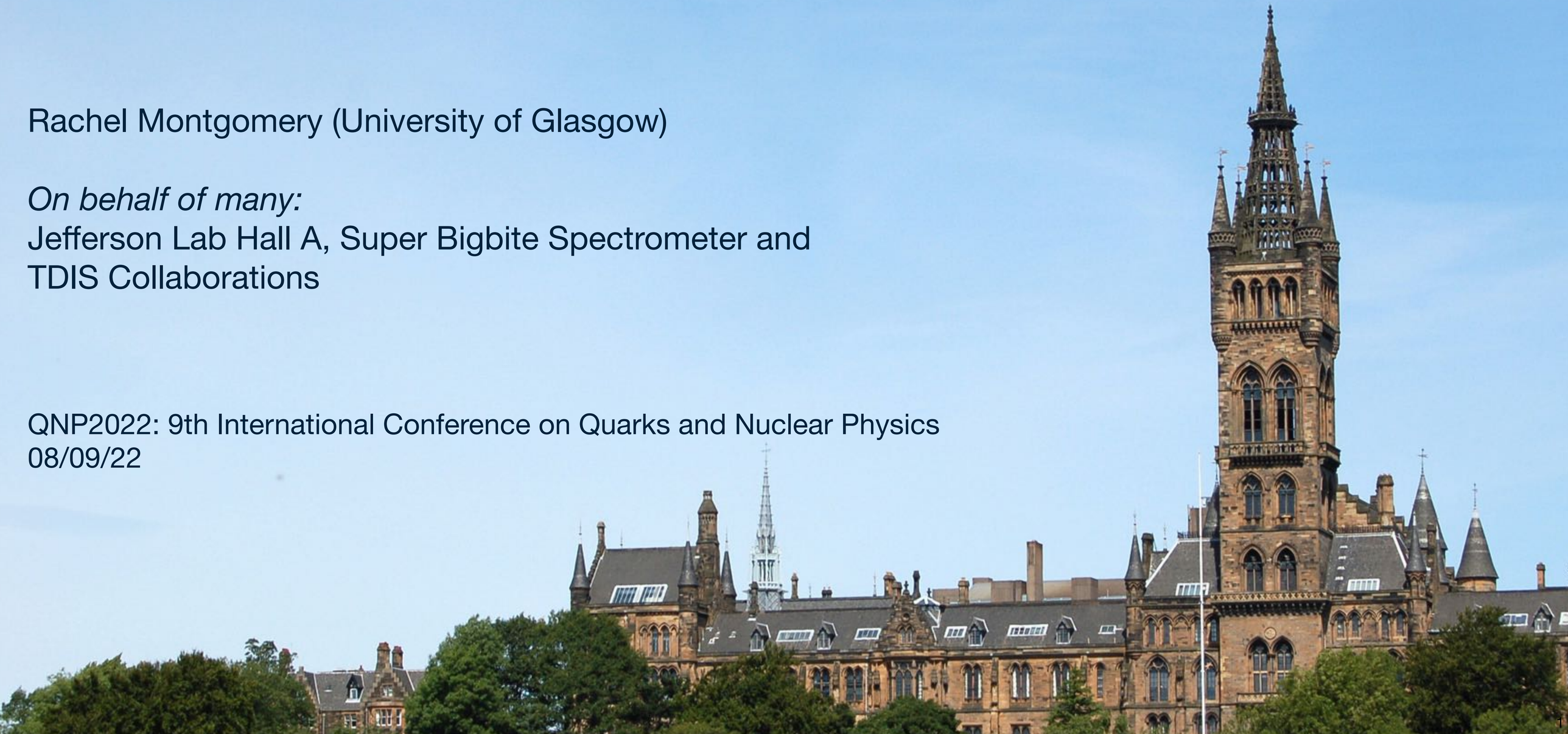
Probing Light Meson Structure via Tagged Deep Inelastic Scattering (TDIS)

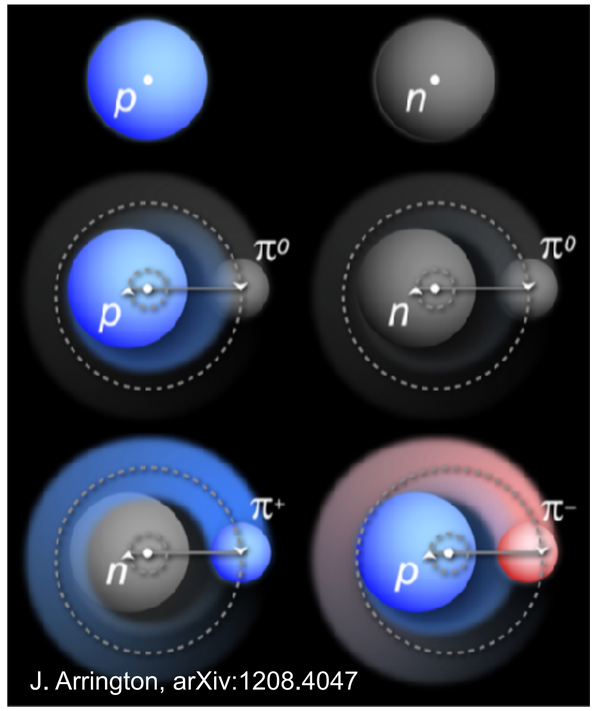
Rachel Montgomery (University of Glasgow)

On behalf of many:
Jefferson Lab Hall A, Super Bigbite Spectrometer and
TDIS Collaborations

QNP2022: 9th International Conference on Quarks and Nuclear Physics
08/09/22

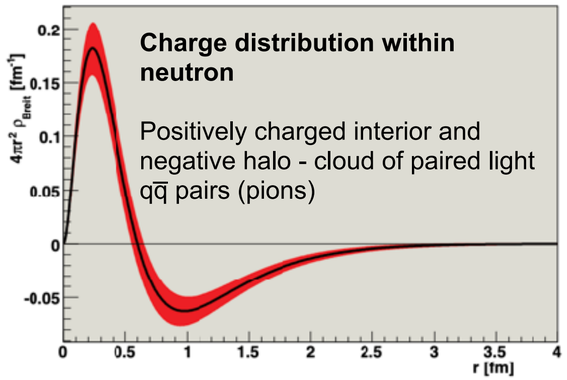


Why Meson Structure?



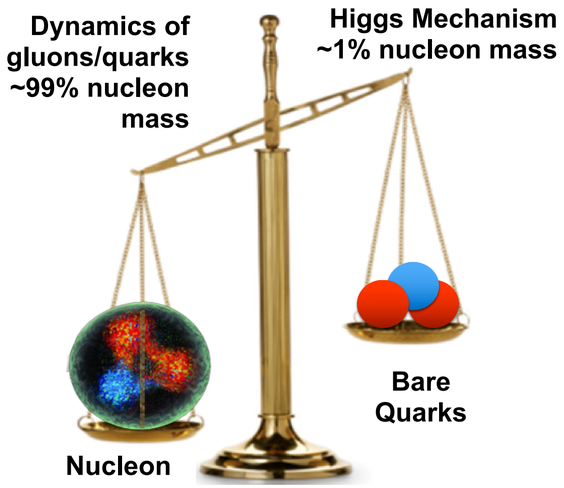
J. Arrington, arXiv:1208.4047

DOE/NSF NSAC, arXiv:0809.3137v1



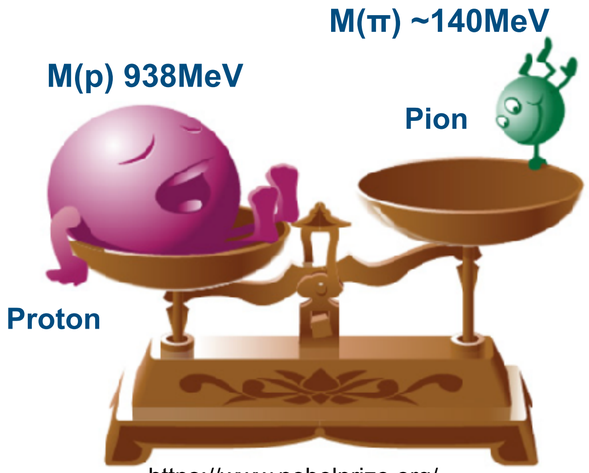
- Understanding structure of light mesons (pions/kaons) key for full understanding of nucleon
- Experimental evidence for mesonic content of nucleon exists
  - e.g. nucleon charge densities; pion/kaon form factors from electroproduction off nucleon…
  - Exact mesonic content of nucleon unknown!
- Pion and kaons are key topics in nucleon/nuclear structure
- Pion
  - Long range NN interaction; simplest QCD state; dynamical mass generation; nucleon/nuclear parton distribution functions (PDF)…
- Kaon
  - Momentum fractions carried by sea/glue; different gluon content than pion, combine with valence quark for full PDF evolution…
- Comparing structure of different light mesons provides unique insights into nucleon mass enigma

Why Meson Structure?



- Standard model and mass generation via Higgs ~1% nucleon mass

- Strong interactions in QCD ~99% nucleon mass: emergent hadronic mass (EHM)
- Mass scale of nucleon defined by QCD mechanisms



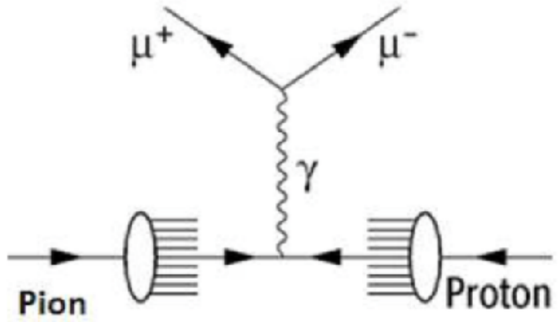
https://www.nobelprize.org/prizes/physics/2008/illustrated-information/

- Mass budgets for **light pion and kaon** vastly different from **heavy nucleon,** and each other
- Comparing distributions of light quarks versus strange quarks within mesons → measurable signals EHM

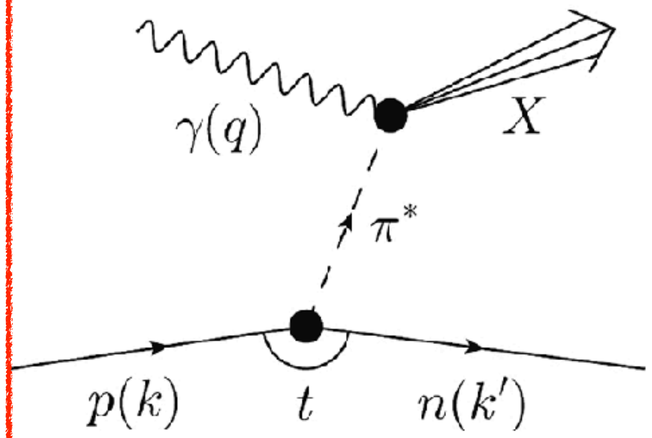
- Understanding pion/kaon structure one key tool for understanding EHM
- π/K structure practically unknown experimentally!
- Several observables:
  - e.g. elastic EM form factors, or **structure functions (SF)**

How Can We Access Pions/Kaons?

Drell-Yan

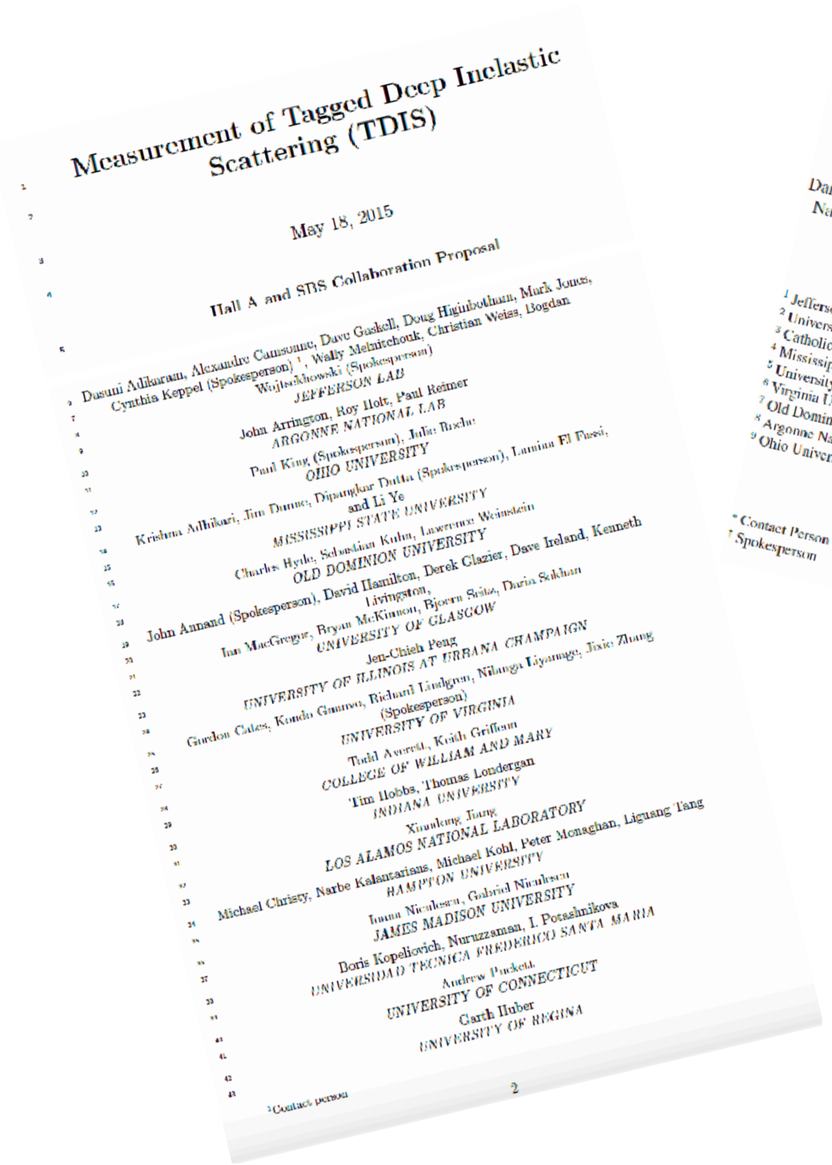


Sullivan



Hard scattering from virtual meson cloud of nucleon

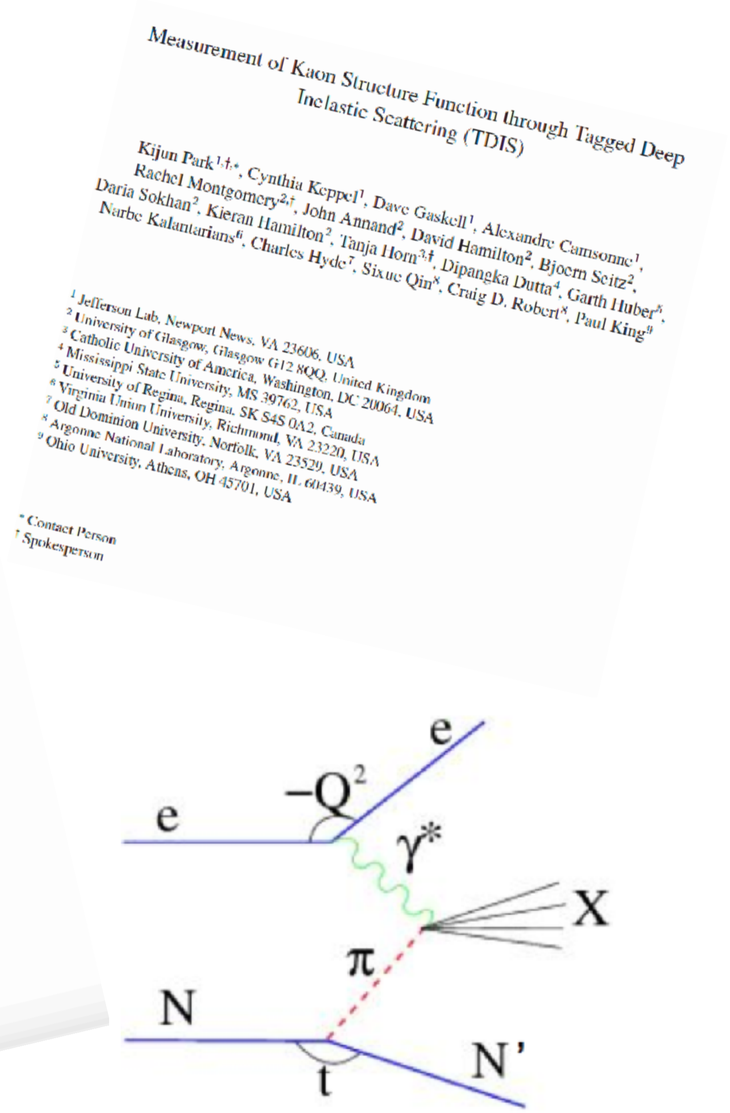
Upcoming TDIS at Jefferson Lab



Measurement of Tagged Deep Inelastic Scattering (TDIS)

May 18, 2015

Hall A and SBS Collaboration Proposal



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

- DIS with spectator tagging:
  → effective free targets not easily found in nature
  → directly tag mesonic content of nucleon!

- Measure ratio of full inclusive to tagged DIS cross sections:
  - Access SF (i.e. hadron sub-structure)
  - SF → input for parton distribution functions

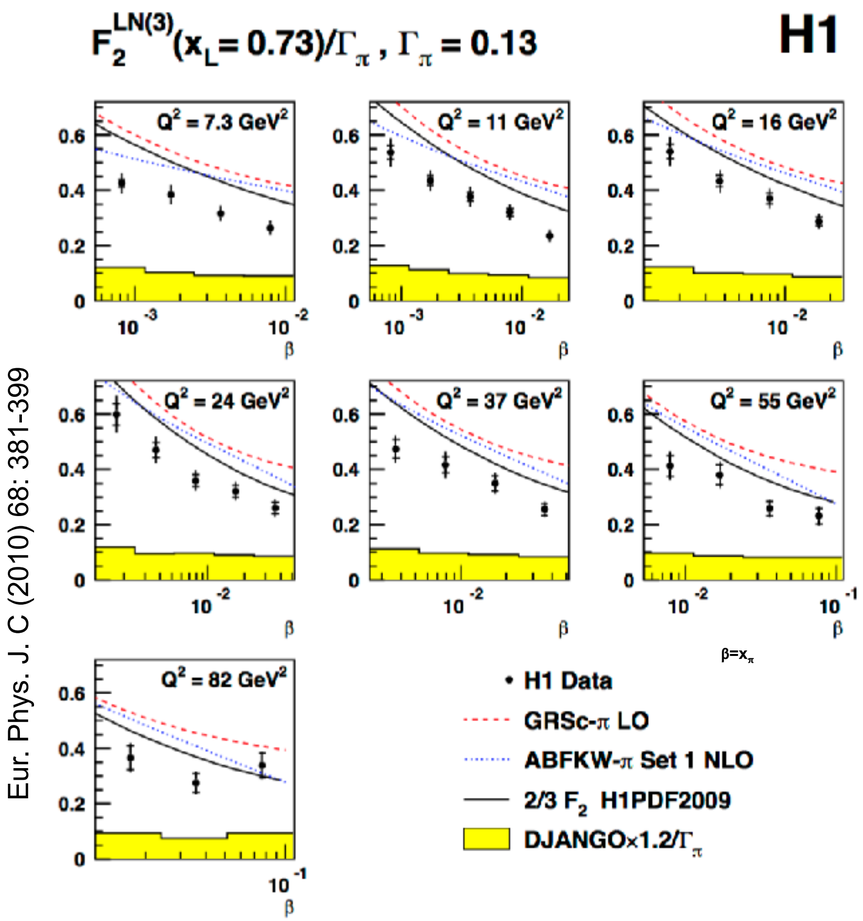
$$\frac{d^2\sigma}{d\Omega dE'} = \frac{\alpha^2}{4E^2{}_0 \sin^4\frac{\theta}{2}} \cos^2\frac{\theta}{2}\left[\frac{1}{\nu}F_2(x,Q^2) + \frac{2}{M}F_1(x,Q^2)\tan^2\frac{\theta}{2}\right]$$

- x = fraction of hadron's longitudinal momentum carried by struck quark
- Q^2 = (4-mom transferred by γ^*)^2

- TDIS aims:
  - Pion and kaon F_2 SF in valence regime

- Where will TDIS lie amongst existing meson SF data?

Previous Data

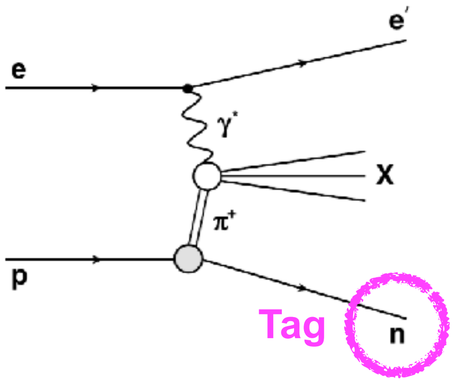


Eur. Phys. J. C (2010) 68: 381-399

HERA Tagged DIS

- Sullivan process and meson cloud virtual target
- Pion sea region, low Bjorken x, high Q^2
- $6<Q^2<100GeV^2$; $1.5e^{-4}<x<3.0e^{-2}$
- Leading neutron tagged in ep → e'Xn
- Charged pion SF extracted

Diffractive scattering and forward detectors

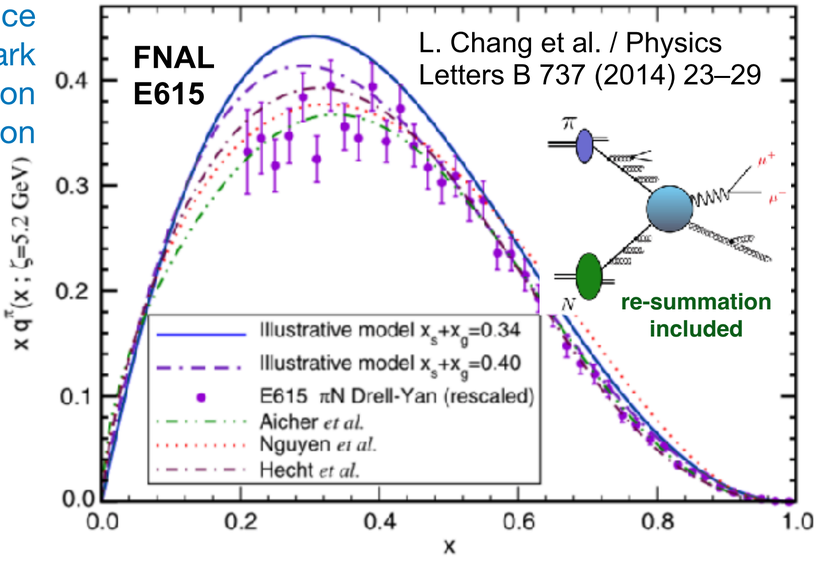


TDIS:

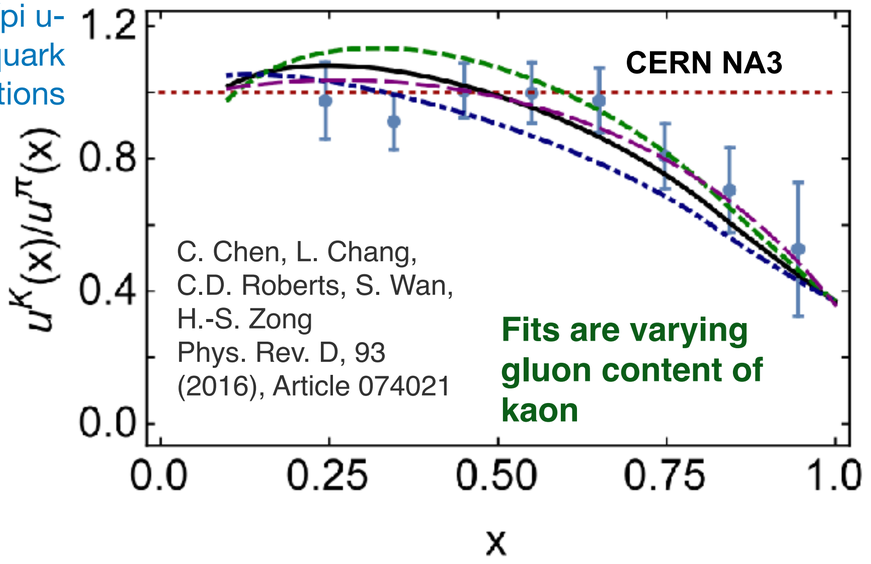
- Valence regime
- Higher x, lower Q^2
- Evolution between kinematics

Previous Data

Pion valence quark distribution function

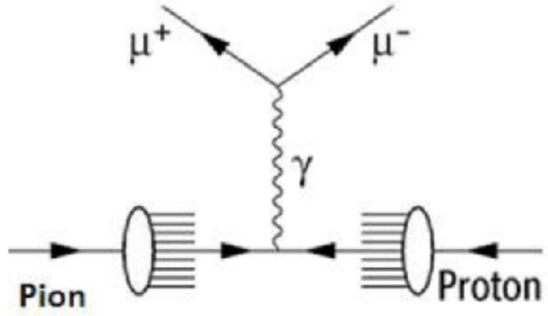


Ratio K/pi u-quark distributions



Valence region - Drell Yan

- CERN/Fermilab data



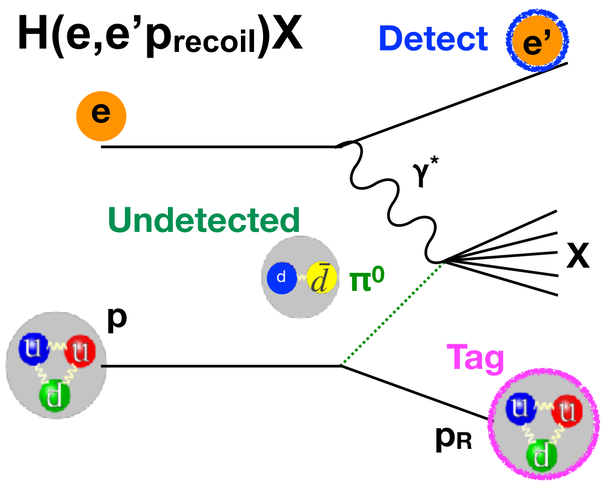
- Large-x region - QCD model tensions (pQCD, DSE, light-front), gluon re-summation and non overlapping uncertainties in some global PDF analyses
- Practically non-existent data for kaon

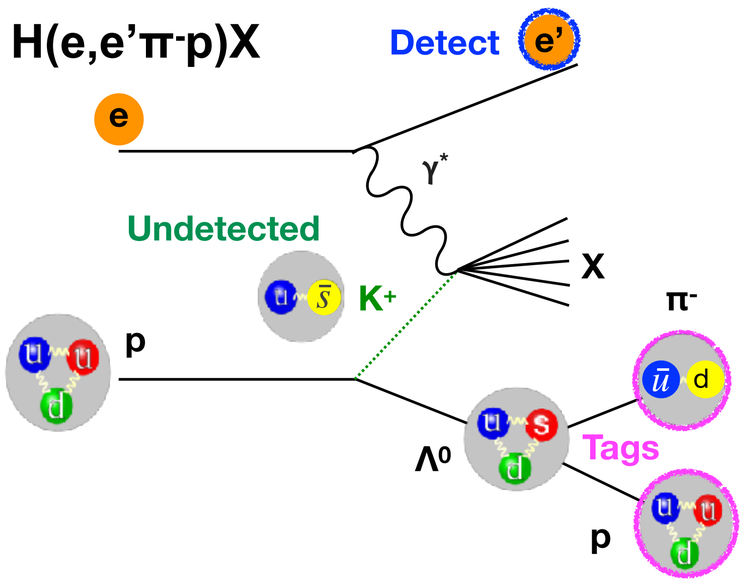
TDIS

- Independent cross-check
- Extend to neutral pions
- More data also coming from Drell Yan with COMPASS++/AMBER at CERN SPS (see 2019 LOI arXiv:1808.00848, pion beams on tungsten/carbon targets)
- More data essential

TDIS Measurements

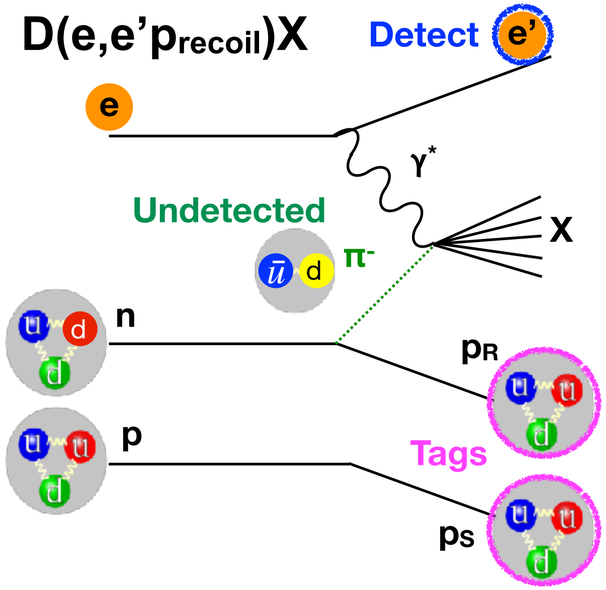
1st direct neutral pion extraction





1st direct kaon extraction

Resolve QCD model tensions/ add data for charged pion



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

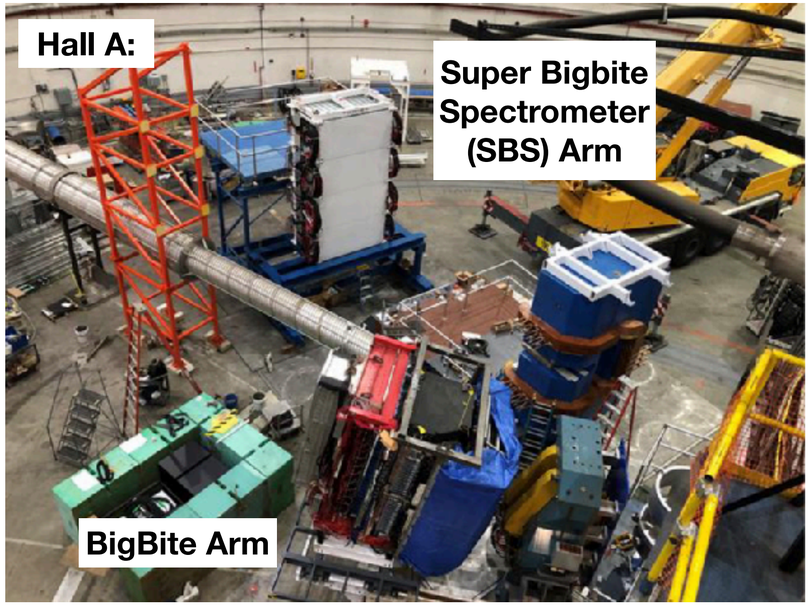
DIS Regime

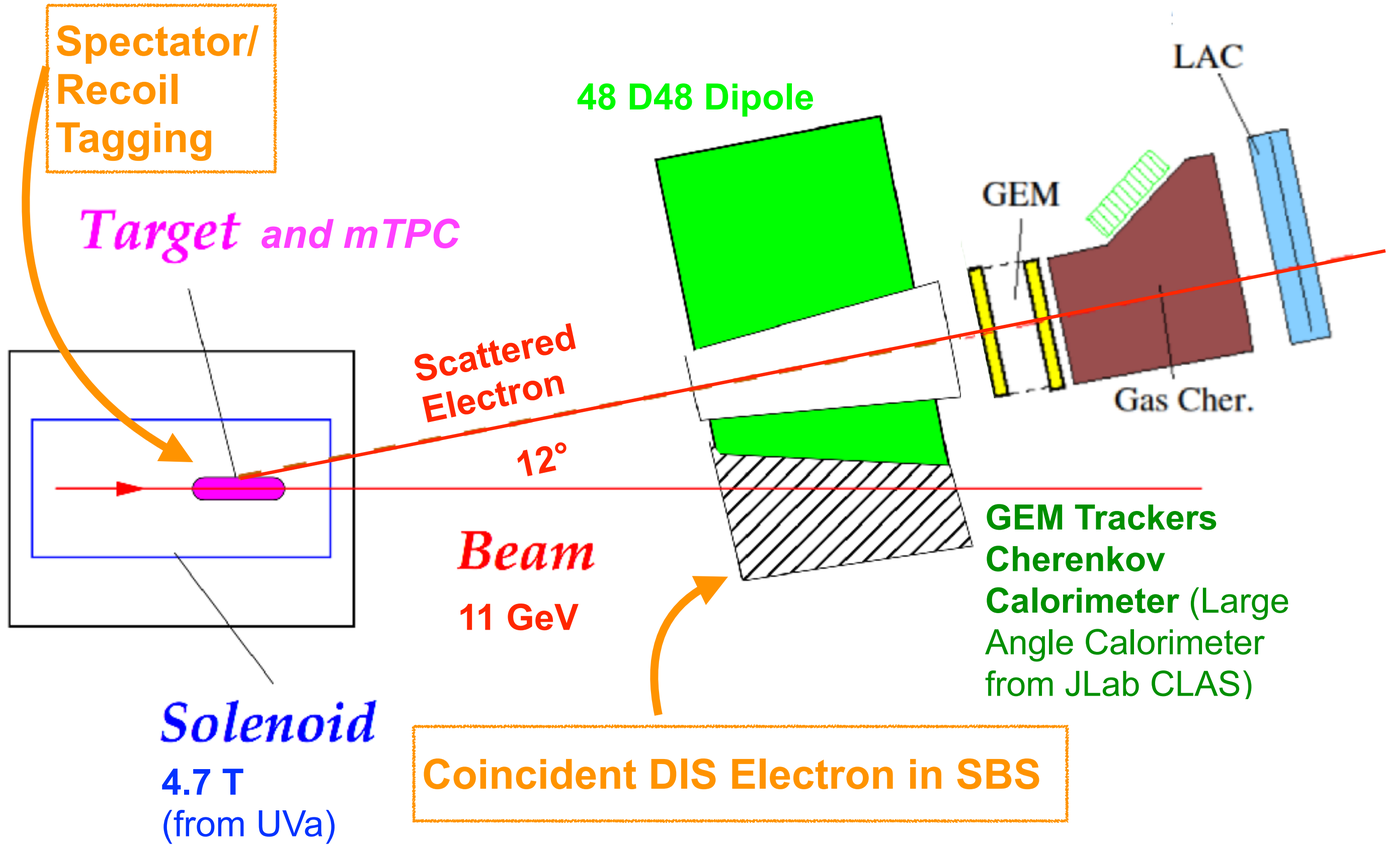
Novel detector essential for tagging very low momentum recoiling hadrons (60 - 400 MeV/c)…

Experimental Setup

Jefferson Lab, VA, USA:

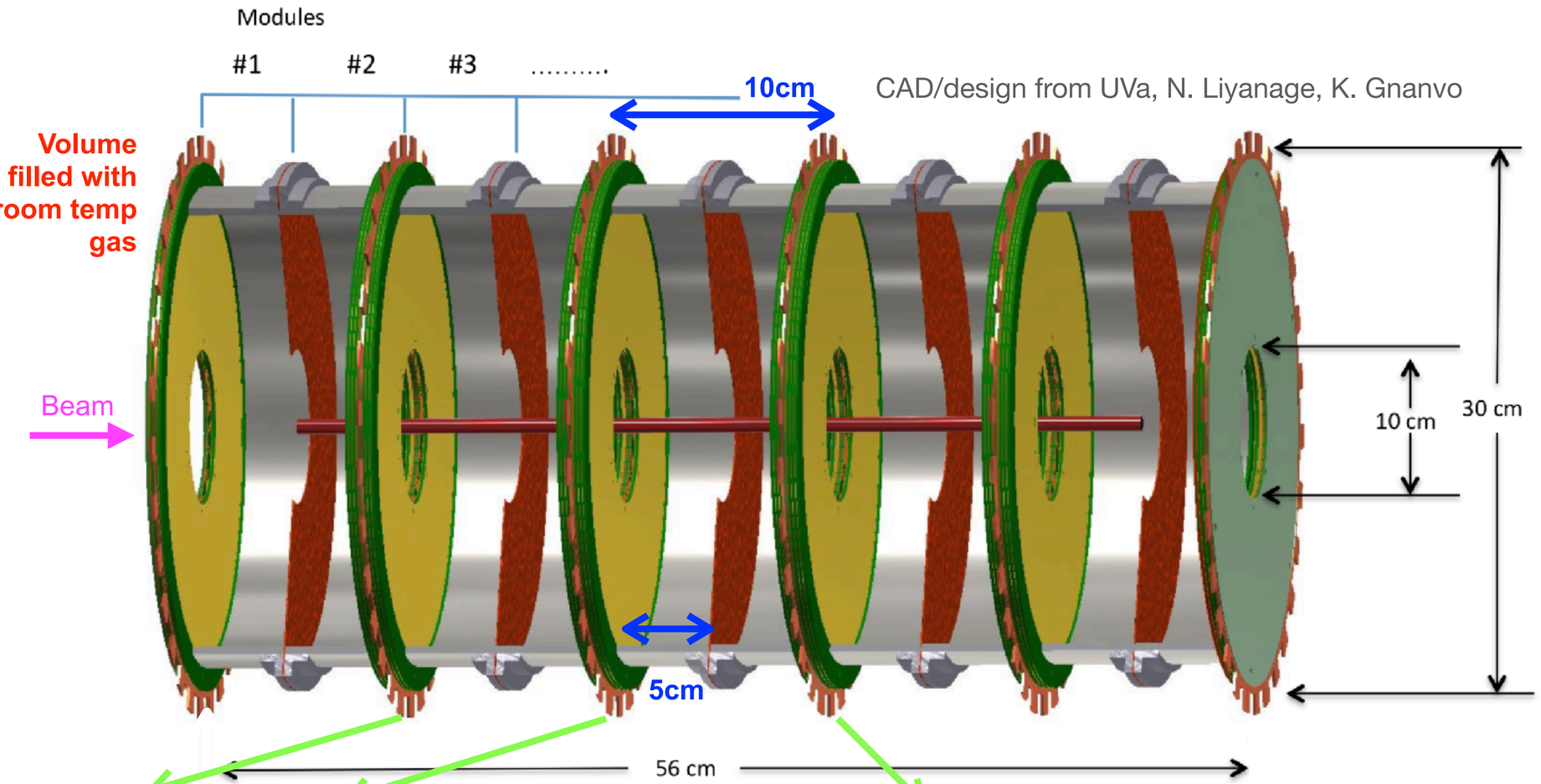
- Hall A:
  - New open geometry spectrometers
  - Higher luminosities
  - $10^{38\text{-}39}$Hz/cm^2
  - Increased acceptance
  - Decreasing cross-sections at higher Q^2 (>10GeV^2)
  - Rare DIS processes

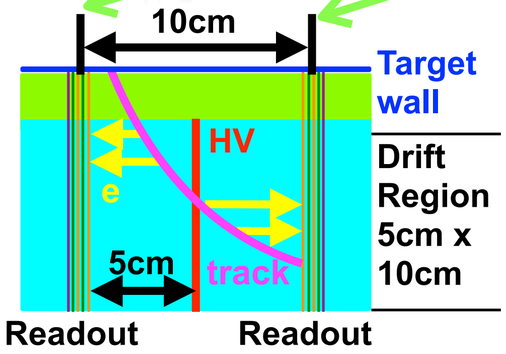


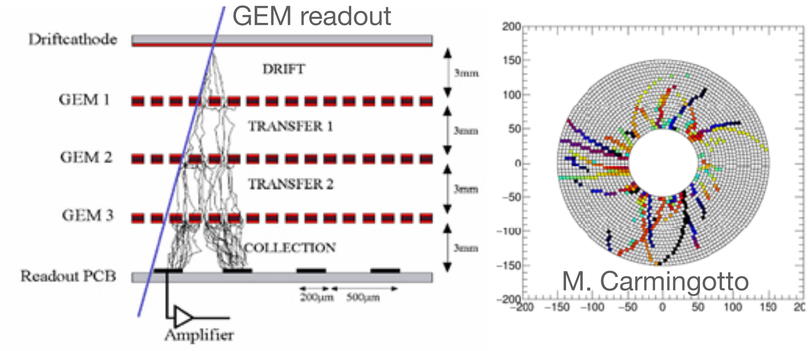


- SBS: Refurbishments/upgrades underway (MSU (D. Dutta)/UConn (A. Puckett)/ JLab (S. Malace)/U Tenn (N. Fornin)….)
- High density room temperature H/D target; 40cm length; 1cm diameter; 4atm
  - Development and prototyping: D. Dutta (MSU) with JLab
- 11 GeV e^- beam, 50μA, high luminosity ~$3\text{x}10^{36}$Hz/cm^2
- Multiple Time Projection Chamber (mTPC)…

High Rate mTPC

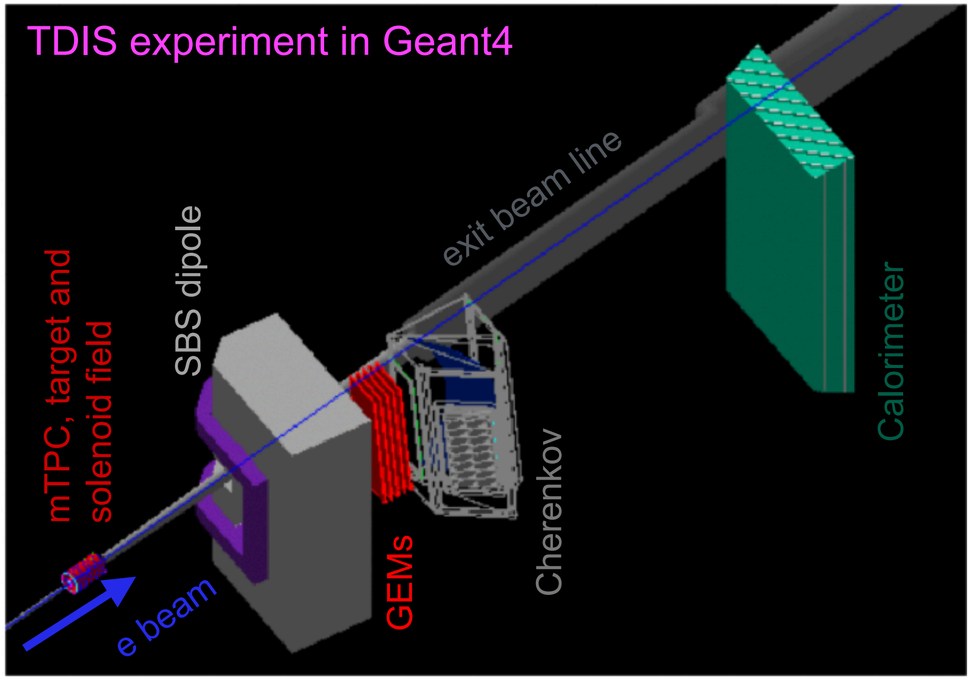




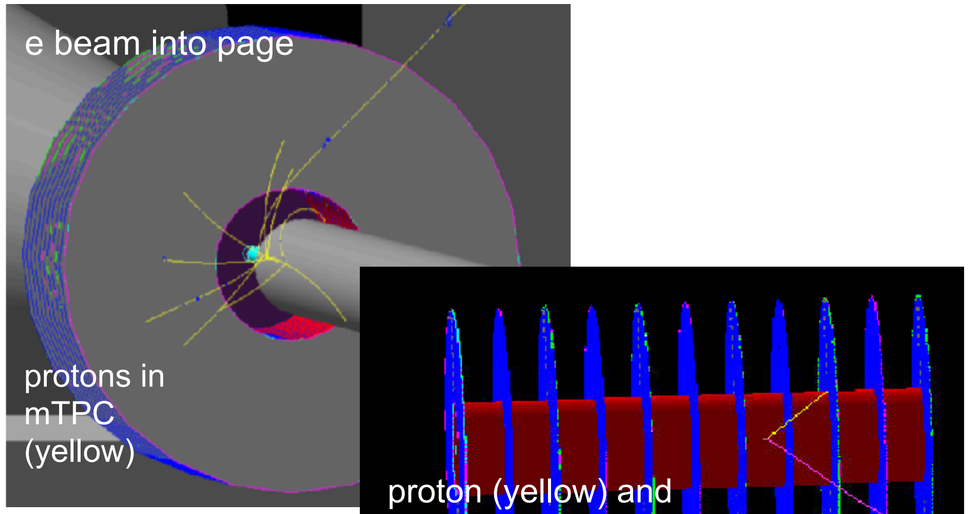


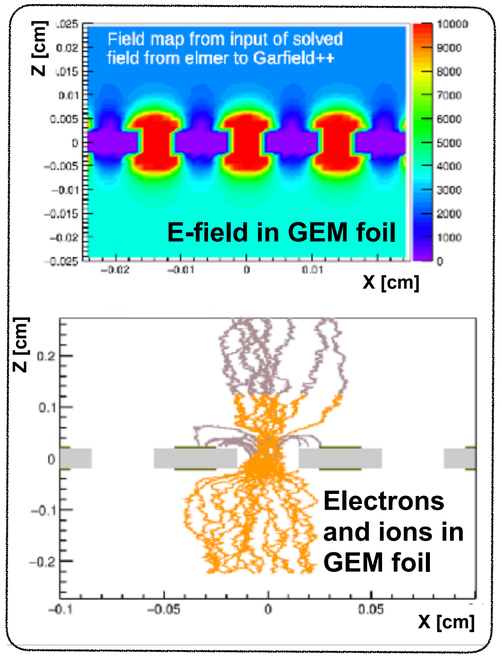
- Tagging recoils/spectators
  - Vertex and momentum analysis
  - PID by dE/dx
- Division of volume into chambers reduces background rates
  - e.g. ~700MHz → 70MHz/module
- Readout planes
  - Multi layer GEM foils
  - Segmented readout pads

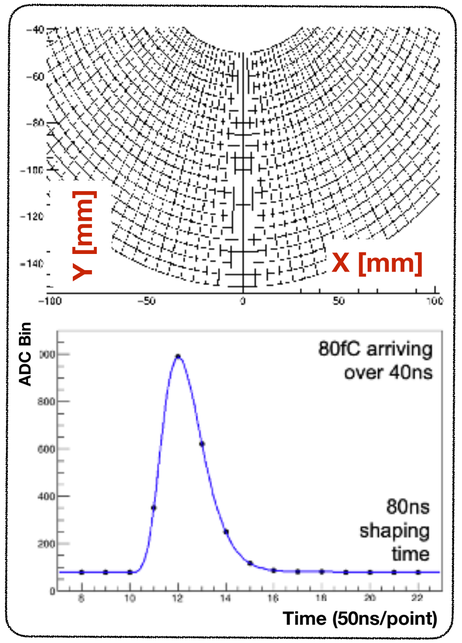
TDIS Simulations

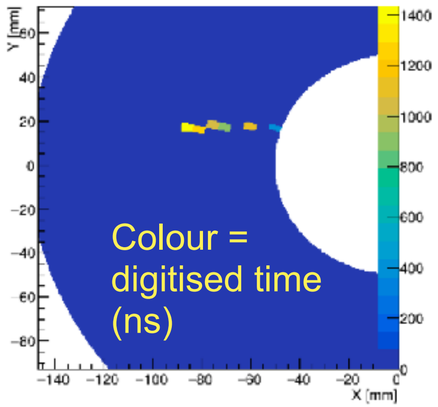


- Fully described in Geant4 (within SBS collaboration framework)
- Team of contributors (e.g. C. Gayoso, E. Fuchey, S. Wood, A. Tadepalli, D. Dutta, S. Ali, M. Carmingotto, R. Montgomery…and more)
- mTPC simulated using CERN's magboltz/garfield
  - Gas mixtures; electric field; drift properties
- Event generators and background/accidentals rate studies
  - H2 - elastic protons; D2 - photodisintegration/QE scattering/delta production
- Digitisation and tracking underway
  - Initial chain finding algorithm demonstrated mTPC capability for challenging TDIS high rate demands



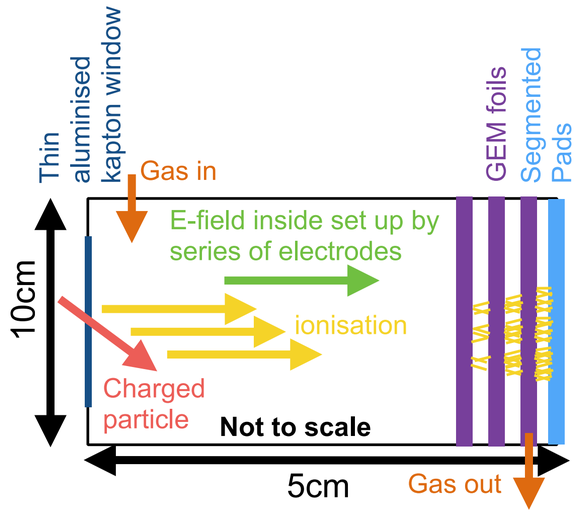




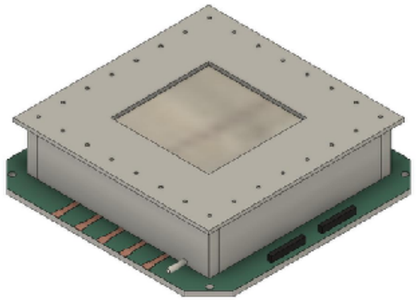


Example pad configuration
22 rings
122 pads/ring

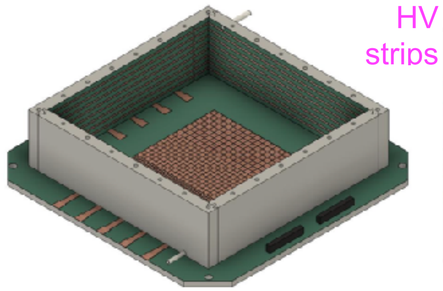
mTPC Prototyping



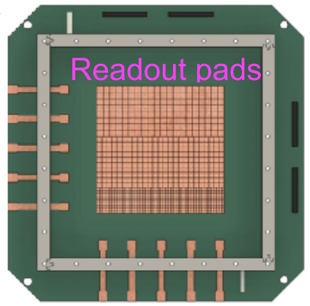
- Currently University of Virginia constructing 1st prototype mTPC chamber
  - S. Ali, N. Liyanage,…
  - Square design; 10 x 10 cm^2 GEM active area
  - Three GEM foils stacked with 2mm spacing
  - 5cm drift
- Aims: tune simulation, test readout pads, electronics, gas mix choice, field, ion back flow…
- Further prototyping planned



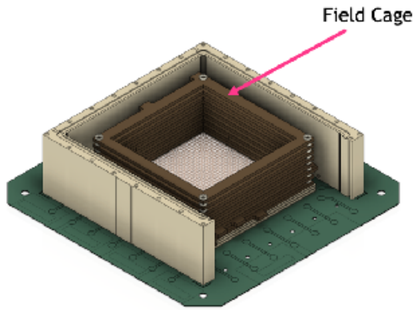
Design and CAD model:
S. Ali, UVa

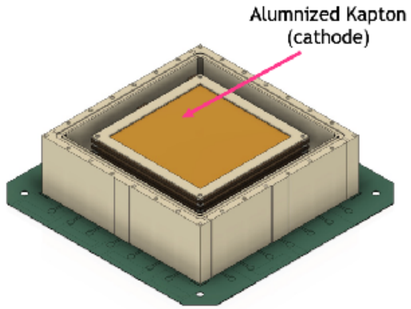


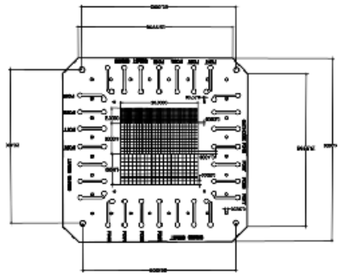
Field set up by electrode strips

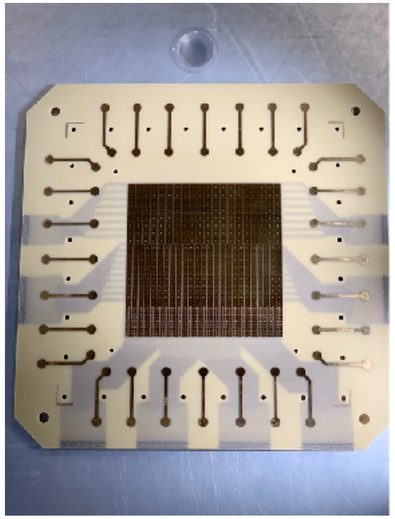


Different sized pads



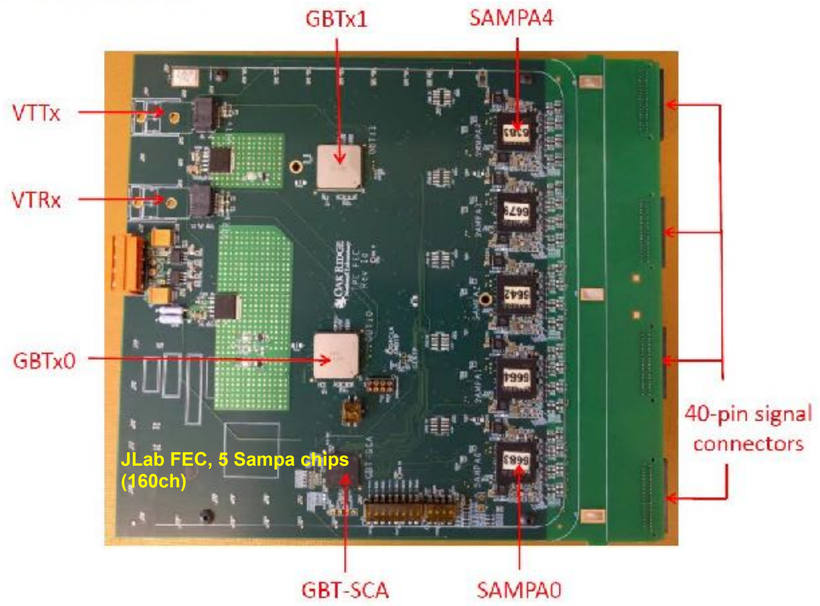


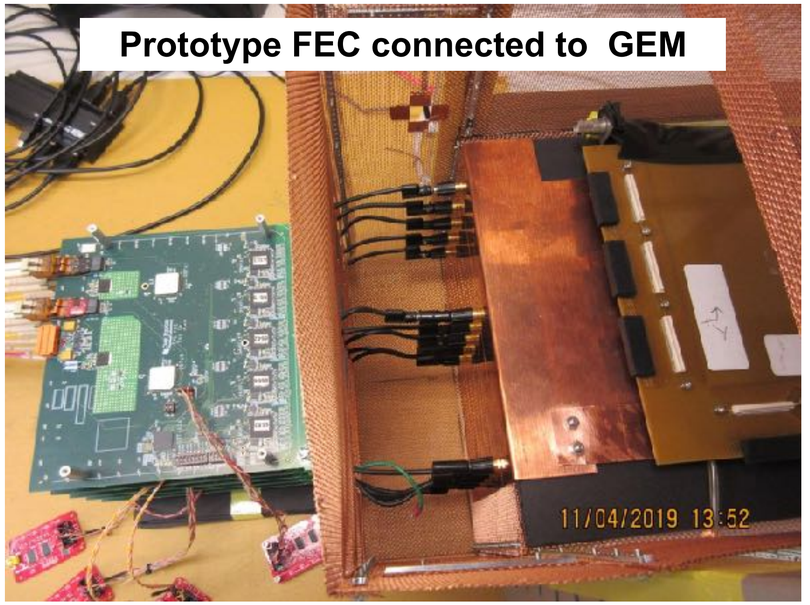




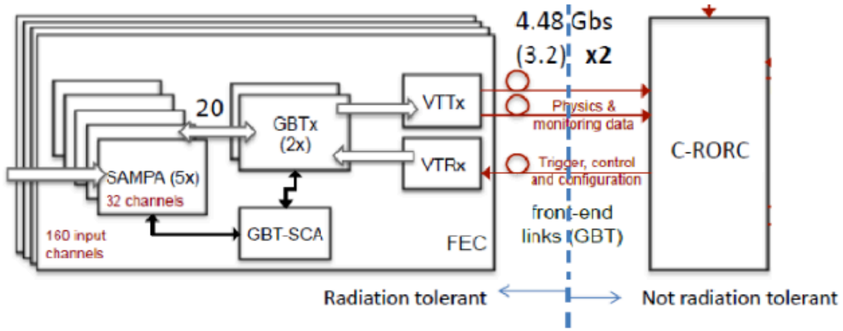
All images: S. Ali (UVa)

Streaming Readout Development





All pics:
E. Jastrzembski
JLab

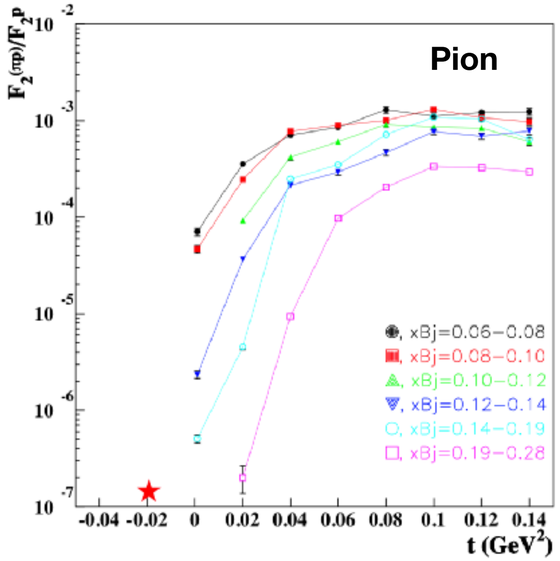


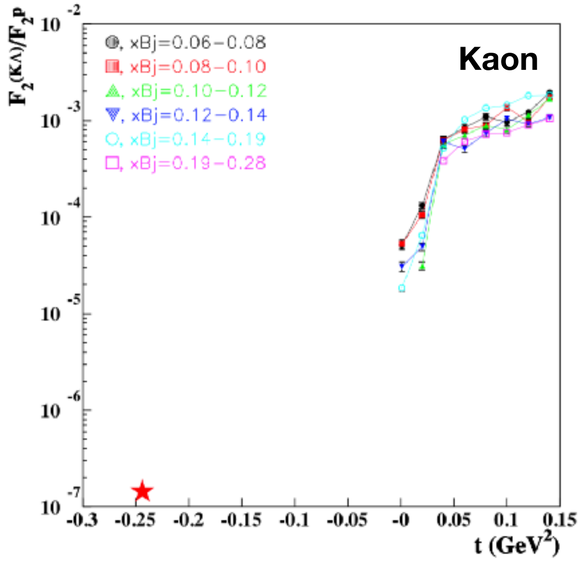
FEC – Front End Card (160 ch / FEC) (5 FEC = 800 ch)
C-RORC – Common Read Out Receiver Card (PCIe)
GBTx – Giga Bit Transceivers
GBT-SCA – GBTx Slow Controls Adapter
VTTx, VTRx – Fiber optic transceivers

- Goals:
  - data read continuously from all channels (~35k)
  - local digitisation/zero-supression/noise rejection
  - parallel data flow to storage
  - event synch with data from other triggered detectors

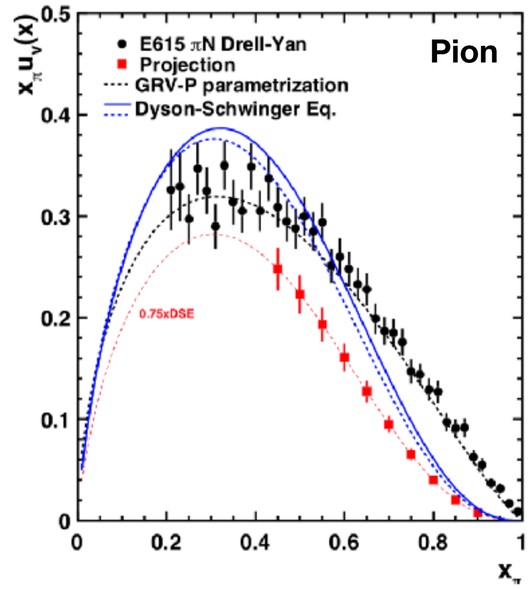
- Testing/prototyping on-going @JLab (E. Jastrzembski, G. Heyes et al.)
- SAMPA ASIC
  - charge-sensitive pre-amp, ADC, zero-suppresion…
  - streaming readout developed for ALICE TPC (M. Bregant, Univ. Sao Paolo)
  - continuous sampling w/ high data readout speed (~1TB/s post zero-supp)
- Trigger-less mode successfully tested @ JLab (5 chips, ~160 chans)
- Obtaining components for mTPC

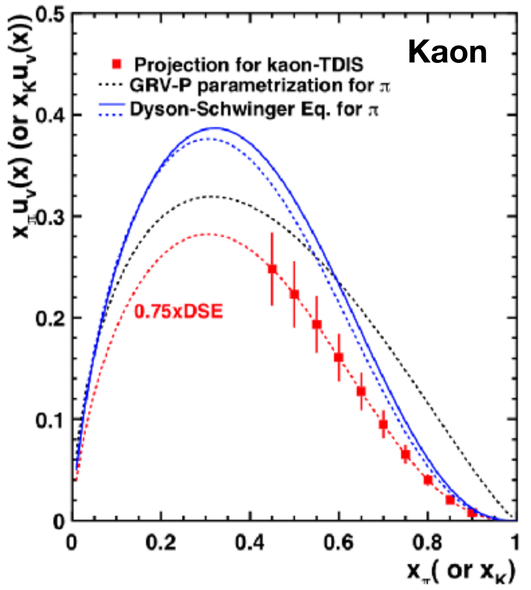
Example Projected Results





- Kinematical mapping of SF
- Low momentum reach of mTPC essential to obtain shape of curve





- Projected valence quark distributions
- 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
- TDIS will serve as valuable input for global PDF analyses

Summary

- Meson structure important for understanding fundamental structure of nucleon

- Experimental data for pion/kaon structure functions, and mesonic content of nucleon, extremely sparse

✓ TDIS at JLab:
  - New data in valence regime
  - Understand nucleon + meson structure on deeper level
  - Kaon SF extraction in almost empty world data set!
  - First prototyping underway…

- TDIS will pave way for spectator tagging and meson structure at EIC
  - Model input, simulation/analysis, validation of Sullivan process, advanced instrumentation
  - EIC Meson Structure Working Group
    - Aguilar *et al*, Eur. Phys. J. A. (2019) **55** 190
    - Arrington *et al* 2021 J. Phys. G: Nul. Part. Phys. **48** 075106

- Also (not covered):
  - TDIS-n run group for independent checks of neutron structure (e.g. F_2^n…)


Thank you