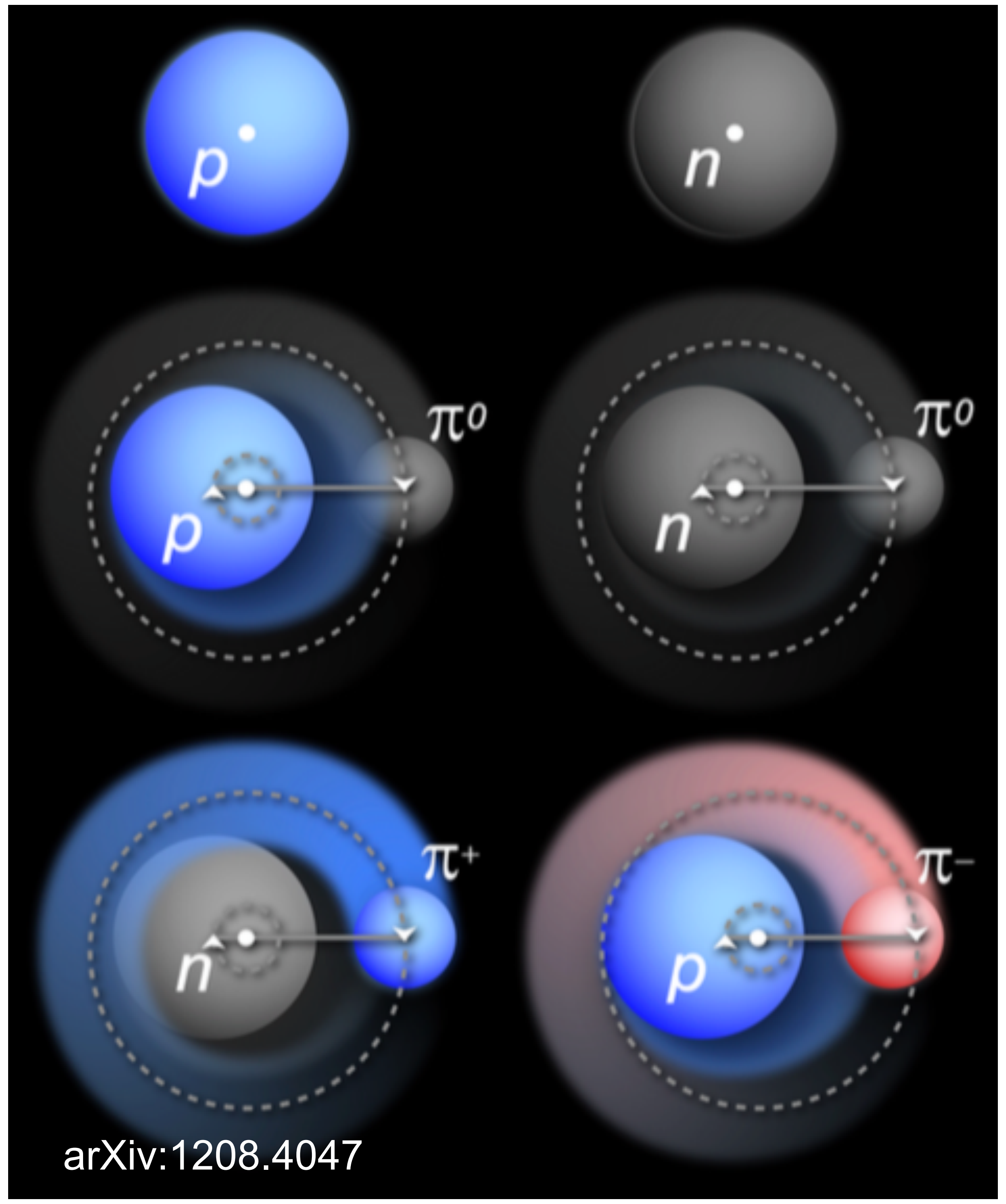


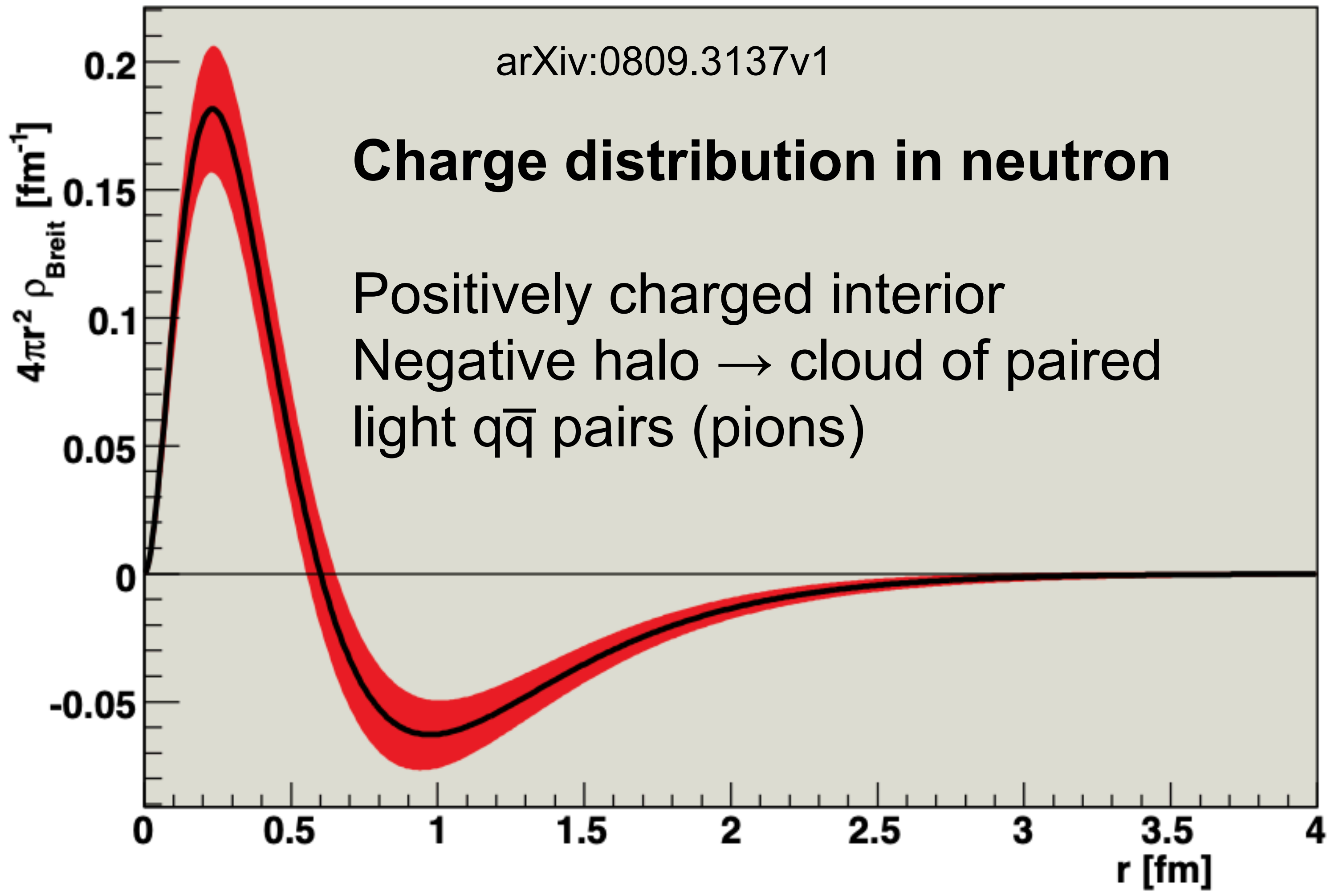
Count:

bPOL12V = 2
bPOL2V5 = 5

From E. Jastrzembski JLab

Why Mesons?

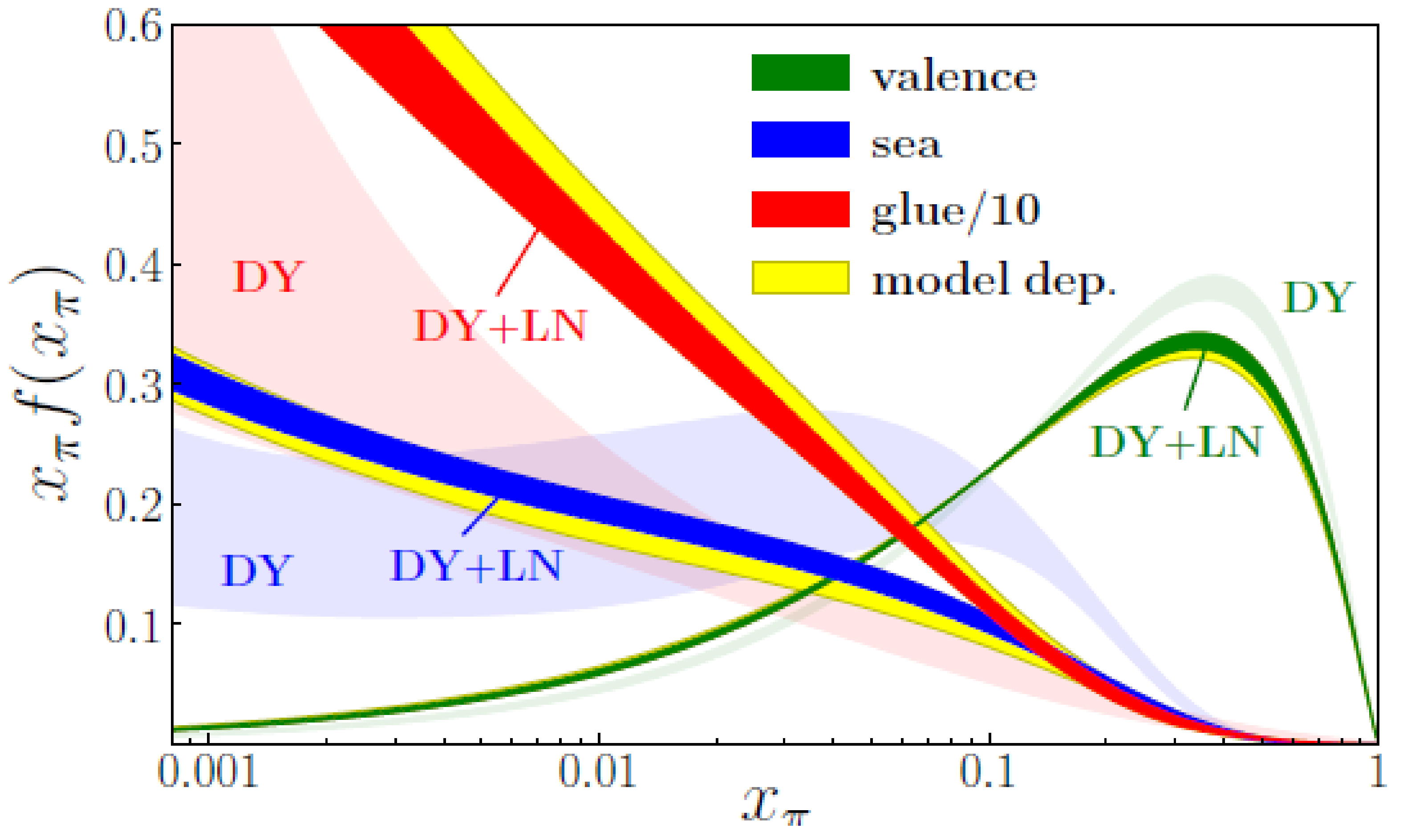


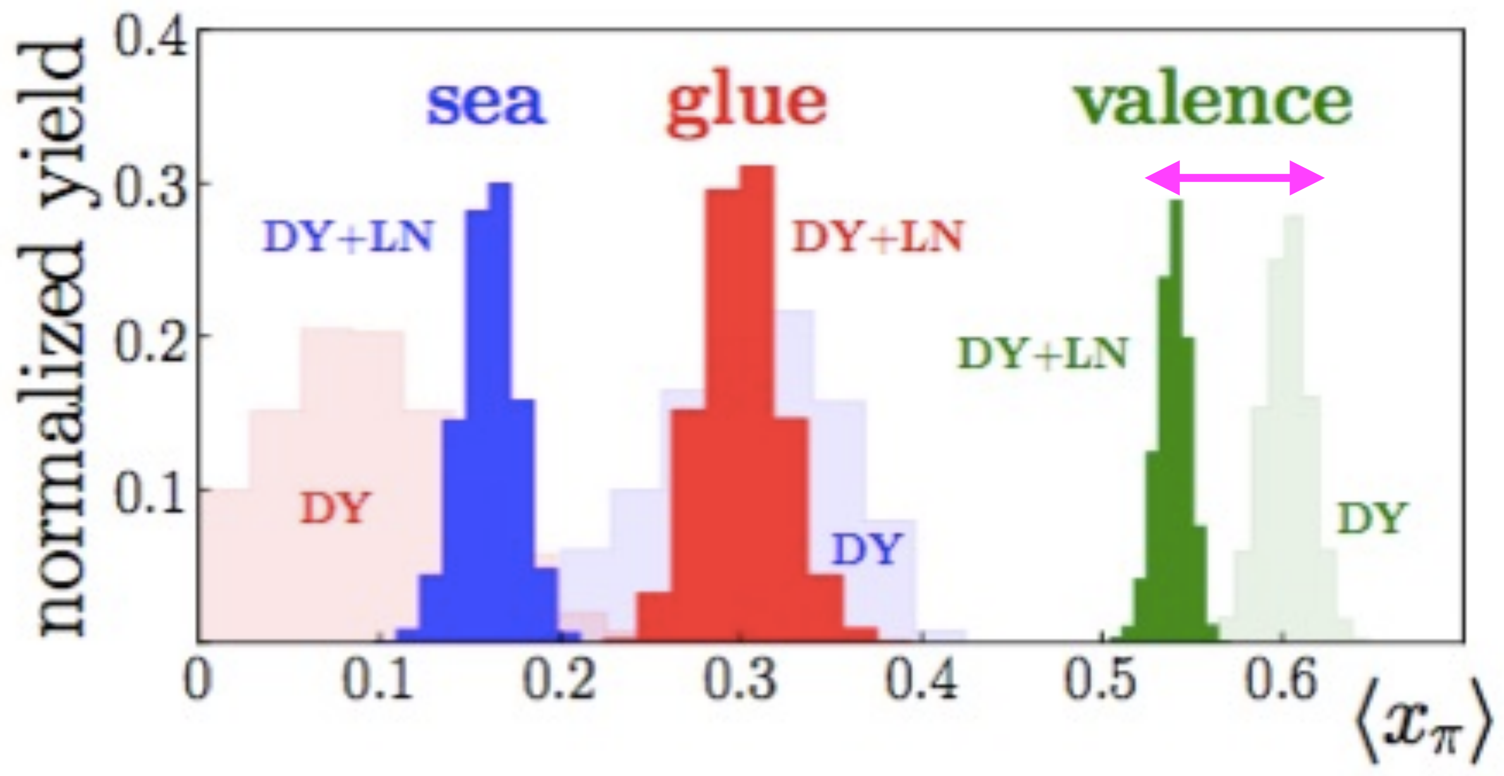


- Experimental evidence for nucleon's mesonic content
  - e.g. Nucleon charge densities; meson form factors from electroproduction off nucleon, up/down sea $q\bar{q}$ flavour asymmetry …
- Substantial theoretical work - data *very* sparse
  - e.g. exact mesonic content of nucleon unknown!
- Light mesons play key roles in nucleon/nuclear structure
- Pion
  - Long range NN interaction; simplest QCD state; dynamical mass generation (Goldstone boson); flavour asymmetry in nucleon sea; nucleon/nuclear PDF…
- Kaon
  - Strangeness; momentum fractions carried by sea/glue; combine with valence quark for full PDF evolution…
- Critically, TDIS will offer new information for unravelling nucleon mass enigma

Example Previous Data

P.C. Barry, N. Sato, W. Meltnichouk, Chueng-Ryon Ji (JAM Collaboration), Phys. Rev. Lett. 121, 152001 (2018)





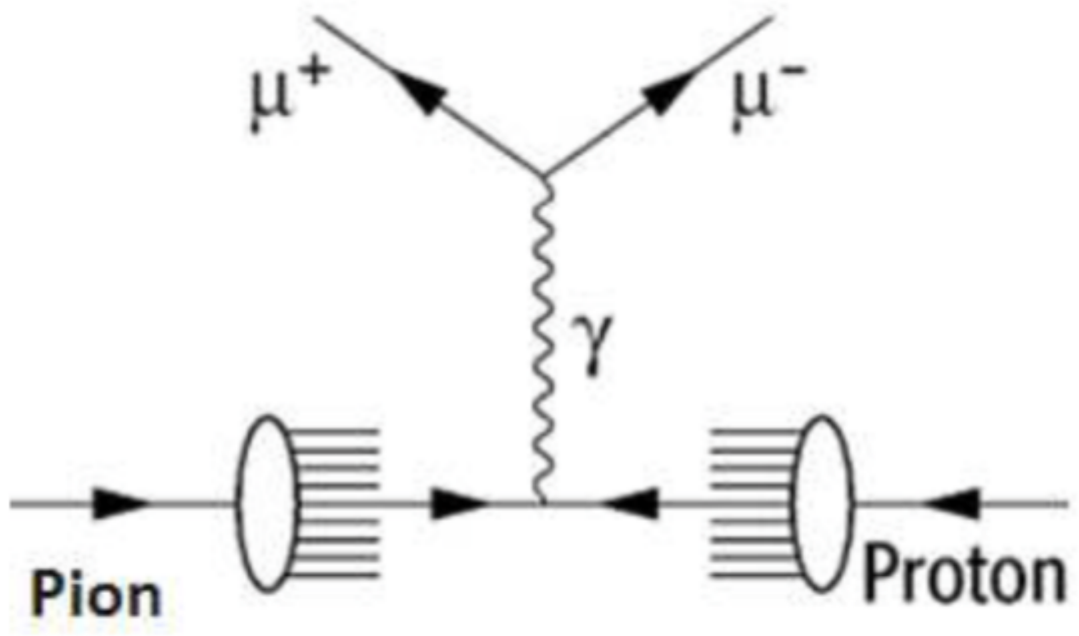
mom fraction carried by sea/glue/ valence

Example: JAM combined HERA/DY analysis for PDF fitting, w/ MC technique for uncertainties

Non-overlapping uncertainties - tension at large x

<u>Valence region - Drell Yan</u>

- Limited CERN/Fermilab data



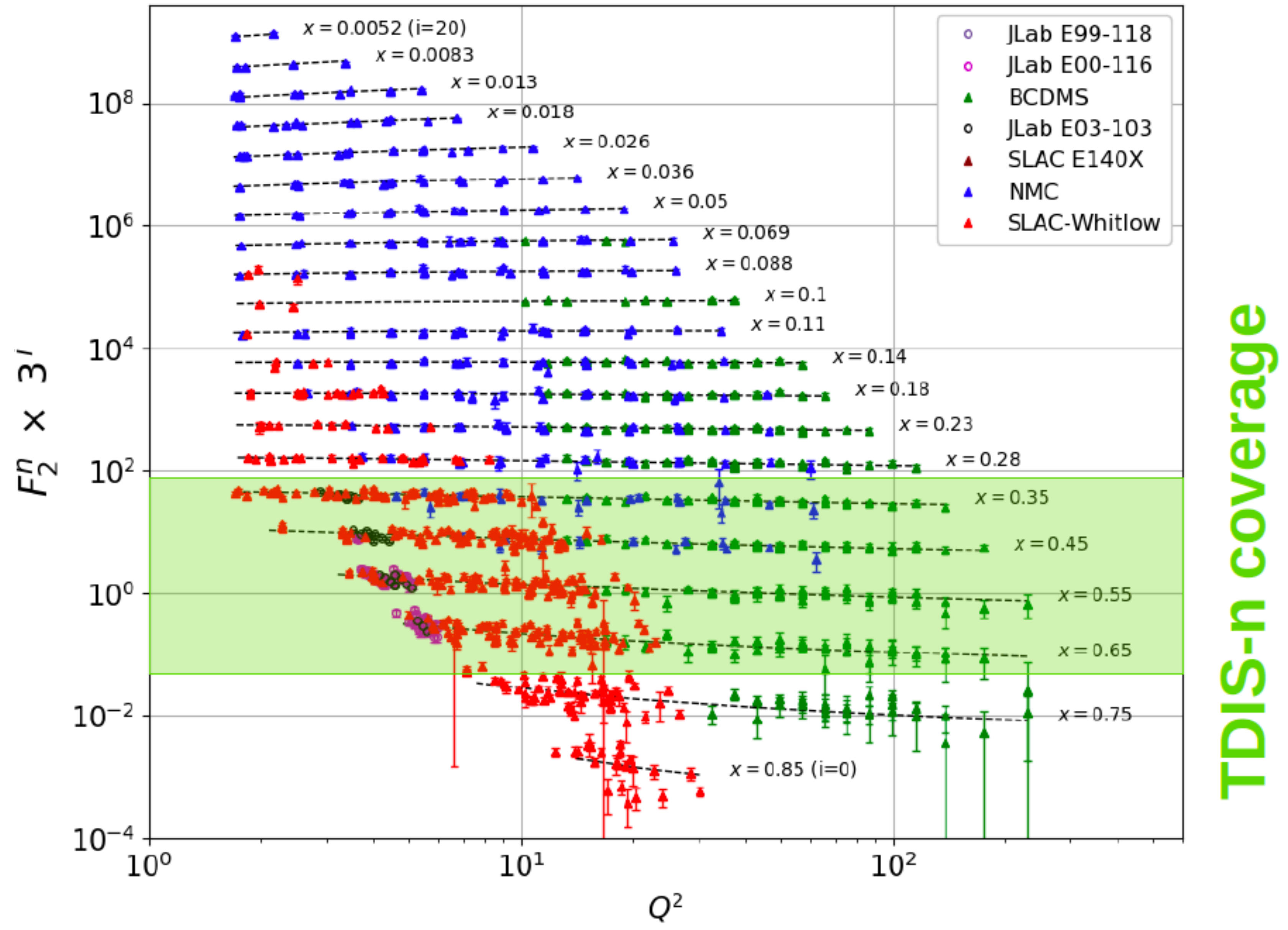
- Large-x interesting - substantial theory
  - pQCD, DSE, light-front, …, NLO, gluon re-summation
- Practically non-existent data for kaon

<u>TDIS</u>

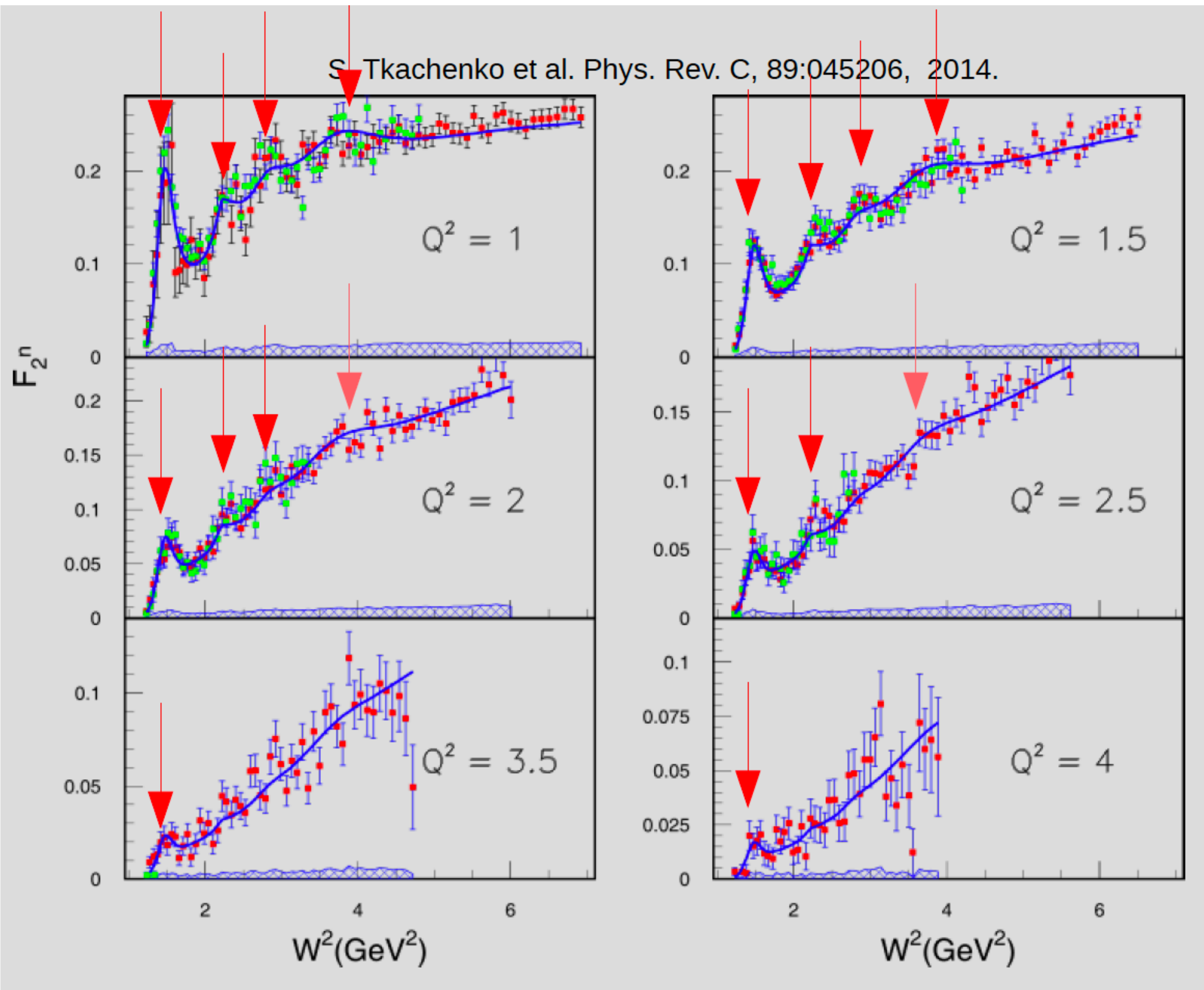
- *Direct* probe
- Independent cross-check
  - gluon re-summation, and PDF universality
- Extend to neutral pions - check for isospin dependence
- More data essential to reduce uncertainties in global PDF

Also…TDISn for Neutron Structure

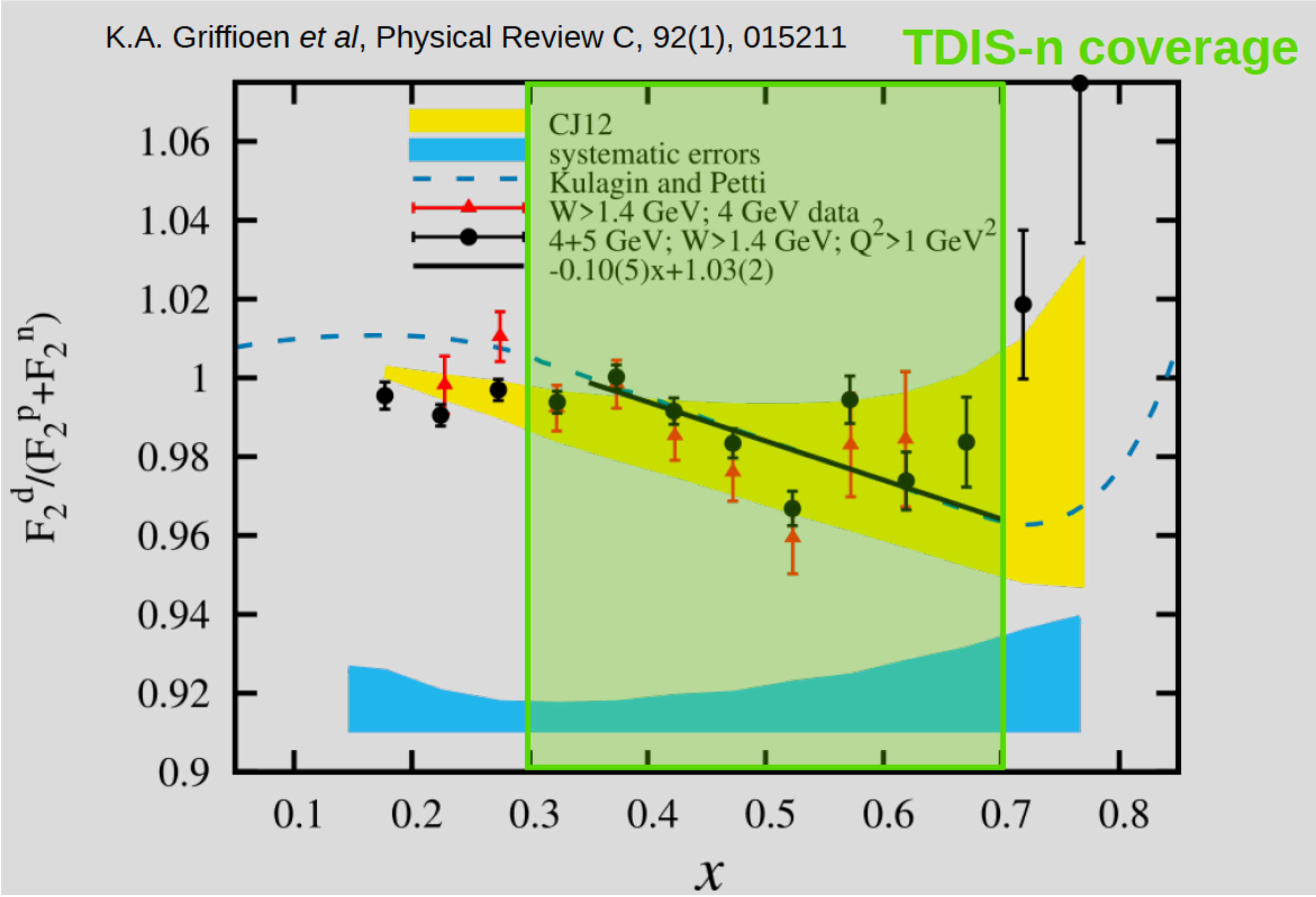
Neutron F_2 SF



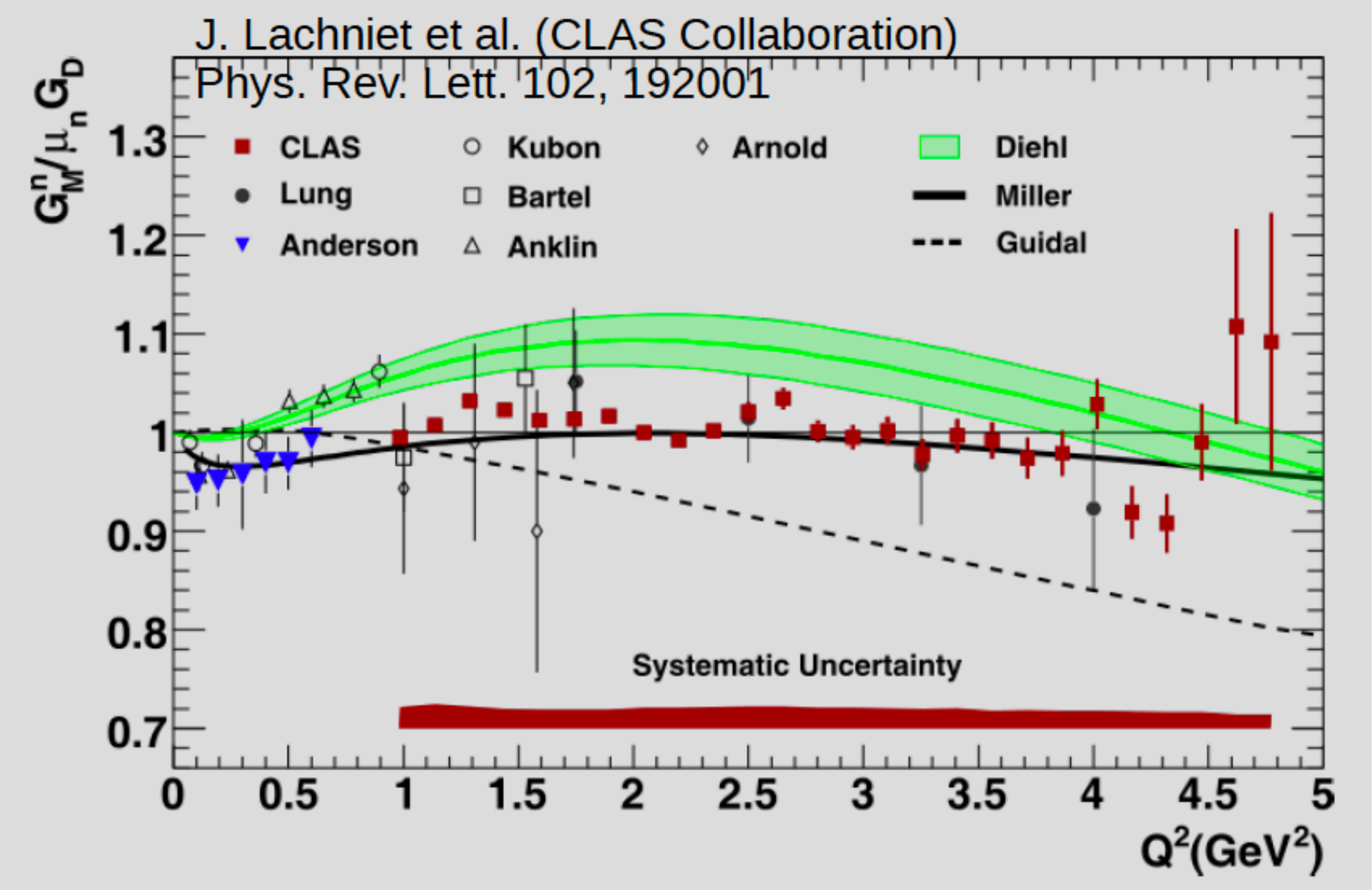
Resonance Region SF



EMC effect in deuteron

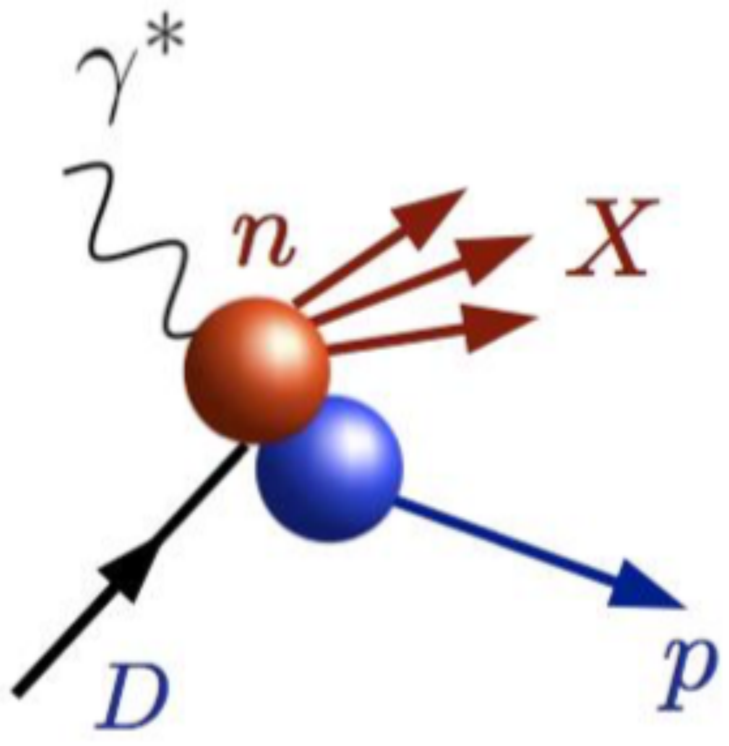


Elastic e-n scattering and EM form factor G_M^n



- Run Group C12-15-006B PAC49 (spokespeople/plots: J. Arrington, C. Ayerbe, E. Christy, E. Fuchey, C.E. Keppel, S. Li, R. Montgomery, A.S. Tadepalli)

- Effective free neutron target
- c.f. BoNuS, BoNuS12, MARATHON
- Neutron SF… plus other topics



- Independent cross-check systematics
- Increased statistics in TDISn range
- Calibrate mTPC acceptance and efficiency
  - QE scattering on deuteron: HCAL for n; mTPC for p; SBS for e′
- Independent normalisation check of tagging method across experiments

Background Rates

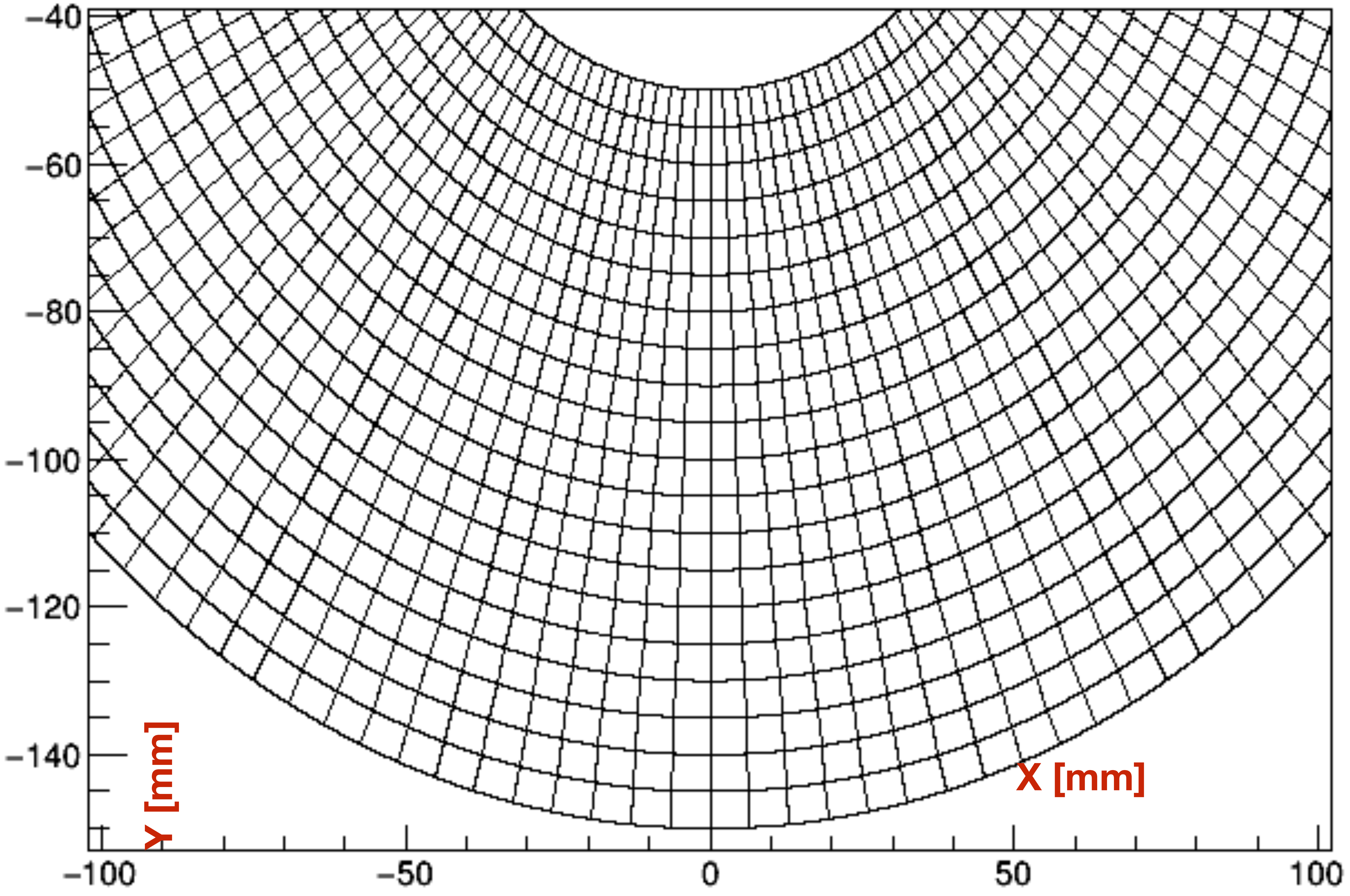
TABLE I: Simulated rates in the entire mTPC for different processes and particle production (**in MHz**).

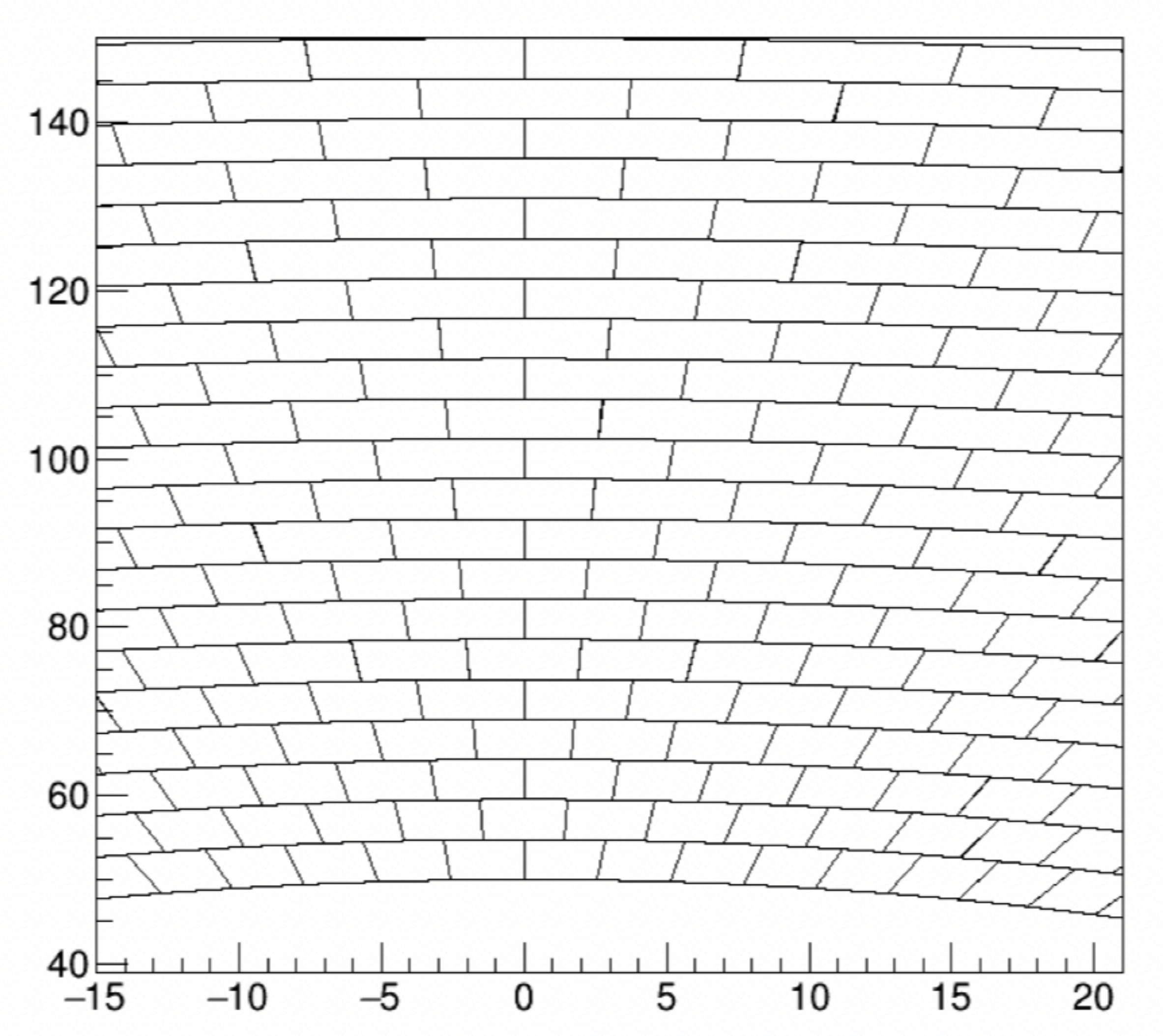
Reaction	π^+	π^-	p
Elastic (H_2)			170
Quasielastic (D_2)			480
Inelastic (p)	0.7	0.5	10.5
Inelastic (n)	0.43	0.69	8.6

Numbers from C. Ayerbe

These are rates in entire mTPC volume, so divide by 10 for rate per chamber

Readout Pads

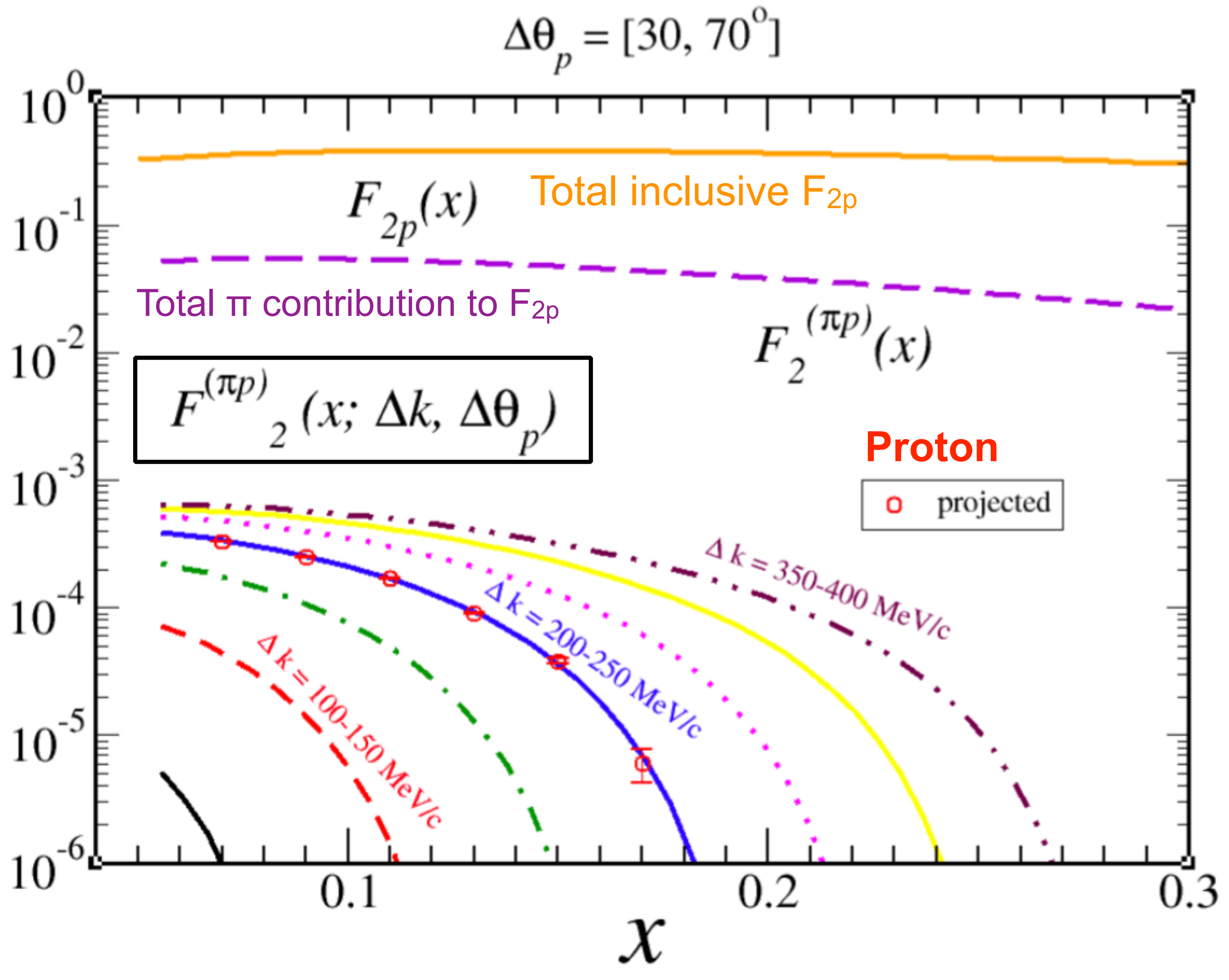


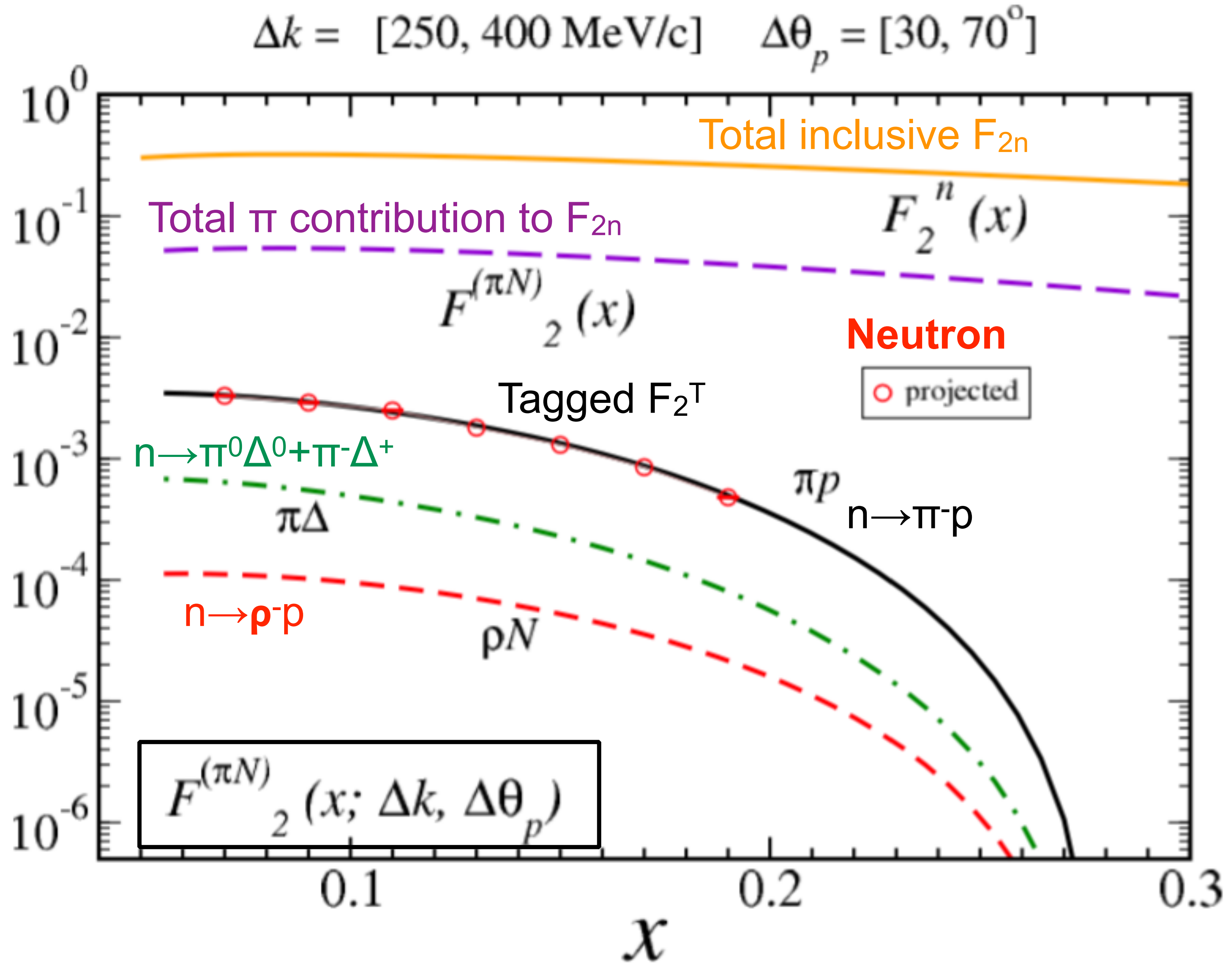


- 122 pads per ring, 21 rings
- Pads staggered by half width
    - First ring has first pad centre at phi-0
    - Pads in each successive ring shifted by ring ID * half angle subtended by pad

Need the Unique Luminosity Available at JLab

T.J. Hobbs, Few-Body Syst 56, 363 (2015)





- Predictions based on phenomenological pion cloud model (T.J. Hobbs)
- Tagged orders of magnitude smaller than DIS signal → need high luminosity!
- Measure ratio of tagged to total inclusive DIS cross-sections (reduce systematic uncertainties)

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

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

TDIS Method

- Projected rates/beam time/results used phenomenological pion cloud model
  - T.J. Hobbs, Phenomenological implications o the Nucleon's Meson Cloud, Few-Body Syst 56, 363 (2015)
  - H. Holtmann et al., Nucl. Phys. A 596, 631 (1996)
  - W. Melnitchouk, A.W. Thomas, Z. Phys. A 353, 311 (1995)

- Contribution to inclusive nucleon F_2 from scattering off virtual pion:

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

(z = light cone momentum fraction of initial nucleon carried by pion)

- Unintegrated distribution function (light-cone momentum distribution of π in nucleon):

$$f_{\pi N}(z) = \frac{1}{M^2}\int_0^\infty dk_\perp^2\, f_{\pi N}(z, k_\perp^2)$$

$k_\perp$ = transverse momentum of pion

- Semi-inclusive tagged SF is un-integrated product:

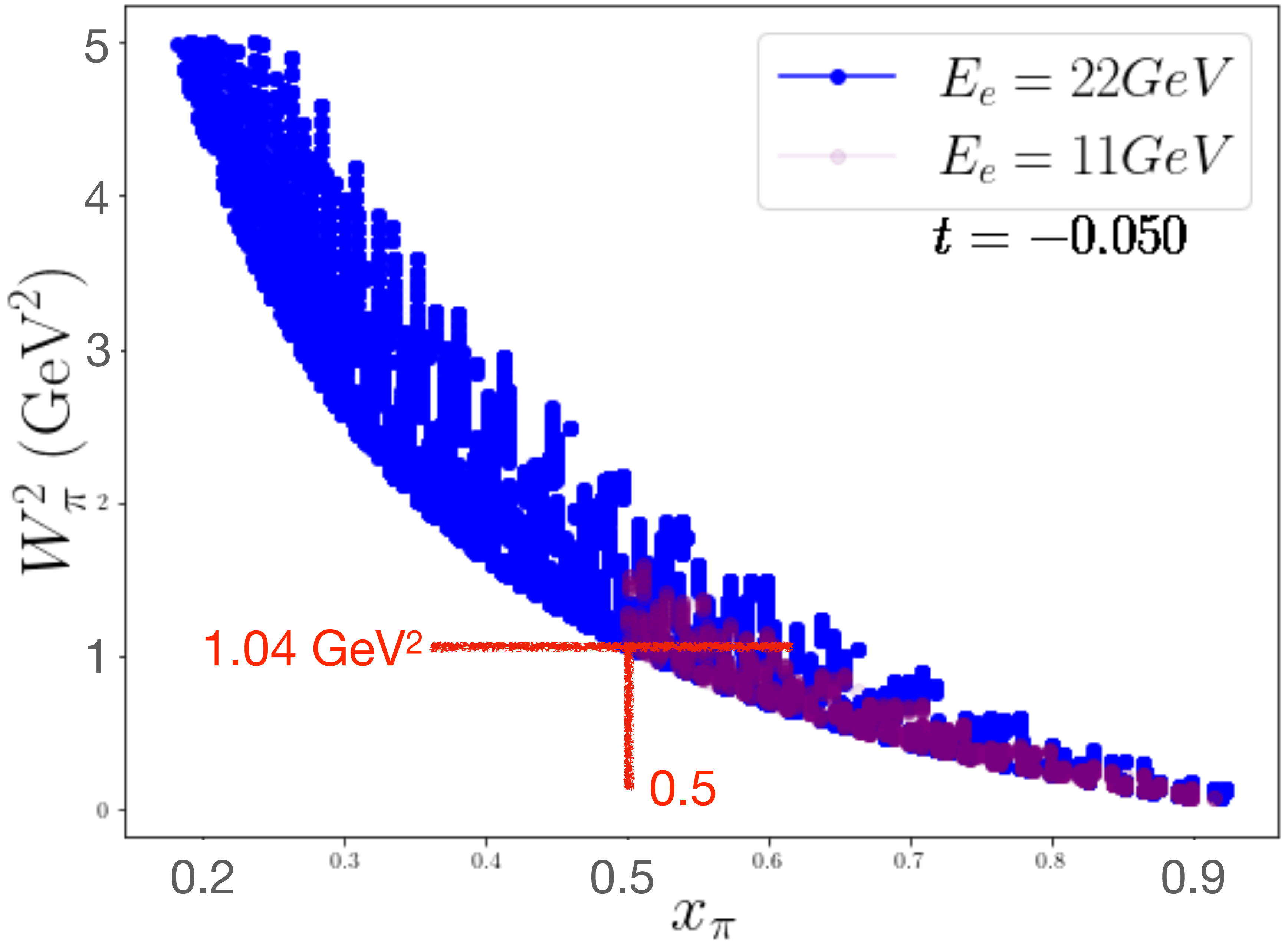
$$F_2^{(\pi N)}(x, z, k_\perp) = f_{\pi N}(z, k_\perp)\, F_{2\pi}\left(\frac{x}{z}\right)$$

Pion "flux" **Pion SF**

- Interested in z≲0.2; x<z → defines maximum x, Q^2 (beam 11GeV)

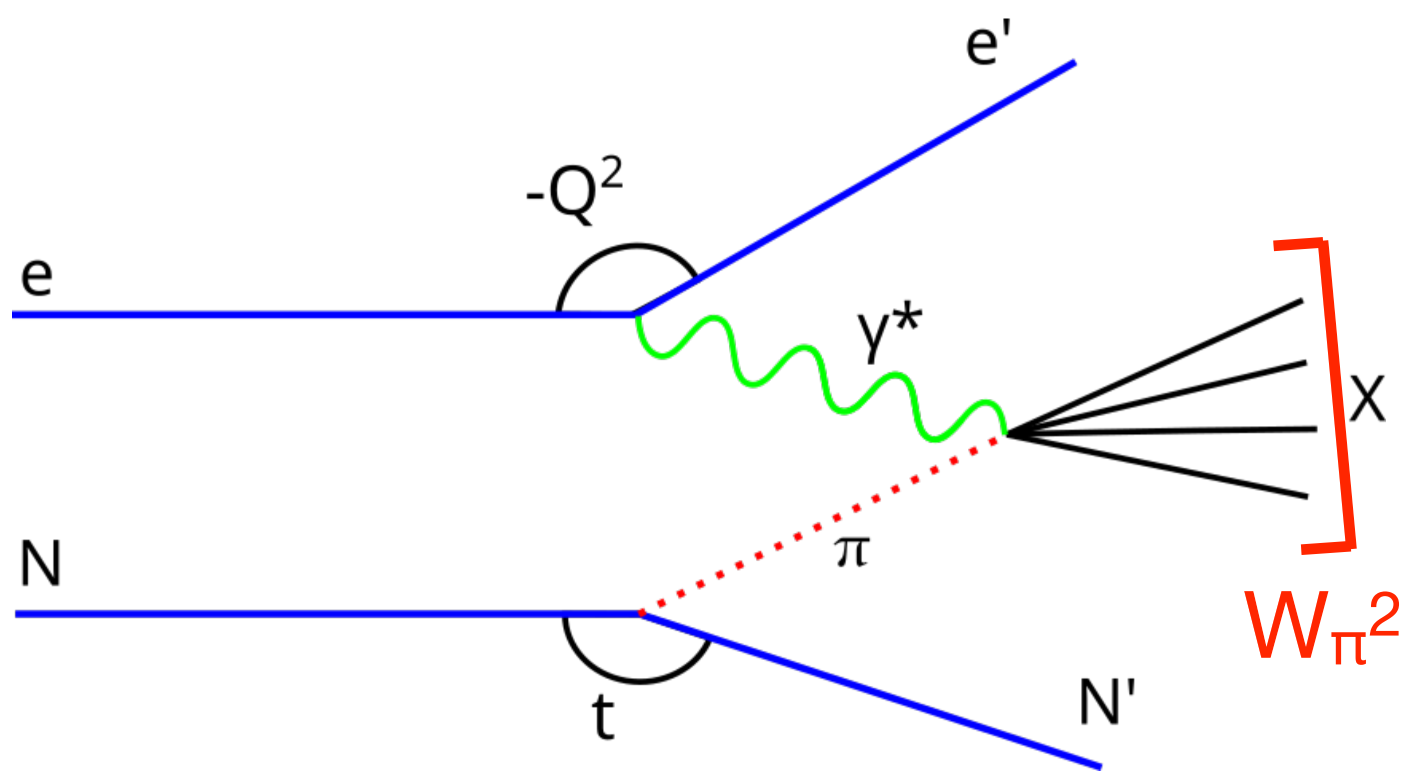
JLab22 Extension Studies

Plot: C. Ayerbe (W&M)

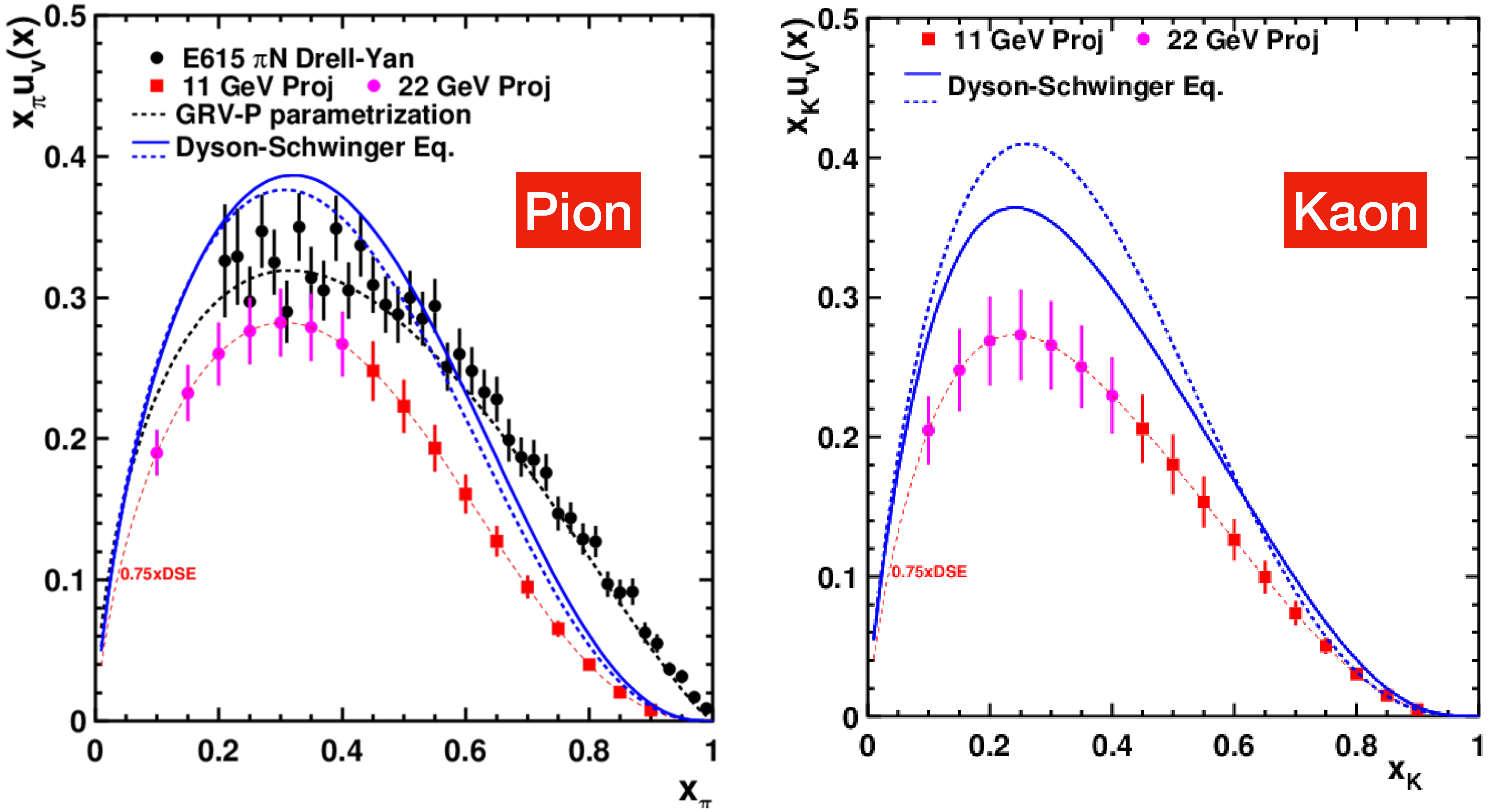


- Phase space projections based on Patrick Barry (JLab)
- Includes T.J. Hobbs' et al. F_2^π model and JAM PDFs

- Vastly expands kinematic phase space (e.g. Q^2, W^2, x_π, k_T)
- e.g. W_π^2 and x_π
- PDF studies: W_π^2 > 1.04GeV^2 to minimise ρ resonance
- 22GeV: More data available above 1.04GeV^2
- 11GeV: still data above 1.04GeV^2 for PDF studies
- 11GeV: novel studies of resonances at low W_π^2
- 11GeV: crucial to realise challenging experimental technique



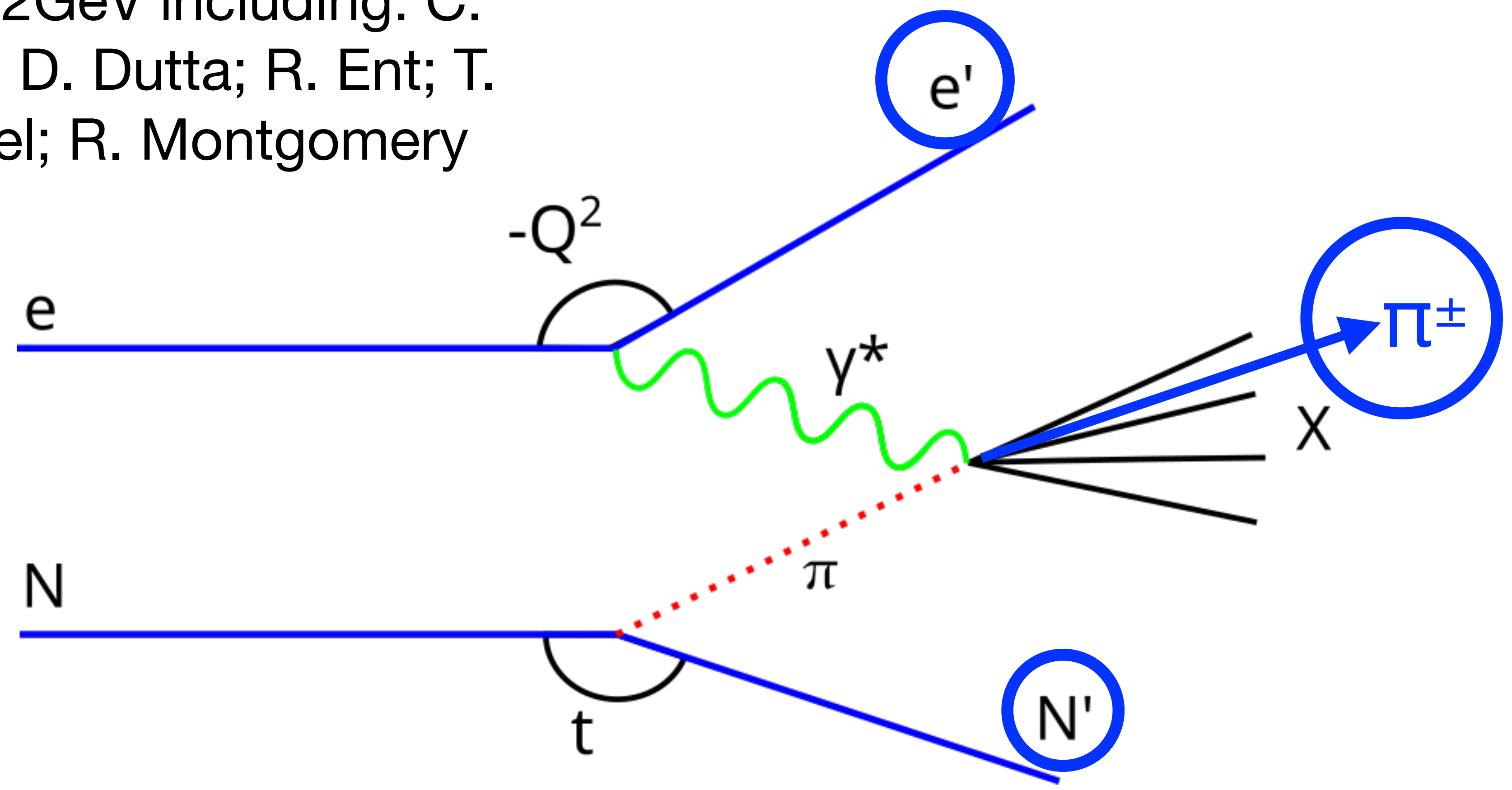
On behalf of members of group studying TDIS 22GeV including: C. Ayerbe; P. Barry; D. Dutta; R. Ent; T. Horn; C. Keppel; R. Montgomery



Plots: D. Dutta (MSU), T. Horn (CUA)

JLab22 Extension Studies

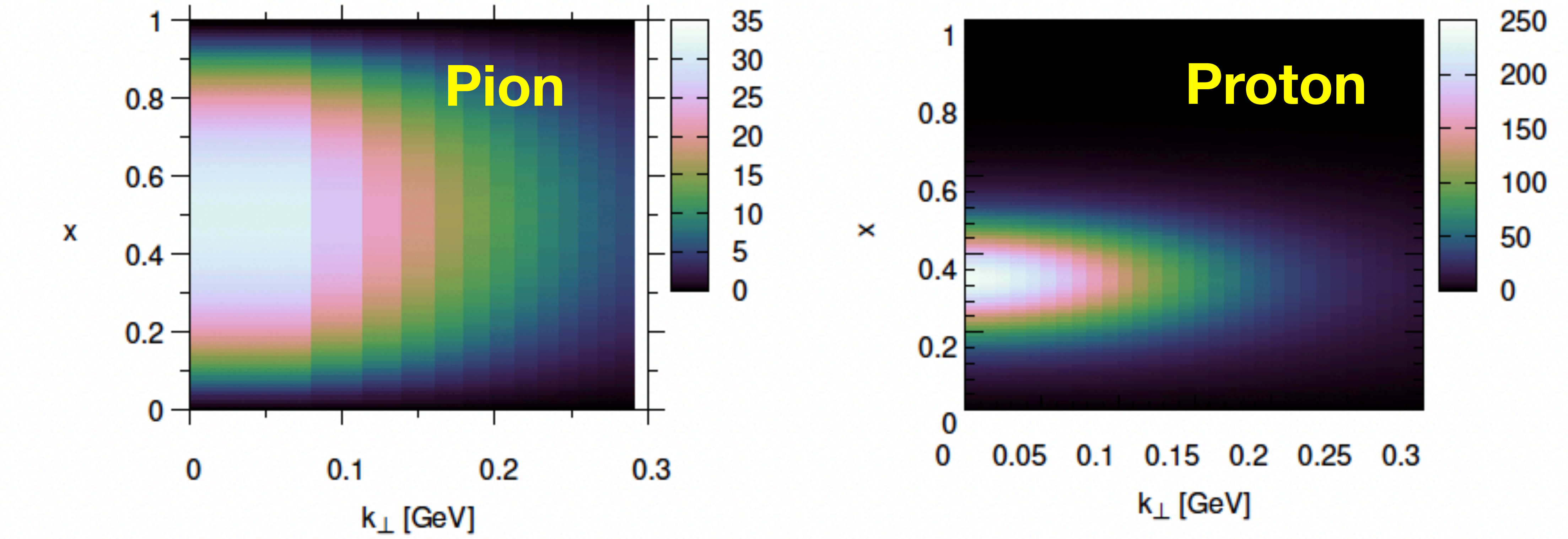
On behalf of members of group studying TDIS 22GeV including: C. Ayerbe; P. Barry; D. Dutta; R. Ent; T. Horn; C. Keppel; R. Montgomery



- Data available between W_π^2 1.04 and 4GeV^2
- SIDIS on virtual meson possibility → meson TMDs!
- Expect interesting differences between meson/nucleon TMDs

- Assume W_π^2 used to produce π
- Measure e', N' and π
- Would need to add detector for π

Leading twist unpolarised proton vs pion TMD



Tobias' slide from Light-Front

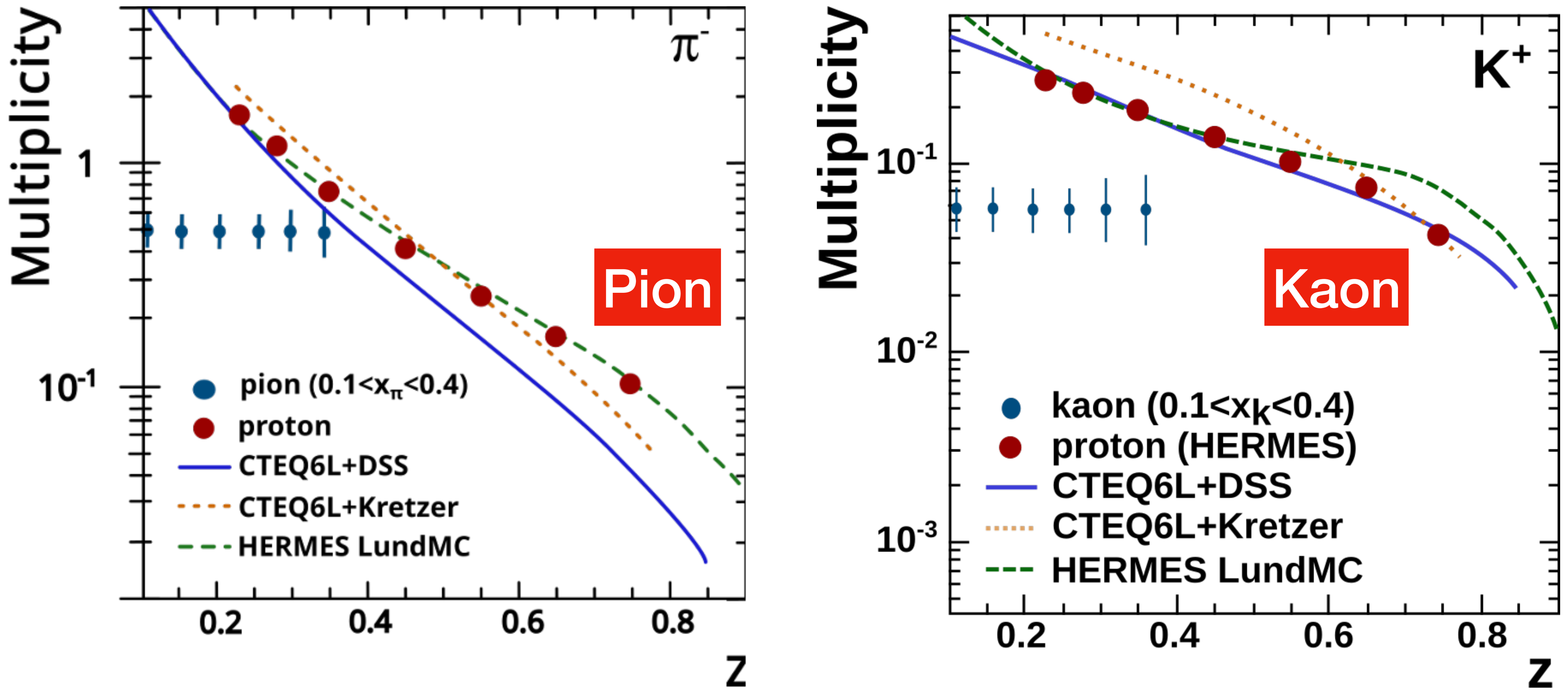
Figure: Leading twist unpolarized TMDs at the hadron scale. Left frame: Pion from Minkowski space Bethe-Salpeter equation model with constituent quarks, massive one-gluon exchange and quark-gluon form factor [1]. Right frame: Proton from a Light-front model with constituent quarks and a scalar diquark [2].

[1] W. de Paula, E. Ydrefors, J.H. Nogueira Alvarenga, T. Frederico, G. Salmè, PRD 105 (2022) L071505, and in preparation.

[2] E. Ydrefors, T. Frederico PRD 104 (2021) 114012; and arXiv: 2211.10959 [hep-ph].

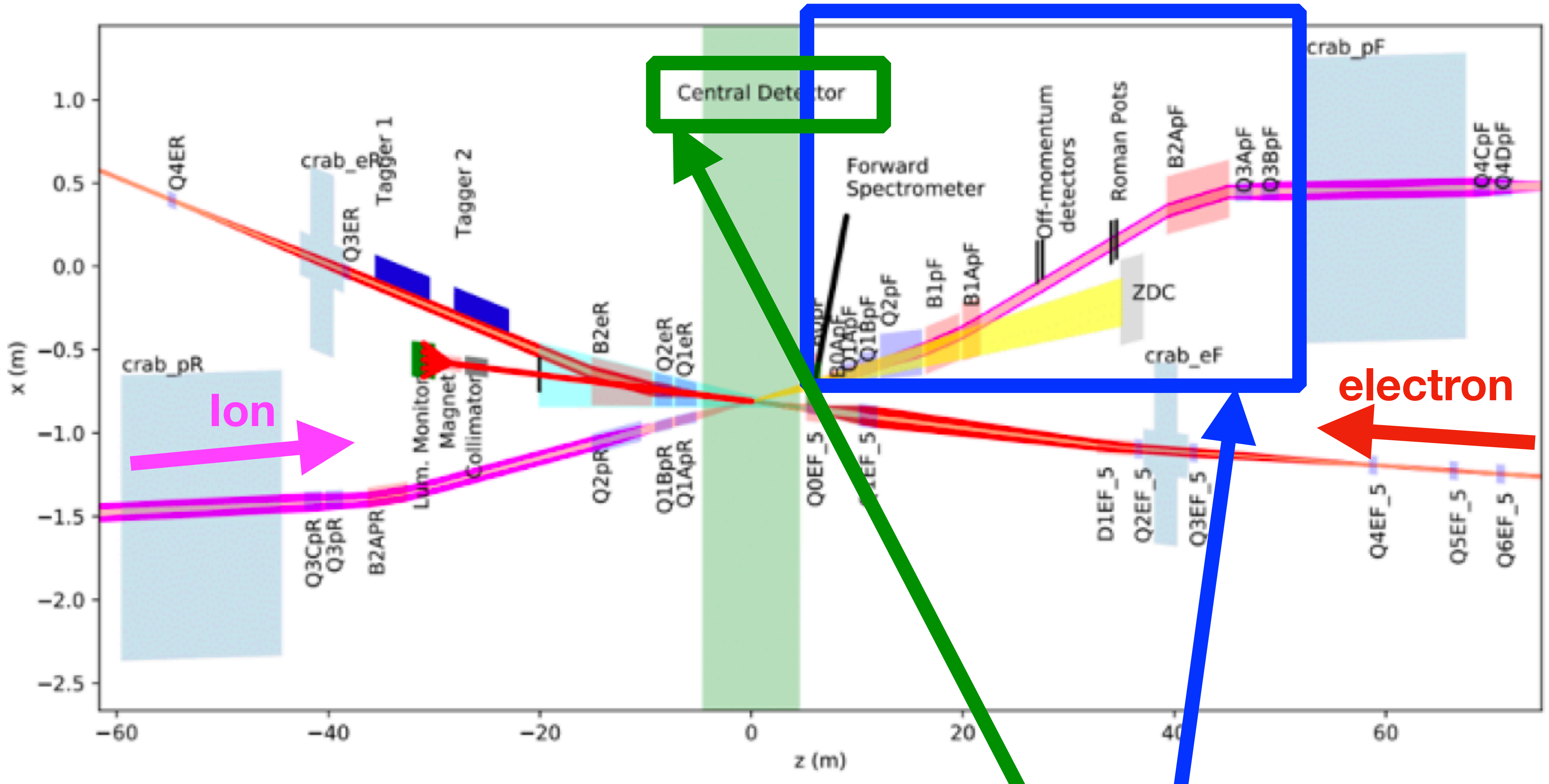
T. Frederico (Instituto Tecnologico de Aeronautica)
E. Ydrefors (Chinese Academy of Sciences)

Plots: D. Dutta (MSU), C. Ayerbe (W&M)

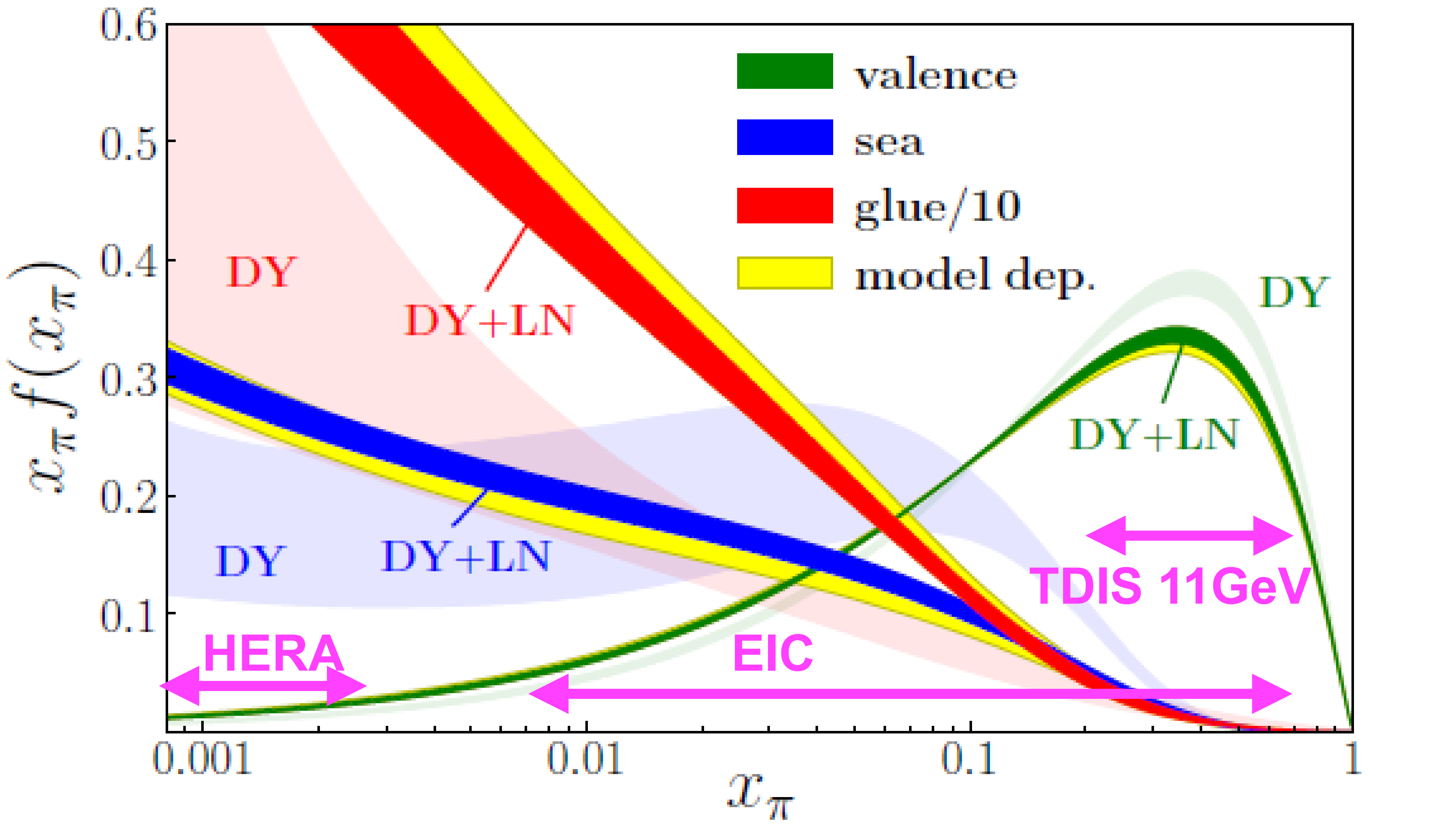


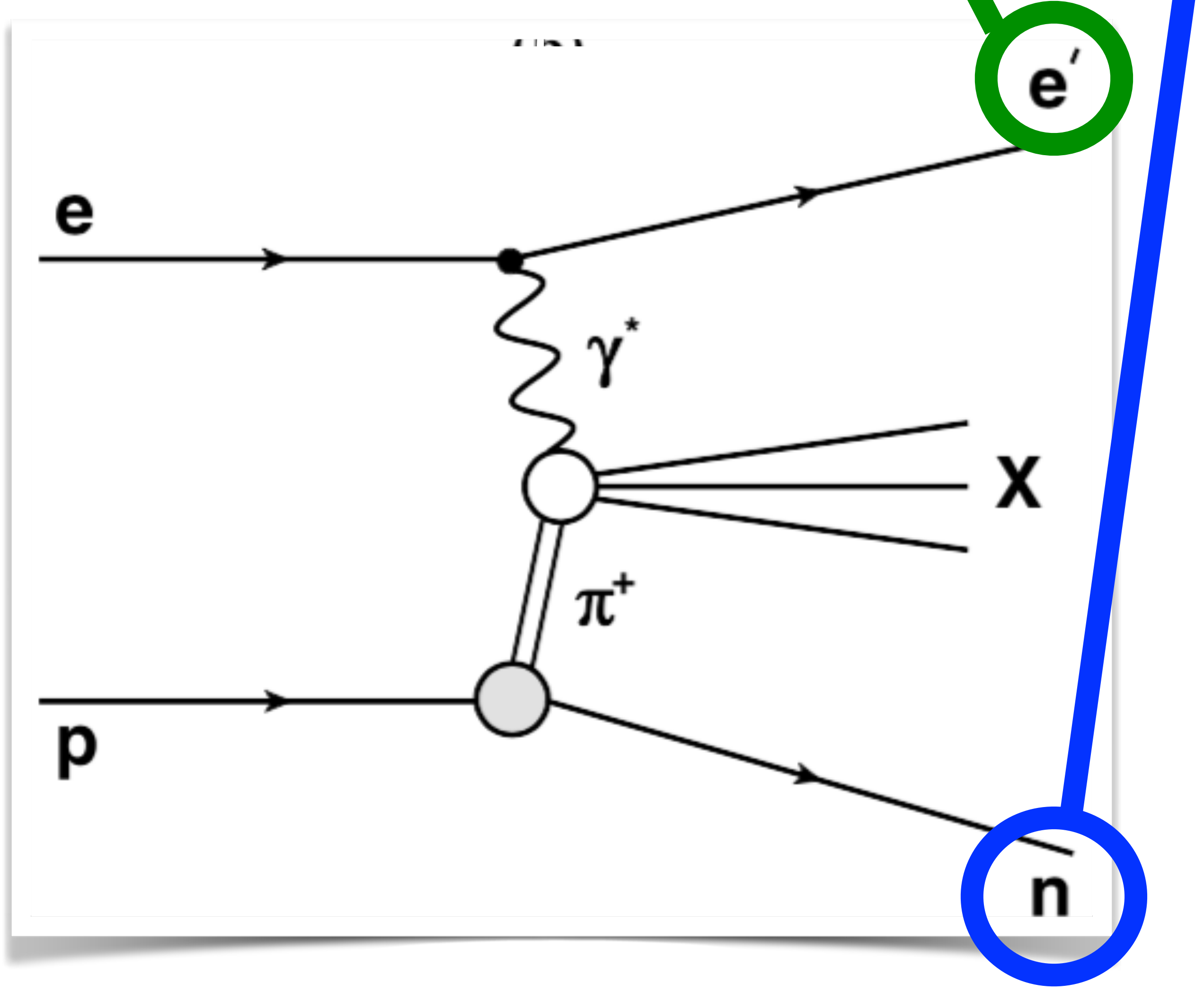
HERMES results: A. Airapetian et al. (HERMES Collaboration), Phys. Rev. D 87, 074029

Gateway to Spectator Tagging at EIC



Global PDF from JAM Collaboration, Phys. Rev. Lett. 121, 152001 (2018)





- Meson SF accessible via Sullivan at EIC
- High luminosity ($\mathcal{L}$=10^{34}Hz/cm^2 = 1000 * $\mathcal{L}_{HERA}$)
- Full acceptance
- Bridge HERA low x and JLab valence regime
- **Uncertainties increase for SF at EIC as $x_\pi \rightarrow 1$**
  - **JLab TDIS is crucial for mid to high x_π range!**

- EIC Meson Structure Working Group, see:
  - Aguilar *et al*, Eur. Phys. J. A. (2019) **55** 190
  - Arrington *et al* 2021 J. Phys. G: Nul. Part. Phys. **48** 075106

Extrapolation to the pole

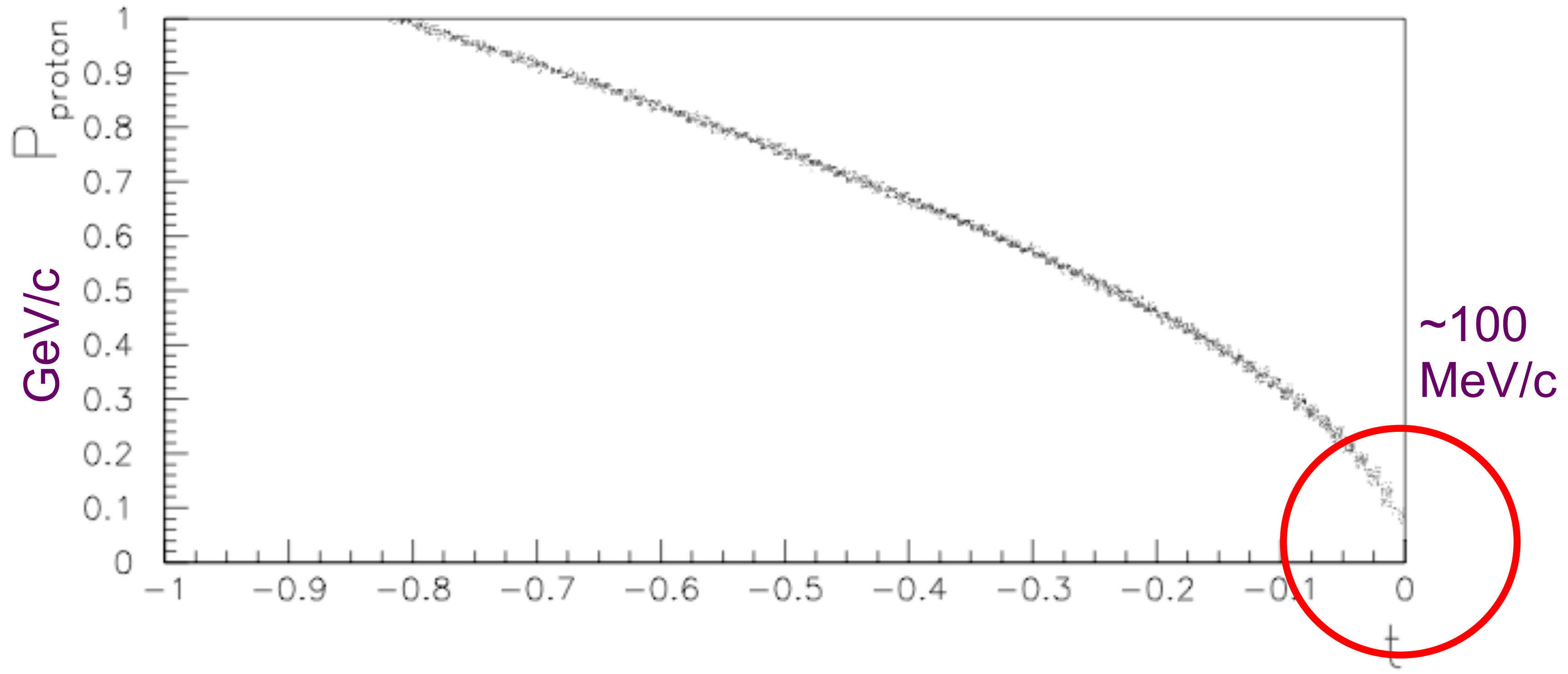
Need range of low momentum protons

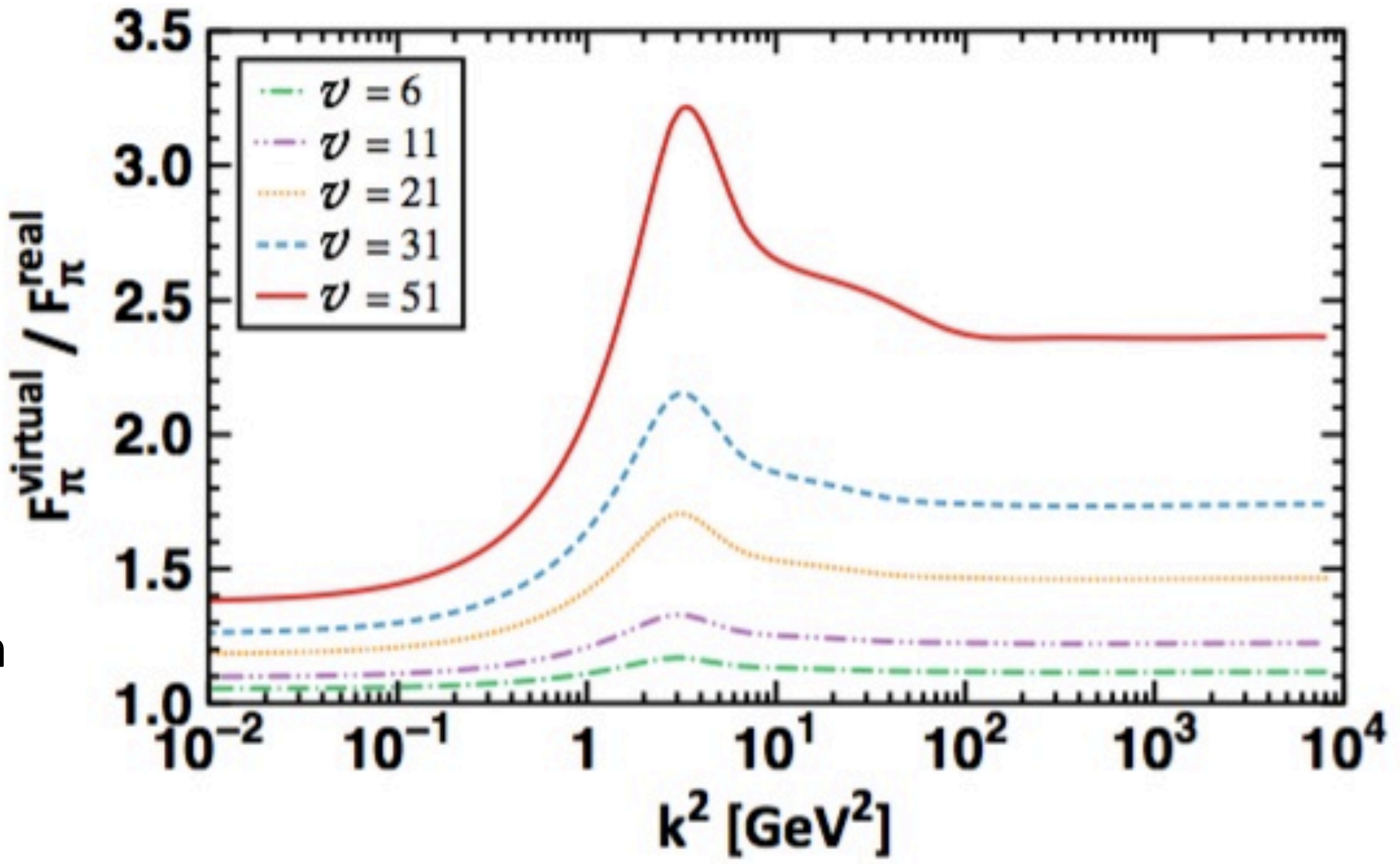
The ratio of off-shell to on-shell pion electromagnetic form factor

Si-Xue Qin, Chen Chen, Cedric Mezrag, Craig D. Roberts
Phys.Rev. C97 (2018) no.1

"…we demonstrated that for $v < v_S$ ~ 31, which corresponds to −t < ~0.6 GeV^2….the off-shell correlation serves as a valid pion target."

JLab TDIS kinematics best at lowest t values





Like BONUS, a challenging low p proton tag experiment – one low mass detector to rule them all

Slide from C.Keppel