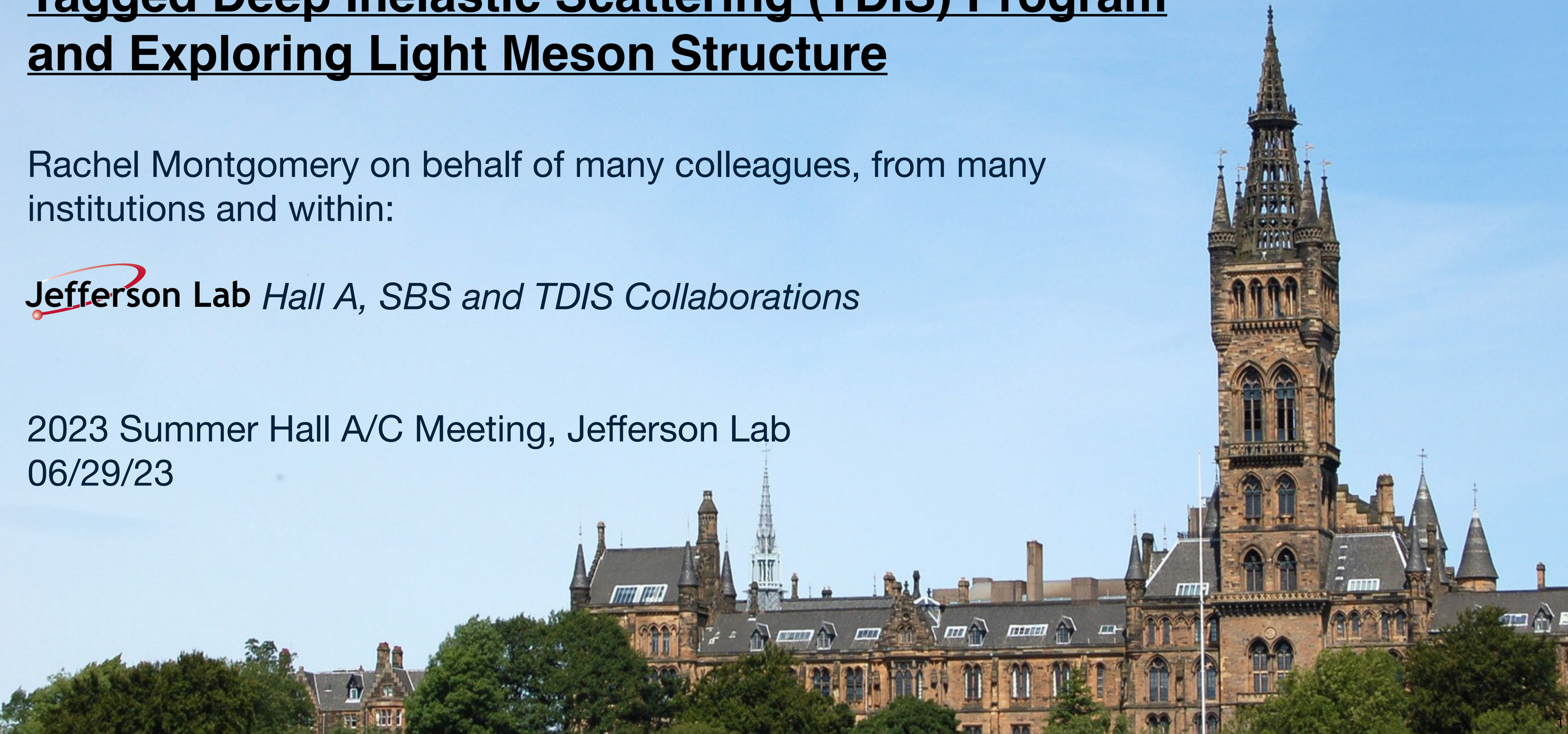
Tagged Deep Inelastic Scattering (TDIS) Program and Exploring Light Meson Structure

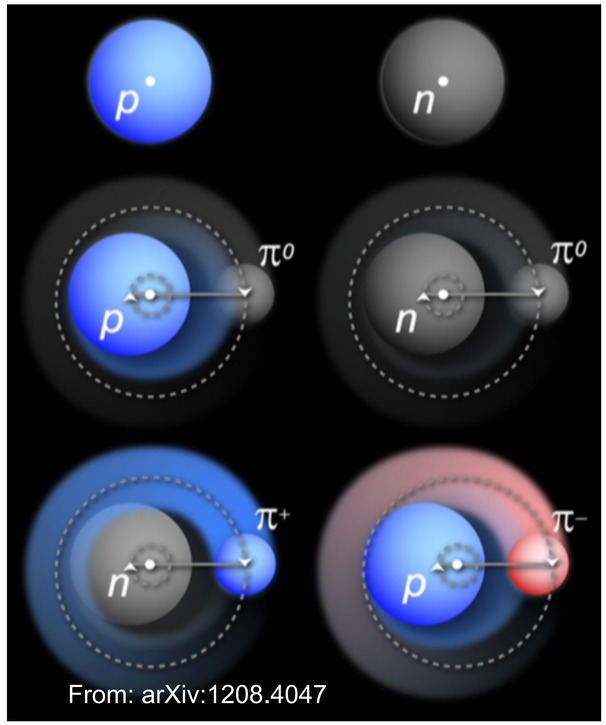
Rachel Montgomery on behalf of many colleagues, from many institutions and within:

Jefferson Lab *Hall A, SBS and TDIS Collaborations*

2023 Summer Hall A/C Meeting, Jefferson Lab
06/29/23

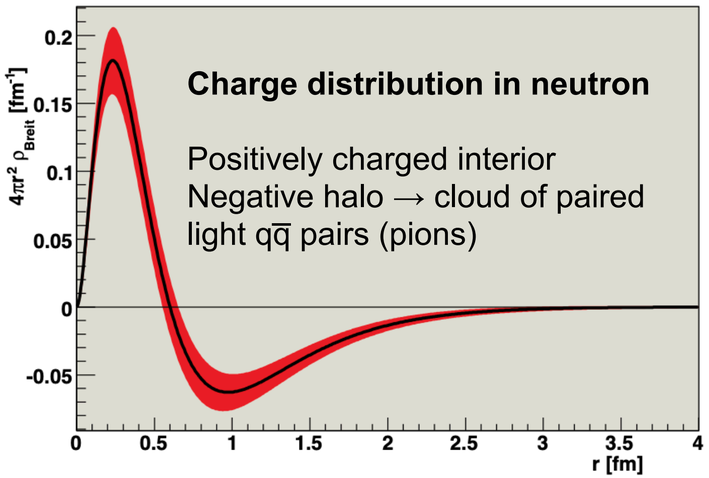


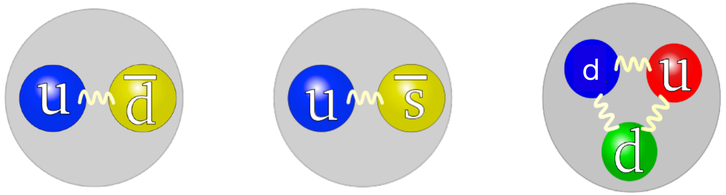
Why Meson Structure?



From: arXiv:1208.4047

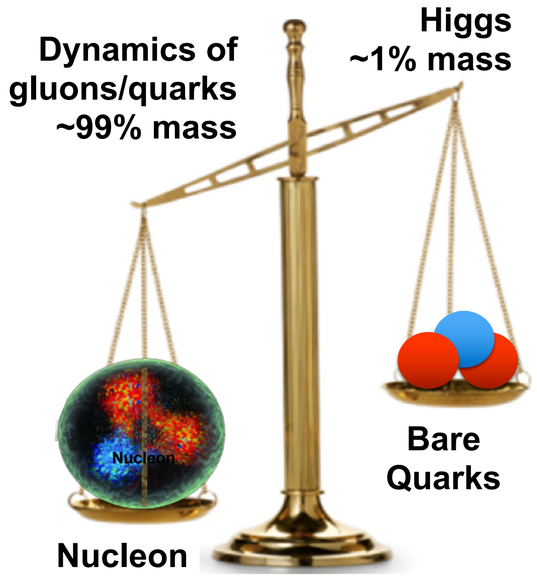
From: arXiv:0809.3137v1



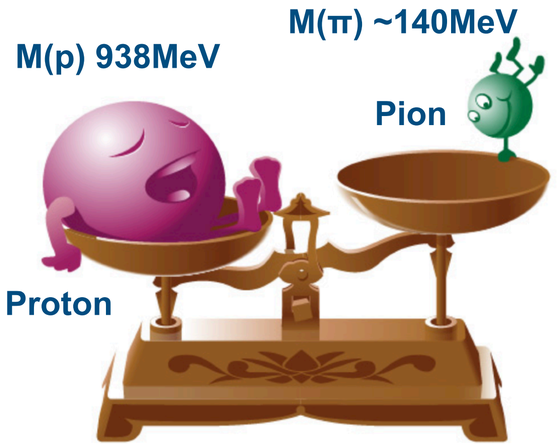


- TDIS ➔ structure of
  - Light mesons (pion/kaon)
  - Neutron
- Crucial in better understanding nucleon structure
- Experimental evidence for mesonic content of nucleon
  - e.g. nucleon charge densities; meson form factors from electroproduction off nucleon…
- Substantial theoretical work - important to combine with data
  - e.g. how does mesonic content affect nucleon/nuclear PDF
  - Exact mesonic content of nucleon unknown!
- Pion and kaons 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; different gluon content than pion; combine with valence quark for full PDF evolution…
- Mass enigma…

Emergent Hadronic Mass (EHM)

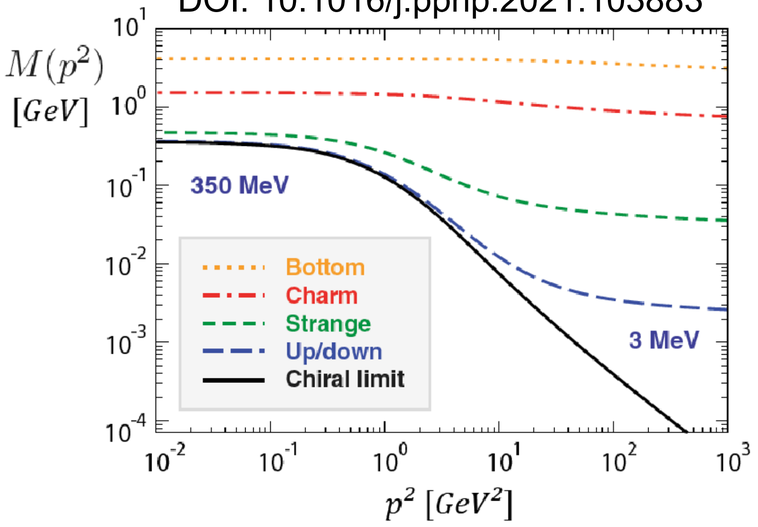


Hadron	Observed Mass (MeV)	Higgs Generated Mass (MeV)
Proton (uud)	~940	~10
Pion ($u\bar{d}$)	~140	~7
Kaon ($u\bar{s}$)	~490	~100



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

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

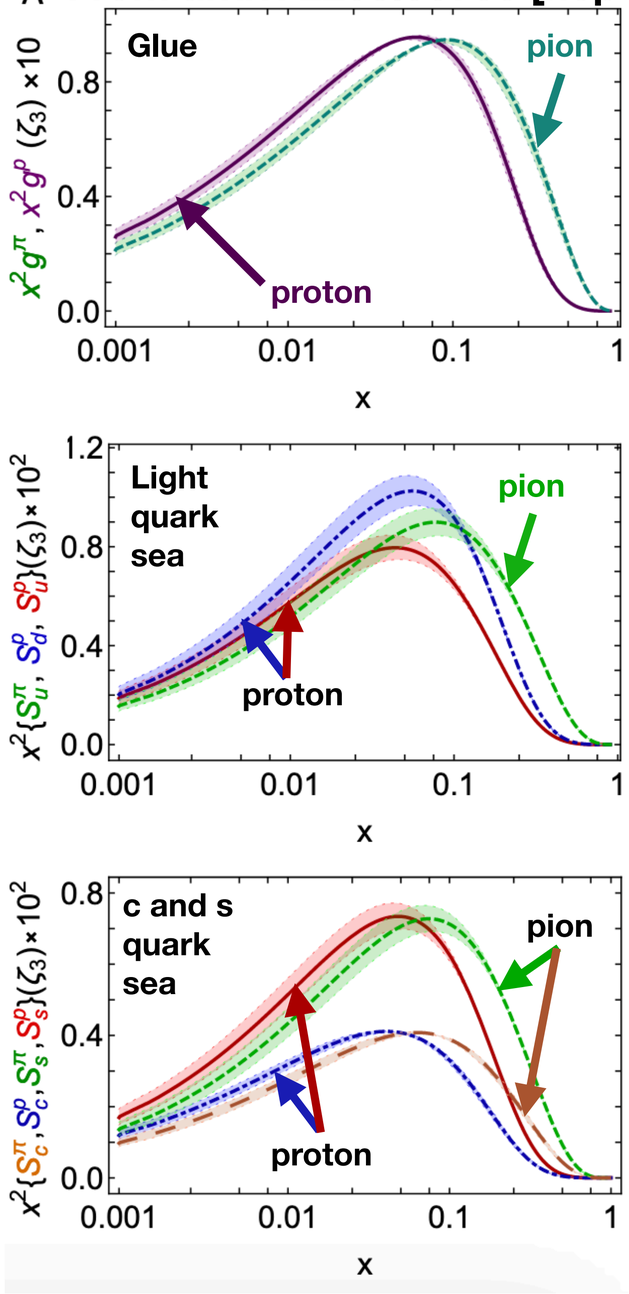


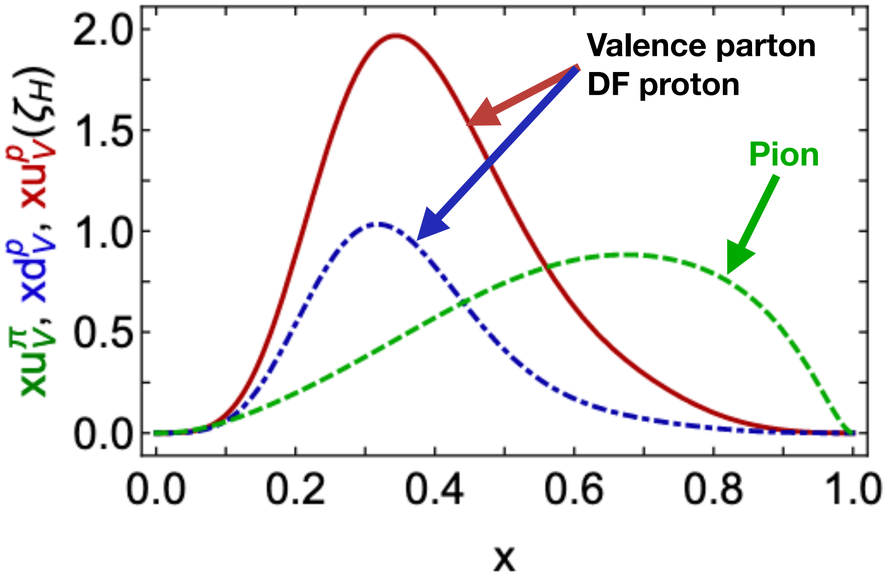
Quark mass acquisition functions from QCD theory: light quark dynamical mass generation from gluon cloud

- Dynamics of strong interactions in QCD:
  - ~99% nucleon mass
  - EHM - see C. Robert's talk!
- Theoretical mass budgets for light π/K (Goldstone bosons) vastly different from heavy nucleon, and each other
- (different gluon contents in π/K?)
- Comparing distributions of light quarks versus strange quarks within mesons
  - → measurable signals of EHM
- Interesting implications for PDFs

Pion vs Proton Valence PDF

A From arxiv: 2203.00753 [hep-ph]





From C. Roberts (INP) and see Craig's talk in this session

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

- Differences between pion and proton valence PDF
- "Much to be learnt before proton and pion structure understood in terms of DF… what is difference between distributions of partons within proton and pion?"
- π/K structure not well known experimentally

Accessing Pions/Kaons

Sullivan Process

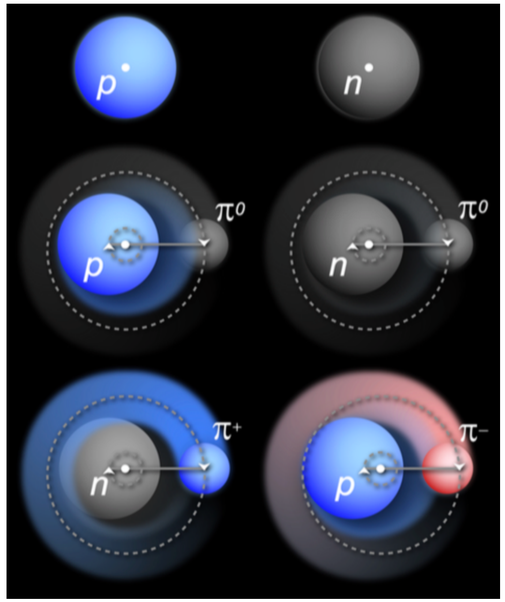
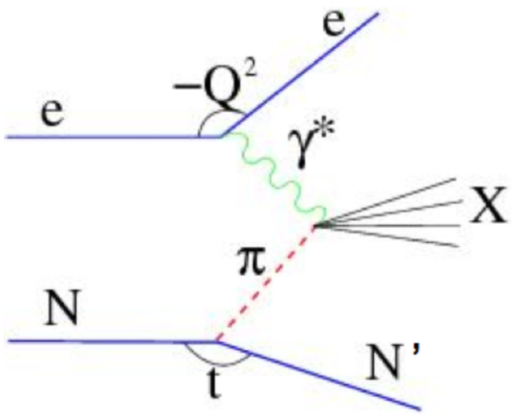
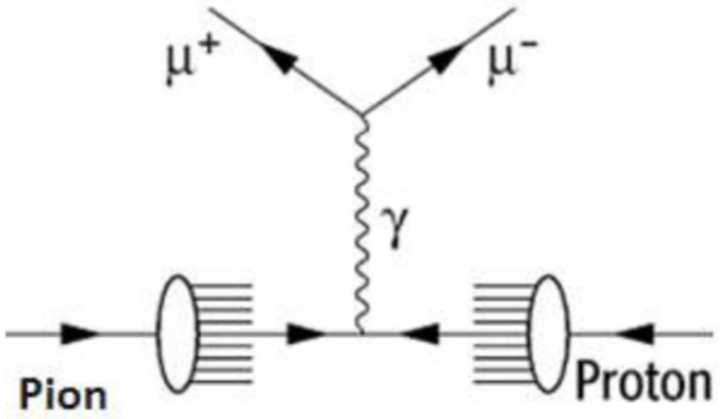


Image from: arXiv:1208.4047

Hard scattering from virtual meson cloud of nucleon



Drell-Yan

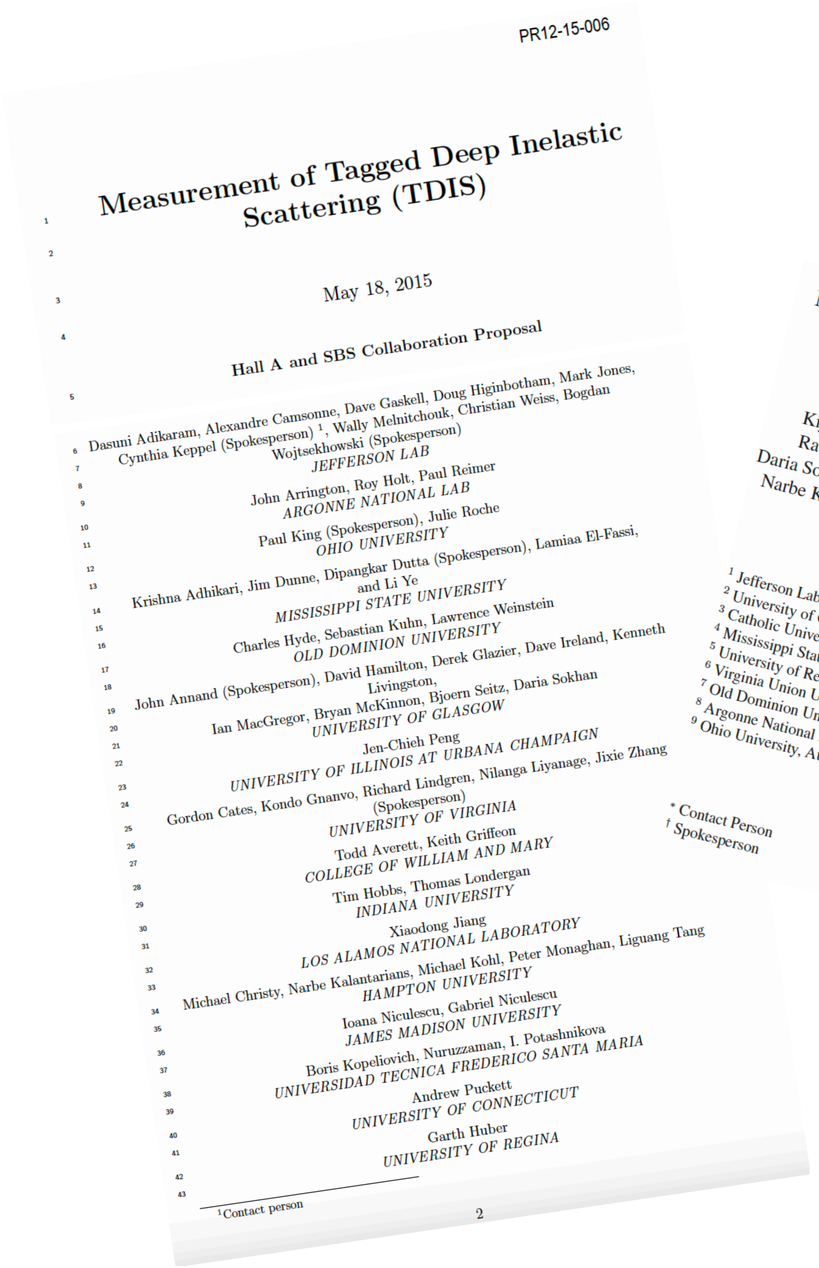


- JLab TDIS experiment
  - DIS with spectator tagging
  - Effective free targets not readily found in nature
  - Directly tag mesonic content of nucleon
- Aims:
  - Pion and kaon F_2 in valence regime

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

- Inclusive DIS cross-section → access hadron sub-structure
- F_1, F_2 structure functions (SF)
- SF → input for parton distribution functions

TDIS History



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
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Tim Hobbs, Thomas Londergan
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Michael Christy, Narbe Kalantarians, Michael Kohl, Peter Monaghan, Liguang Tang
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Ioana Niculescu, Gabriel Niculescu
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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

Collaboration of experimentalists and theorists

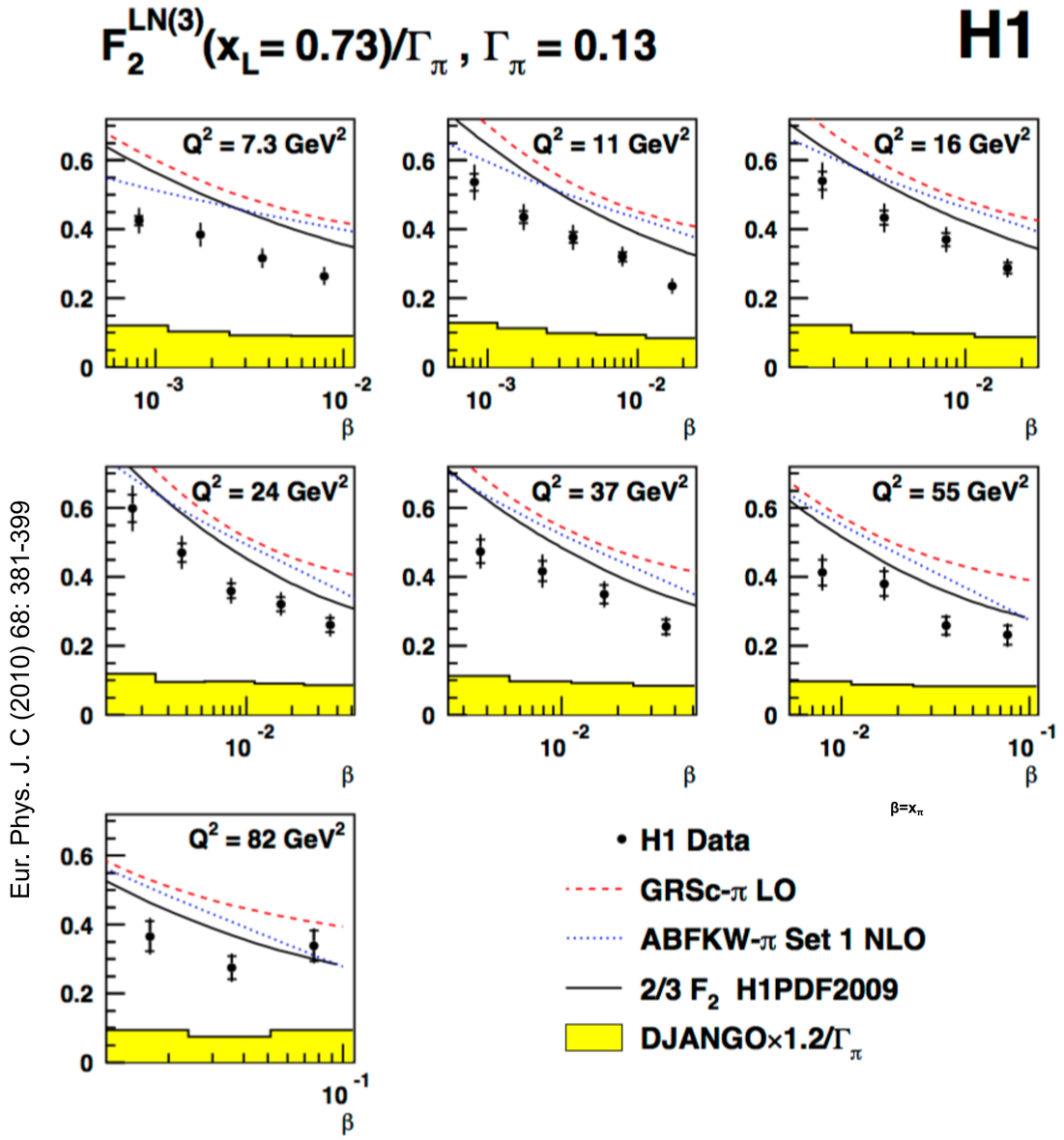
Pion TDIS
- C12-15-006
- PAC43 approved
- (C → subject to technical review)
- Awarded requested beam time
- A- rating - exciting physics: first time Sullivan process with both proton/neutron targets

Kaon TDIS
- Run group C12-15-006A
- PAC45 approved
- No additional beam time/detectors
- First Sullivan process extraction of kaon SF

Jeopardy this year (PAC51)

Where will TDIS lie amongst existing data?

Example Previous Data



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

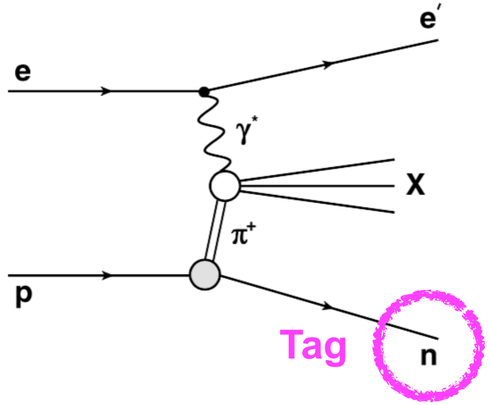
HERA Tagged DIS

- 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

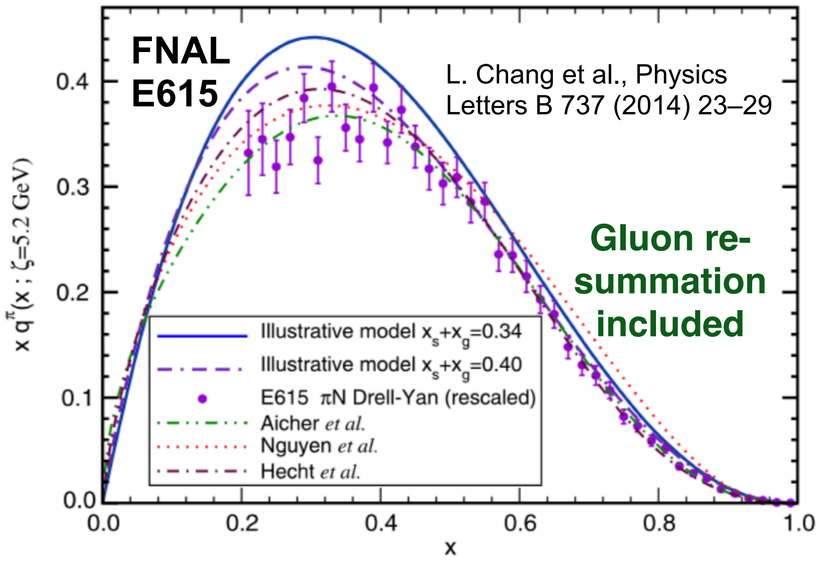


TDIS:

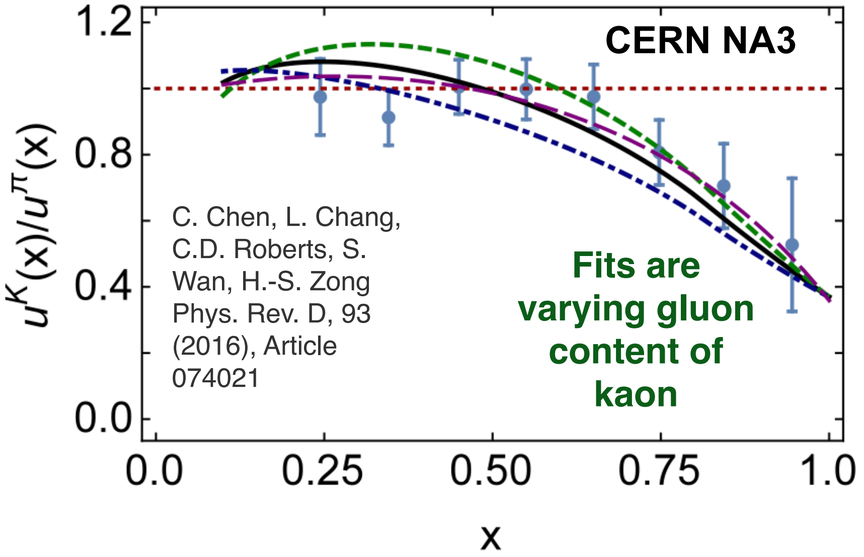
- Valence regime
- Higher x, lower Q^2
- Evolution between kinematics

Example Previous Data

Pion valence quark distribution function

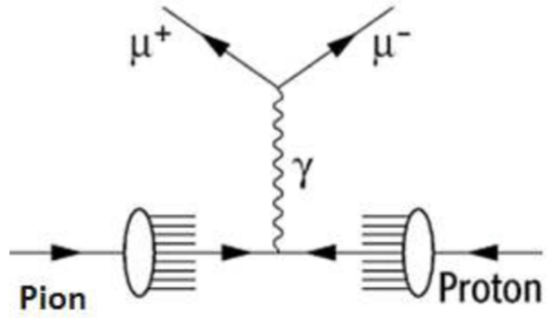


Ratio K/pi u-quark distributions



Valence region - Drell Yan

- CERN/Fermilab



- Large-x region interesting historically - substantial theory
  - pQCD, DSE, light-front, …, NLO, gluon re-summation
- Practically non-existent data for kaon
- More data needed for reducing uncertainties in global PDF
- Future DY data expected from COMPASS++/AMBER at CERN (2019 LOI arXiv:1808.00848)

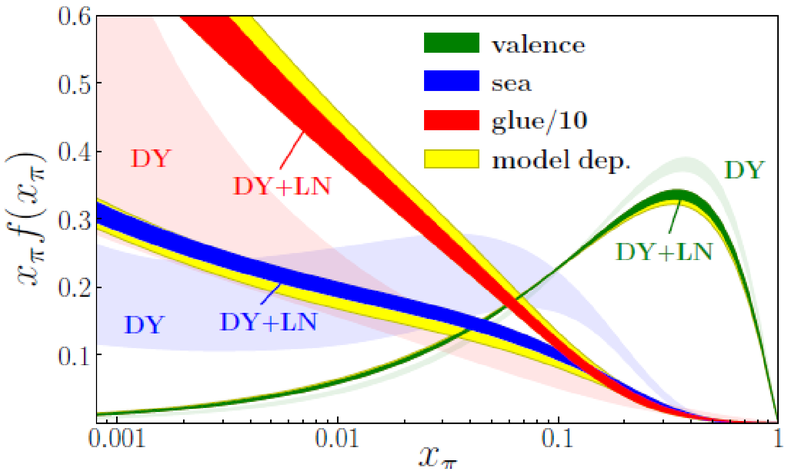
TDIS

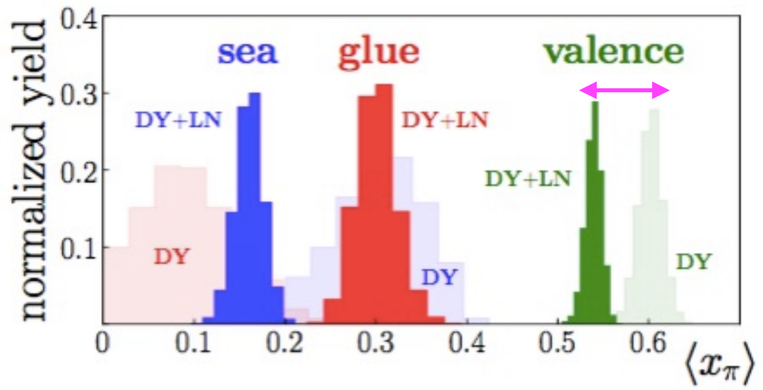
- Independent cross-check → PDF universality
- Extend to neutral pions

- More data essential

Example Previous Data

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





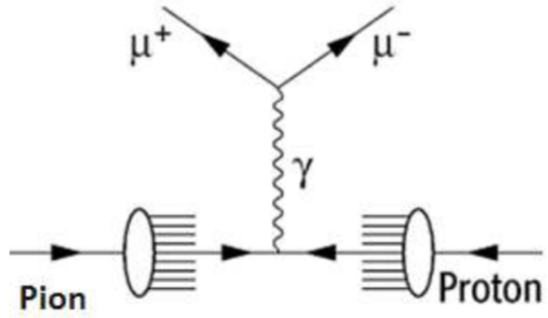
mom fraction carried by sea/glue/ valence

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

Non-overlapping uncertainties - tension at large x

Valence region - Drell Yan

- CERN/Fermilab



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TDIS

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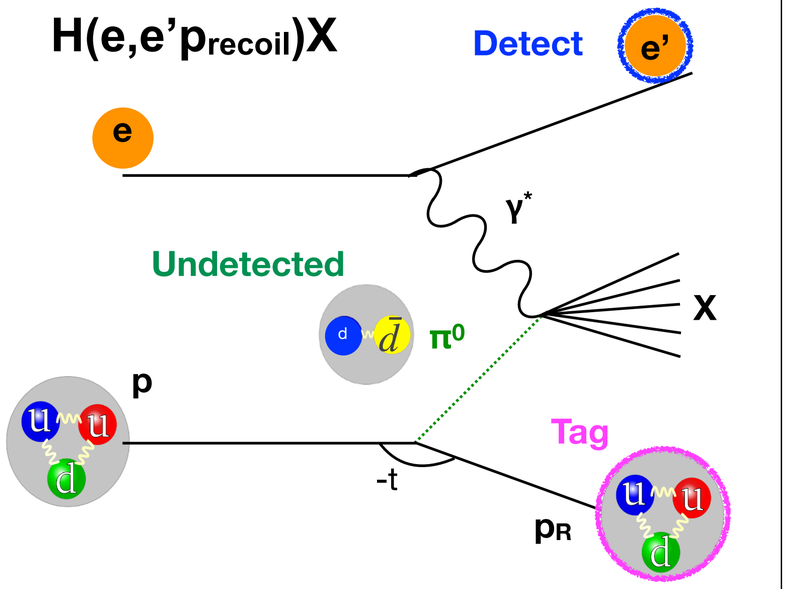
- Extend to neutral pions

- More data essential

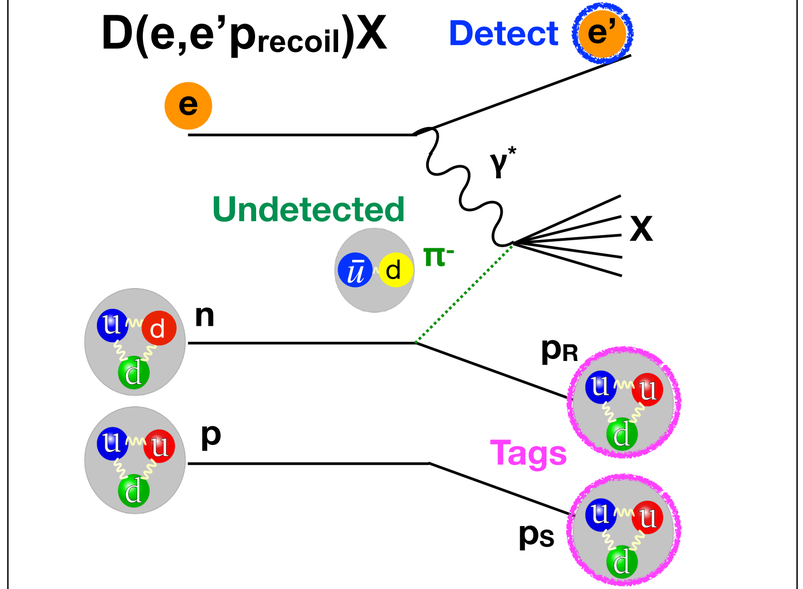
TDIS Measurements

Neutral Pion



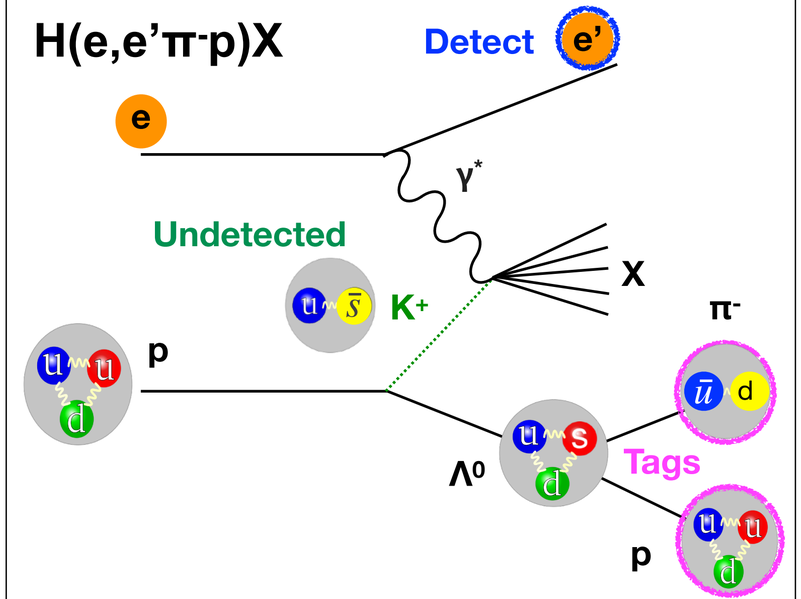
Independent Check, add to sparse data

Charged Pion



Expected world first

Kaon



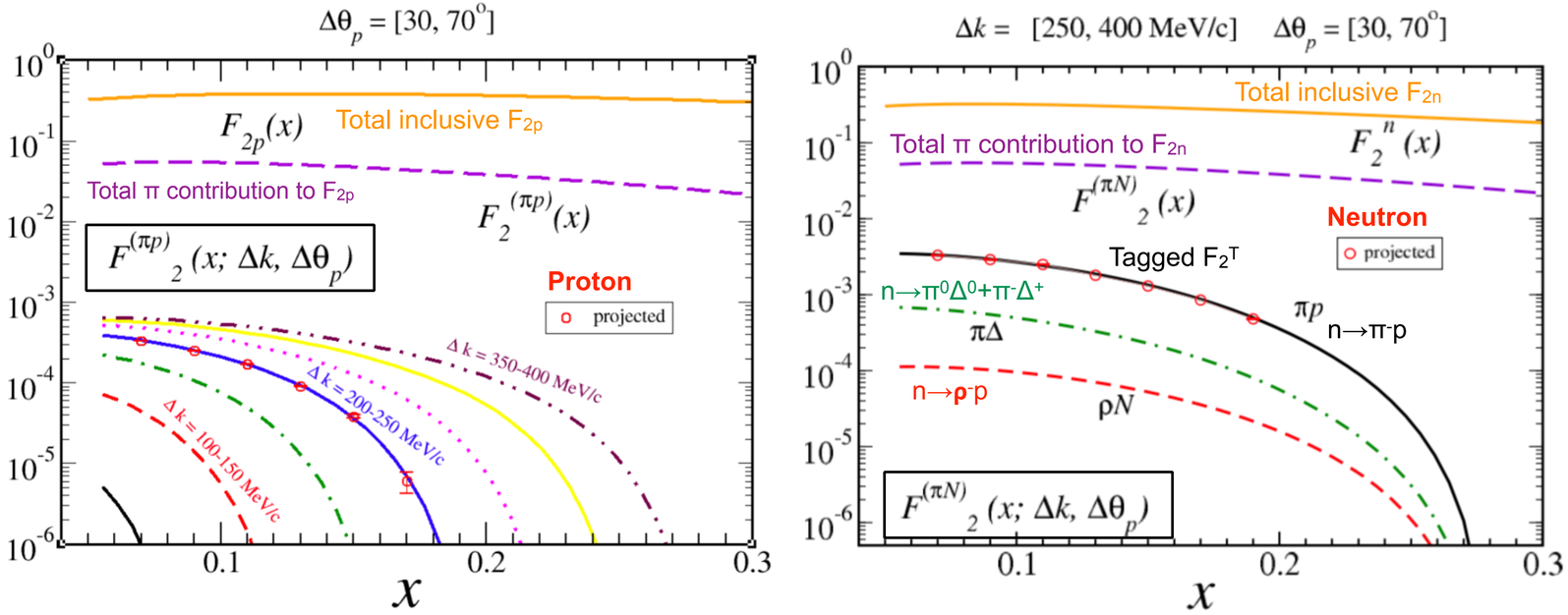
Expected world first

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

- Small -t to maximise “true” pion content
- Very low momentum recoiling hadrons (60 - 400 MeV/c) → need novel detector

Need for High Luminosity

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



- Predictions shown above 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)

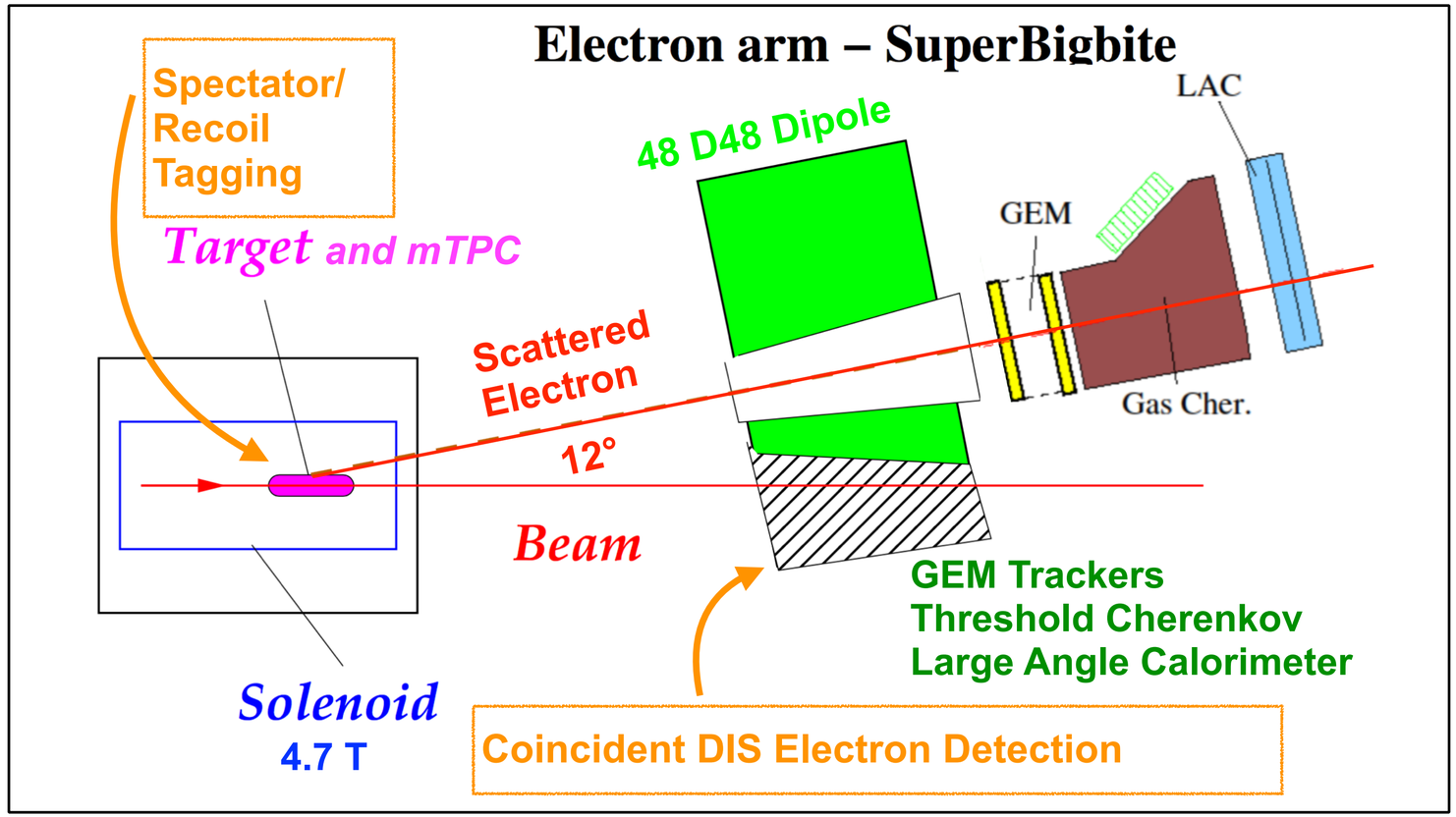
$$R^T = \frac{d^4\sigma(ep \to e' X p')}{dx dQ^2 dz dt} \Big/ \frac{d^2\sigma(ep \to e' X)}{dx dQ^2} \Delta z \Delta t \sim \frac{F_2^T(x, Q^2, z, t)}{F_2^p(x, Q^2)} \Delta z \Delta t$$

Extraction depends on pion flux model
Assuming pion exchange dominant

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

Kaon TDIS will use same method

TDIS Measurements



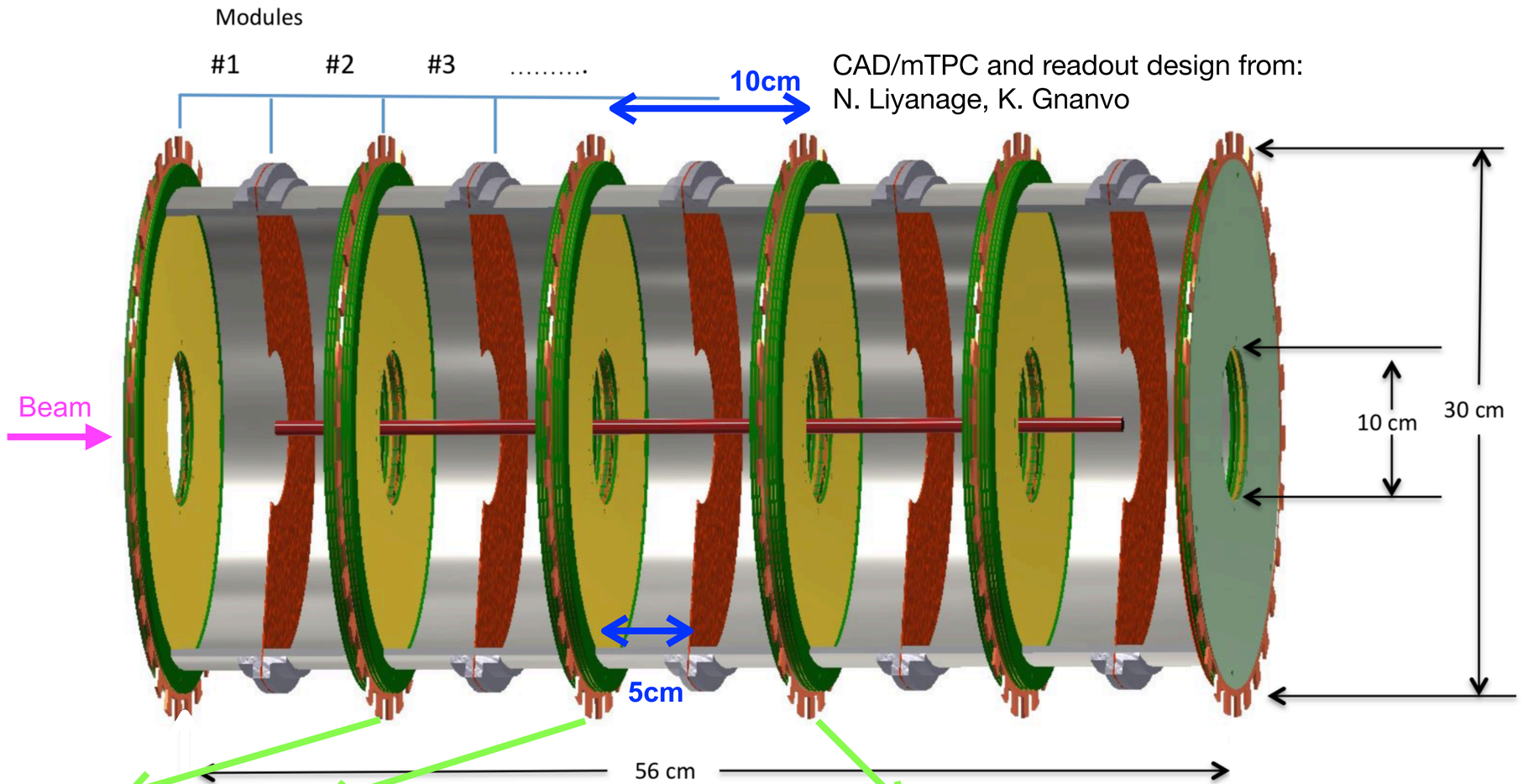
- JLab's fixed target, high current Halls are ideal for TDIS!

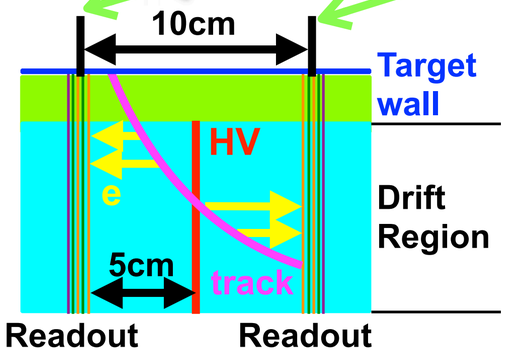
- 50μA 11 GeV e^- beam on high density target
- H/D gas; 40 cm length; 1 cm diameter; 25 μm walls; 3 - 4 atm; room temp (MSU)
- → high luminosity 2.9 x 10^{36} $cm^{-2}s^{-1}$

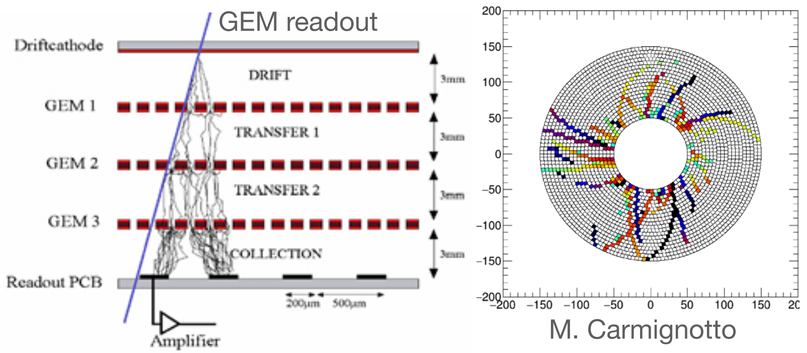
- e' detection in reconfigured SBS
  - Current use in Hall A for nucleon E/M FF suite of experiments
  - GEMs (SBS);
  - threshold Cherenkov (HERMES RICH or new);
  - calorimeter (CLAS LAC)
  - Electron PID and (L2) trigger, tracking and π rejection (~10^{-4})

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

High Rate mTPC







M. Carmignotto

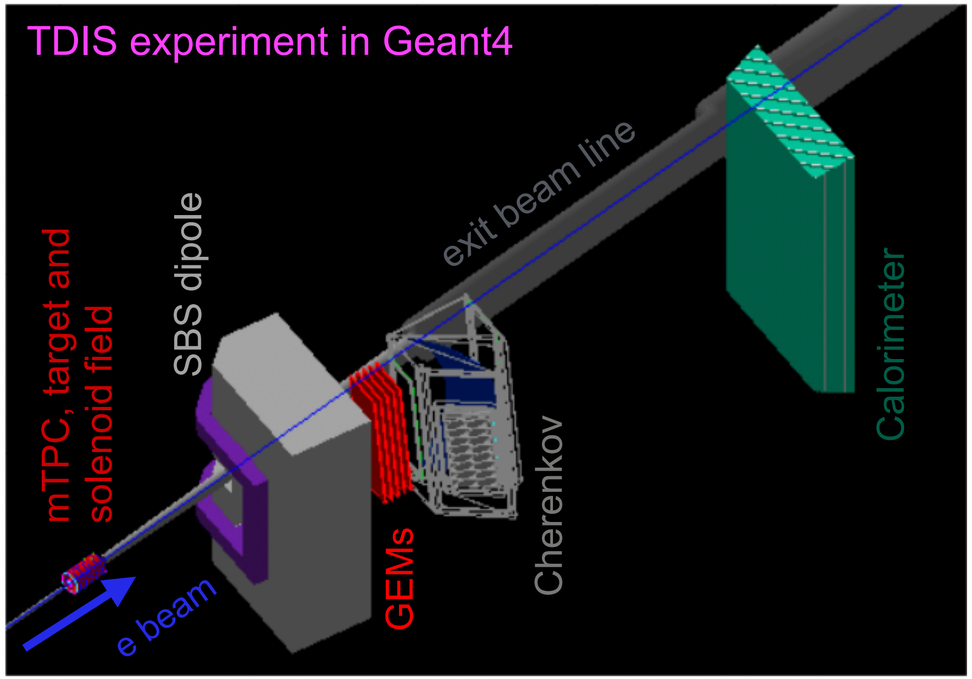
- Division of volume into chambers
- Reduces background rates

- Volume filled with low density gas at STP
- Fast drift times (~2μs)

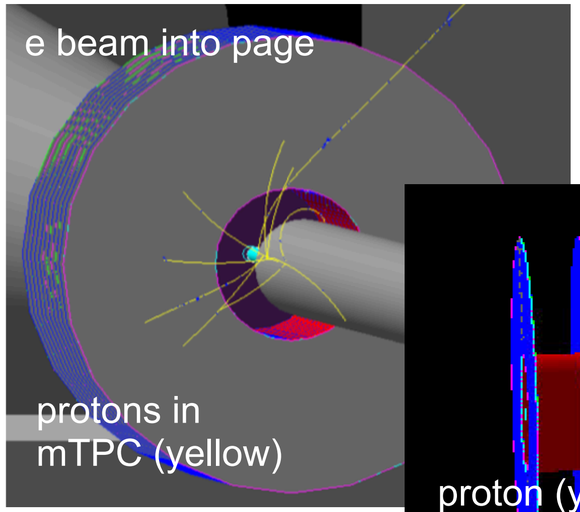
- Readout planes
  - Multi layer GEM foils
  - Segmented readout pads

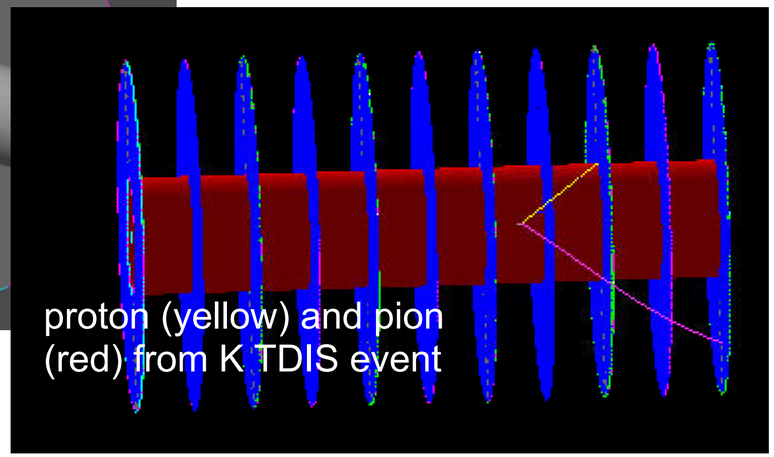
- Tag recoils/spectators
  - Vertex tracking
  - Momentum reconstruction (solenoid)
  - PID by dE/dx

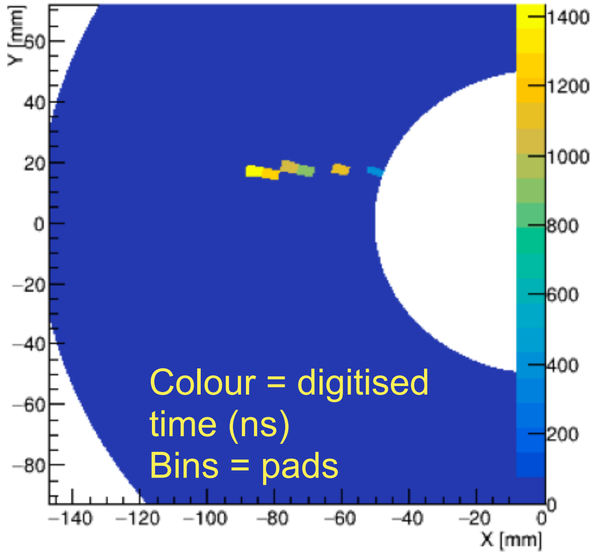
Simulation

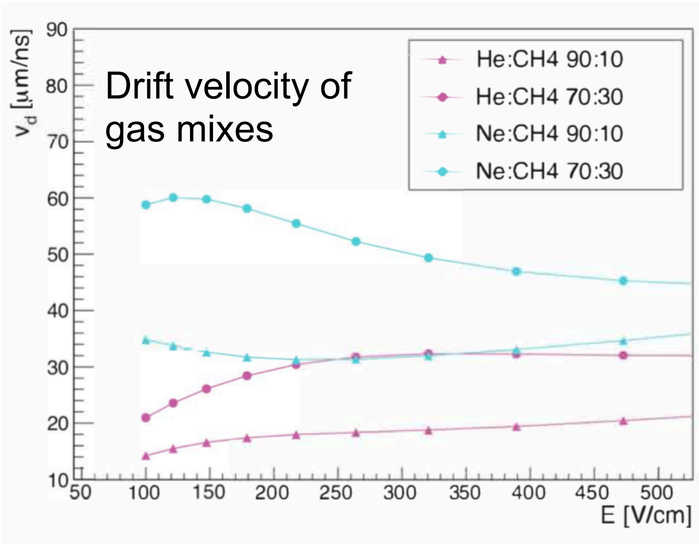


- In-depths studies within SBS collaboration's Geant4 framework g4sbs
  - *Team* of contributors (e.g. C. Ayerbe, E. Fuchey, S. Wood, A. Tadepalli, D. Dutta, R. Montgomery, A. Puckett, M. Carmignotto, A. Nadeeshani…and more!)
- mTPC also simulated separately using CERN's magboltz/garfield
  - Gas mixtures; electric field…
- Recent updates to event generators, background/accidentals rate studies
- Tracking developments on-going, especially for high rate Deuterium case

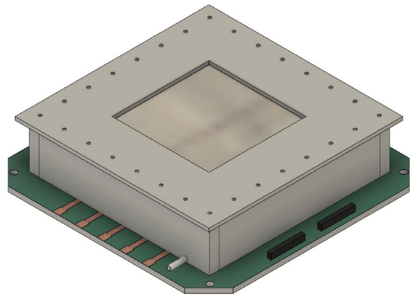


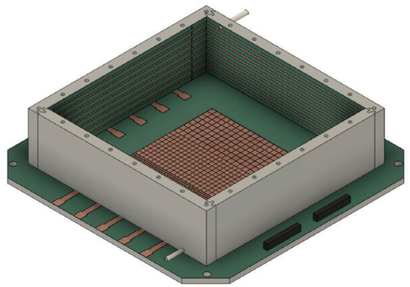






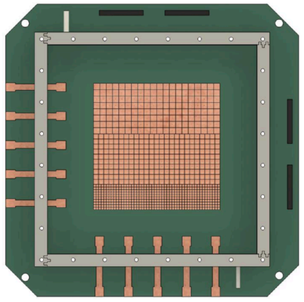
mTPC Prototyping



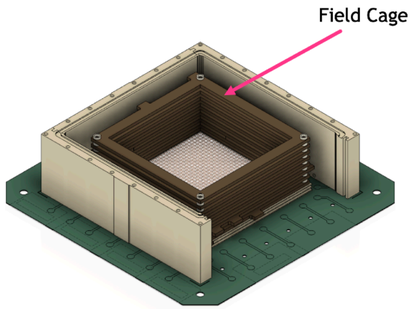


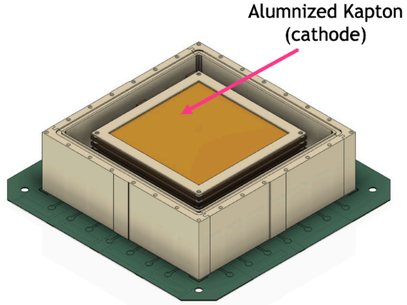
CAD model:
S. Ali (UVa)

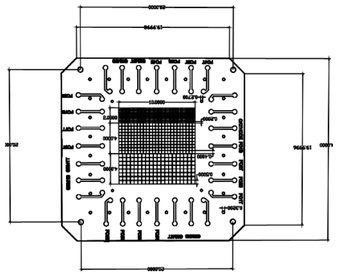
Field set up by
electrode strips



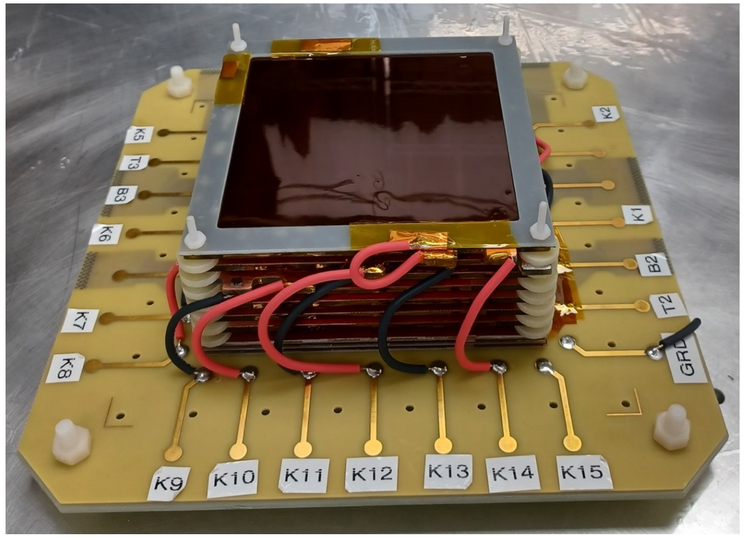
Different sized
readout pads

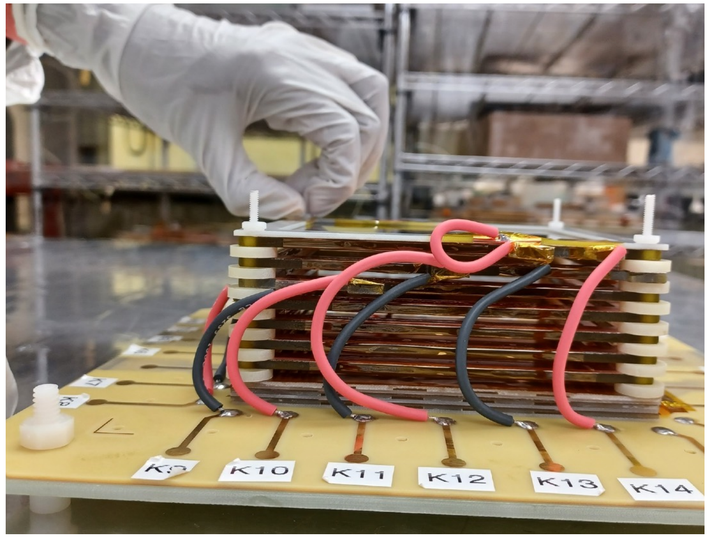


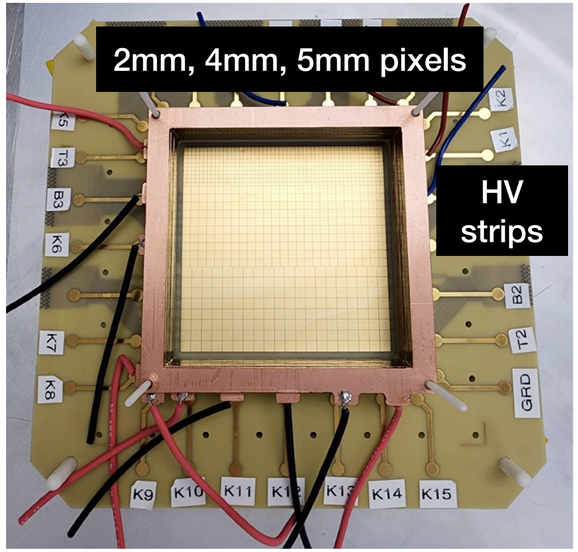


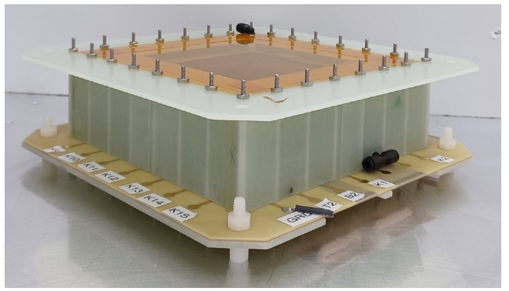


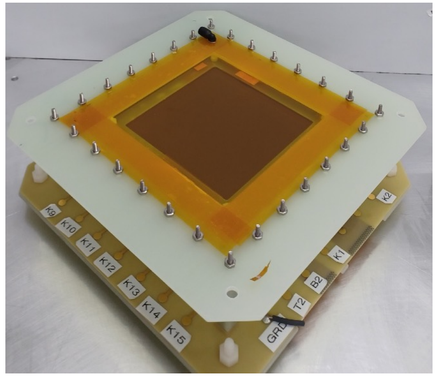
- **University of Virginia recently completed 1st prototype!**
  - (N. Liyanage, H. Nguyen, S. Ali)
  - 10 x 10 cm^2 active area
  - Entrance window → cathode → 4.7cm drift in field cage → triple GEM foils (2mm between foils) → segmented anode PCB → Panasonic connectors/readout
- **JLab/UVa/MSU currently testing prototype!**
- (E. Christy, A. Nadeeshani, D. Dutta, H. Nguyen, C. Cuevas)
- After lab tests → beam test





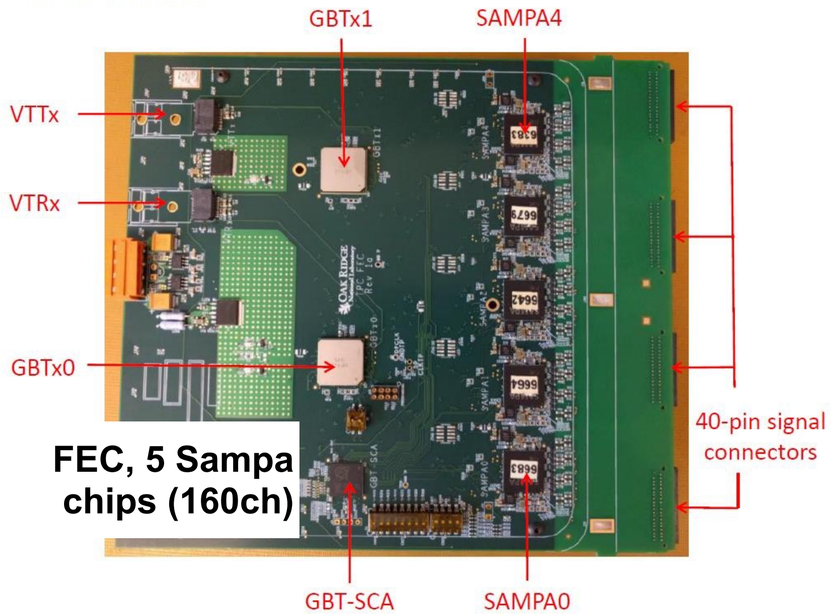




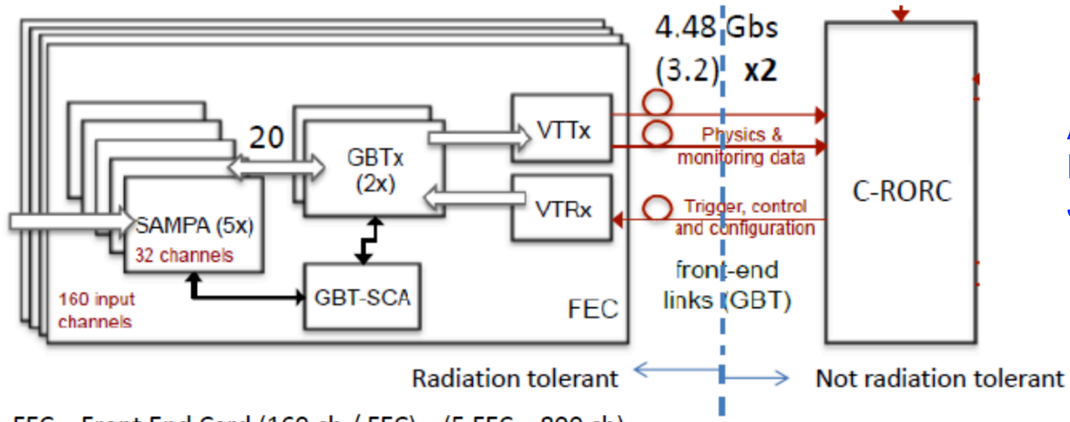


Construction images courtesy of Aruni Nadeeshani (MSU), Huang Nguyen (UVa)

Triggerless Readout at JLab

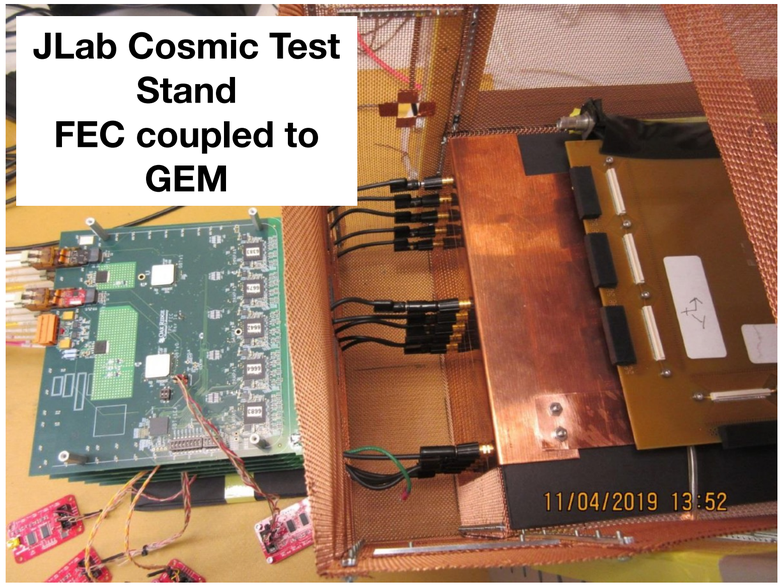


FEC, 5 Sampa chips (160ch)



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

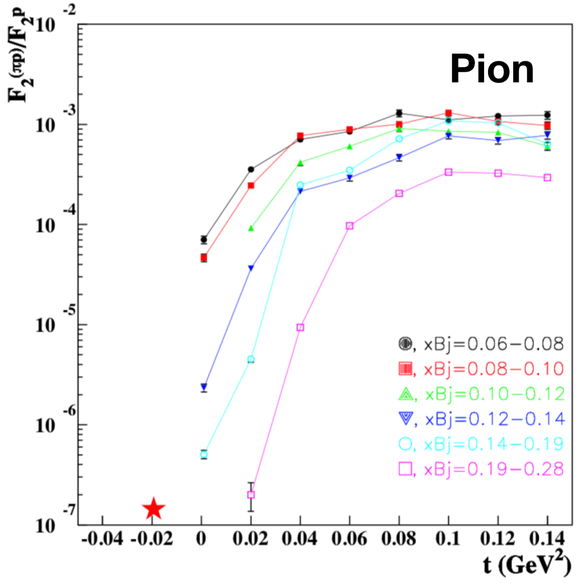


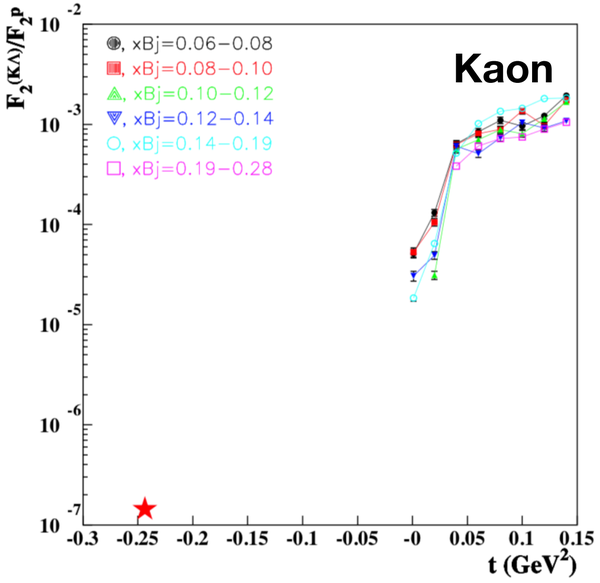
JLab Cosmic Test Stand
FEC coupled to GEM

- Plan to read data continuously from ≥35k channels
- Parallel data flow
- Event synch with triggered detectors (SBS)

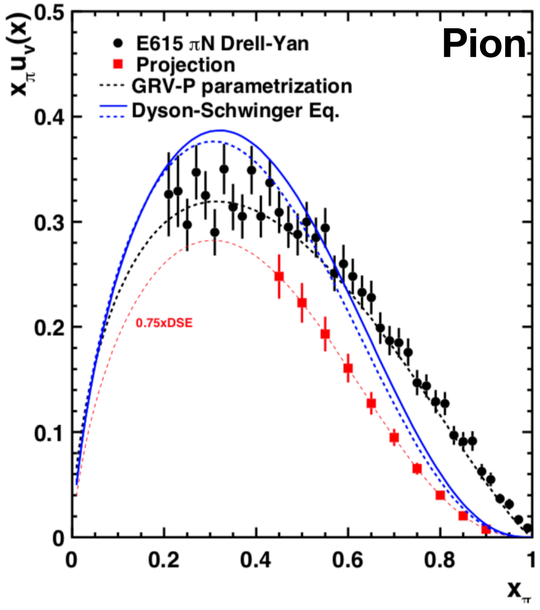
- Prototyping at JLab (E. Jastrzembski, G. Heyes, et al.)
- Using Oak Ridge SAMPA FEC for the ALICE TPC
- SAMPA ASIC: pre-amp, ADC, zero-suppression… (M. Bregant, Sao Paolo)
- Continuous sampling w/ high readout speed (~1TB/s post zero-supp possible for ~35k chan)
- TDIS is a driver for streaming readout developments

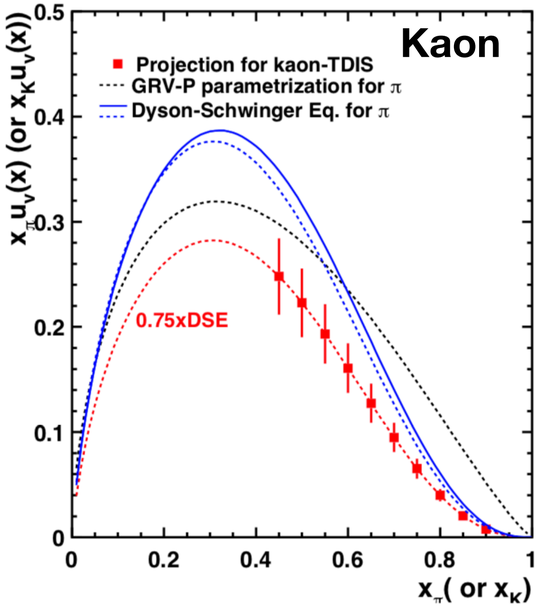
Example Projected Results





- Shown 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 SF
- Low momentum reach of mTPC essential to obtain shapes of curves

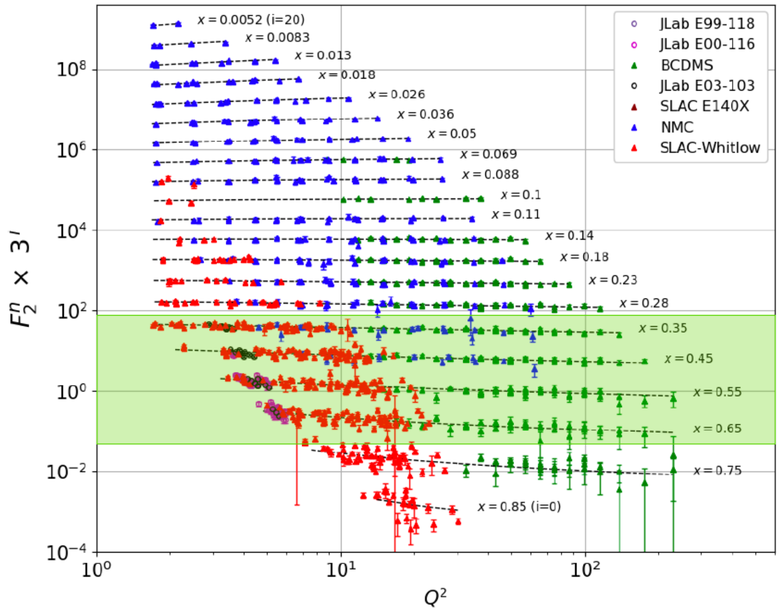




- Projected range of coverage for relevance to valence quark distribution analyses

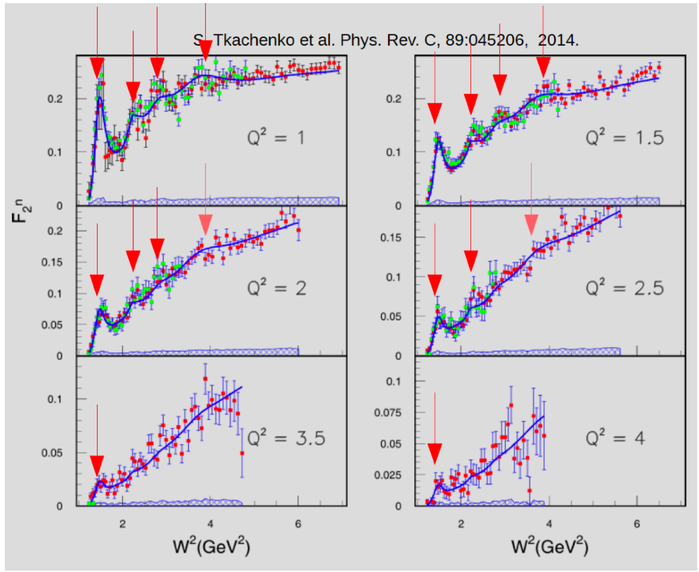
Also…TDISn and Neutron Structure C12-15-006B

Neutron F_2 SF

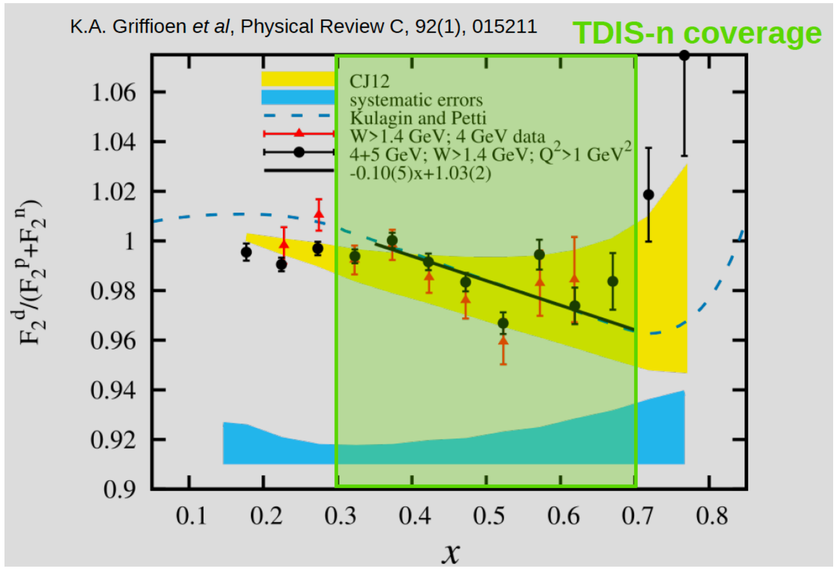


TDIS-n coverage

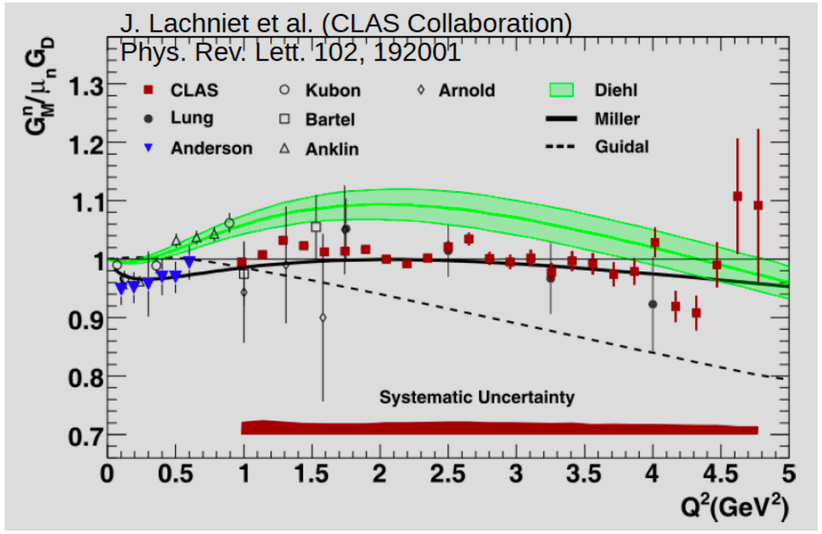
Resonance Region SF



EMC effect in deuteron



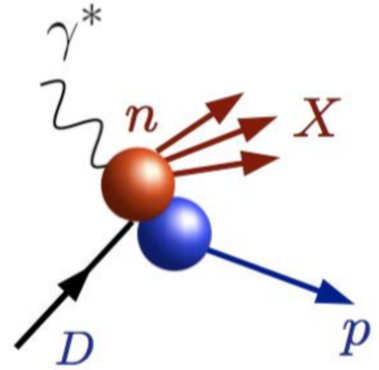
Elastic e-n scattering and EM form factor G_M^n



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

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

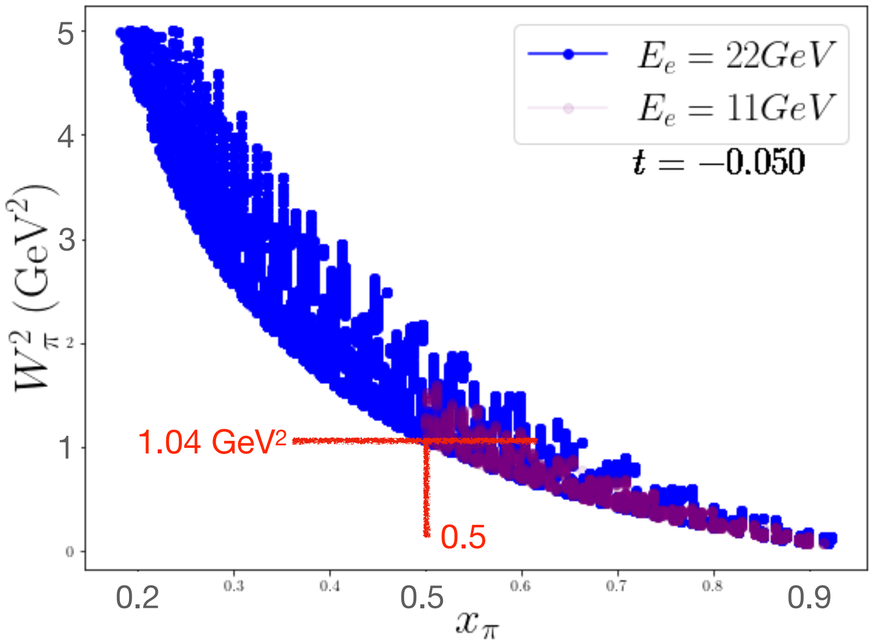
- Independent cross-check systematics
- Increased statistics in TDISn range
- Calibrate mTPC acceptance and efficiency
  - QE scattering on deuteron: HCAL for n; mTPC for p; SBS for e′
- Independent normalisation check of tagging method across experiments

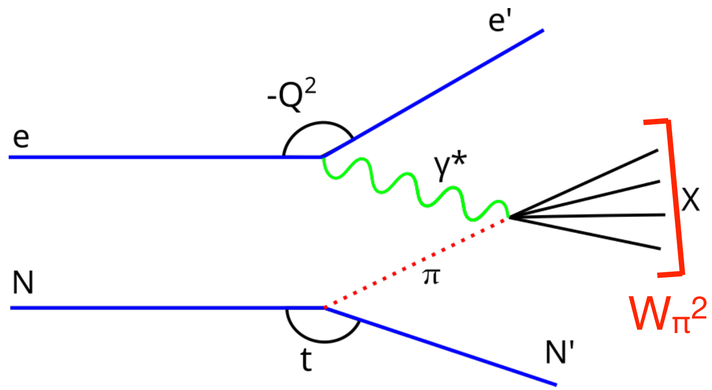


And there is even more… …

JLab22 Extension Studies

Plot: C. Ayerbe (W&M)

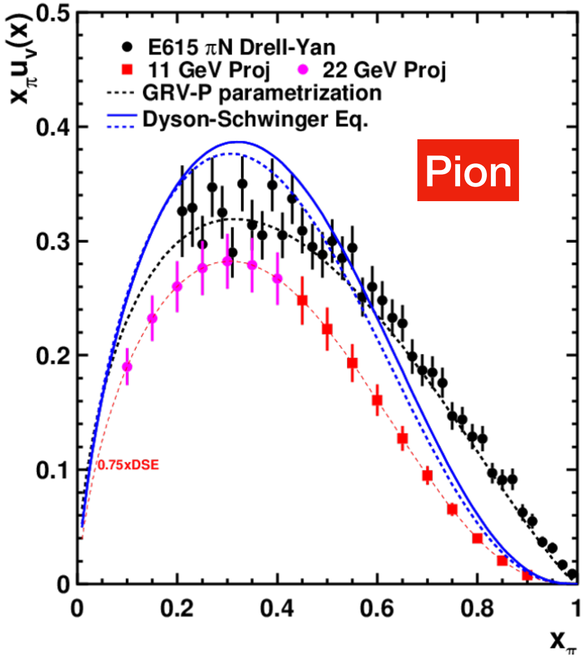


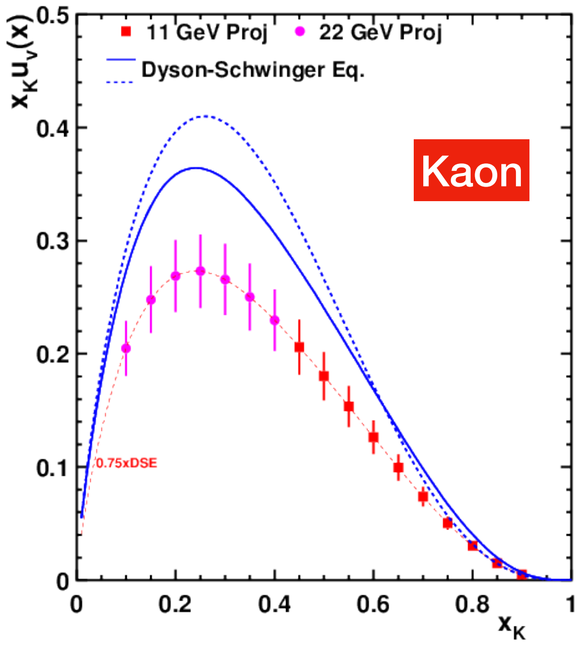


On behalf of members of group studying TDIS 22GeV including: C. Ayerbe; P. Barry; D. Dutta; R. Ent; T. Horn; C. Keppel; R. Montgomery

- 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: $W_\pi^2 > 1.04\mathrm{GeV}^2$ to minimise ρ resonance
- 22GeV: More data available above $1.04\mathrm{GeV}^2$
- 11GeV: still data above $1.04\mathrm{GeV}^2$ for PDF studies
- 11GeV: novel studies of resonances at low W_π^2
- 11GeV: crucial to realise challenging experimental technique

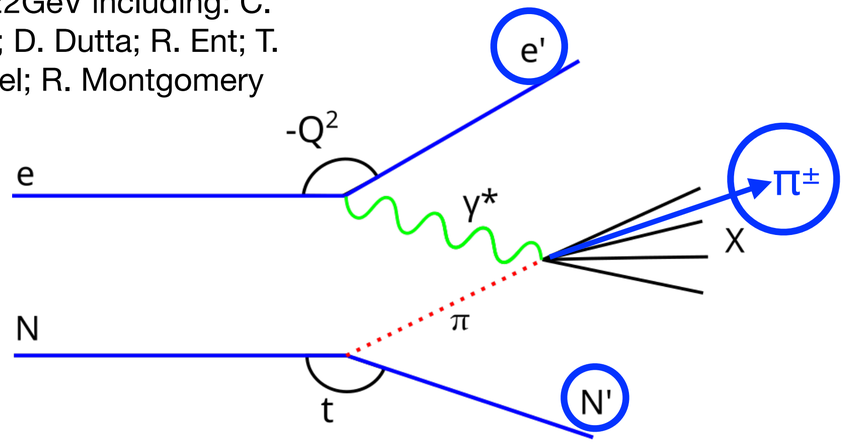




Plots: D. Dutta (MSU), T. Horn (CUA)

JLab22 Extension Studies

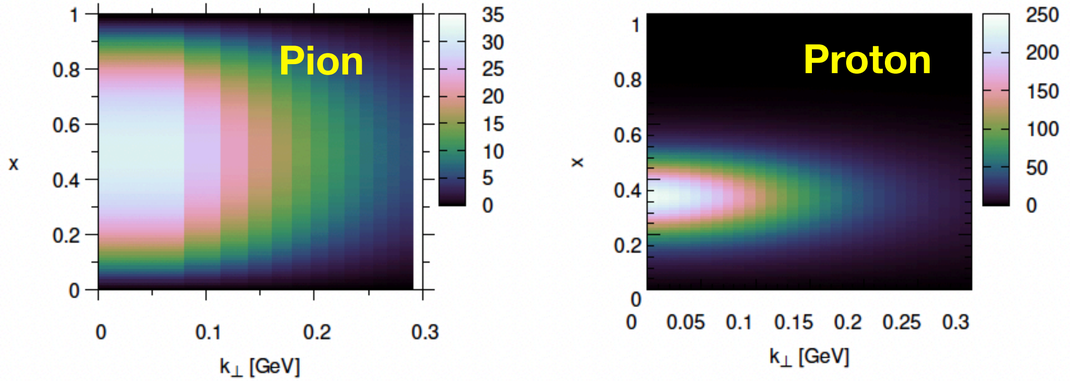
On behalf of members of group studying TDIS 22GeV including: C. Ayerbe; P. Barry; D. Dutta; R. Ent; T. Horn; C. Keppel; R. Montgomery



- 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
  - Next step of study

Leading twist unpolarised proton vs pion TMD



Tobias' slide from Light-Front

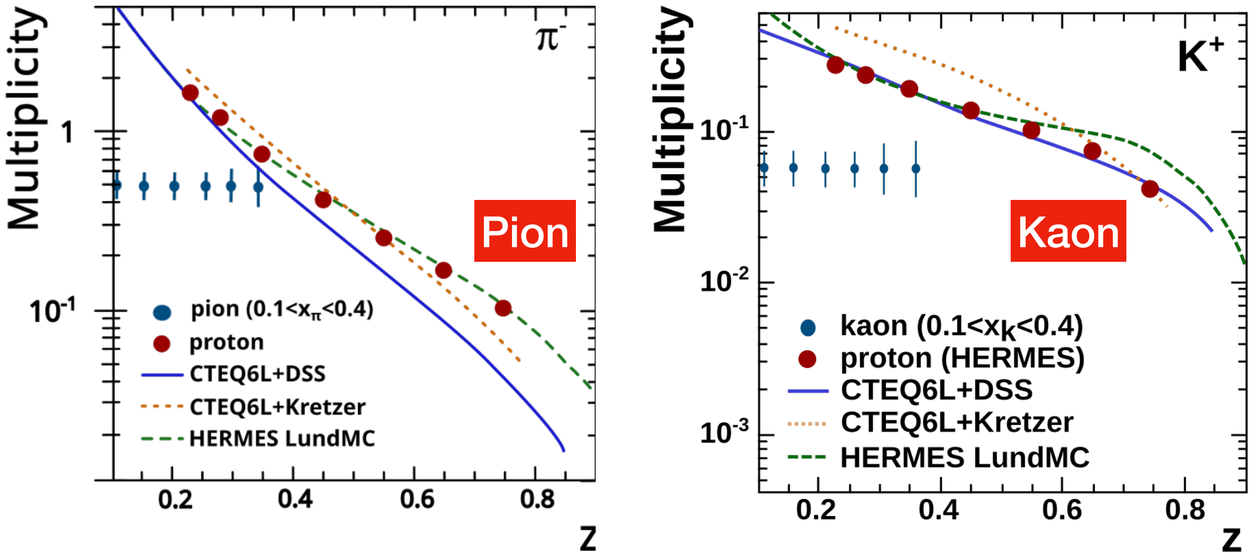
Figure: Leading twist unpolarized TMDs at the hadron scale. Left frame: Pion from Minkowski space Bethe-Salpeter equation model with constituent quarks, massive one-gluon exchange and quark-gluon form factor [1]. Right frame: Proton from a Light-front model with constituent quarks and a scalar diquark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

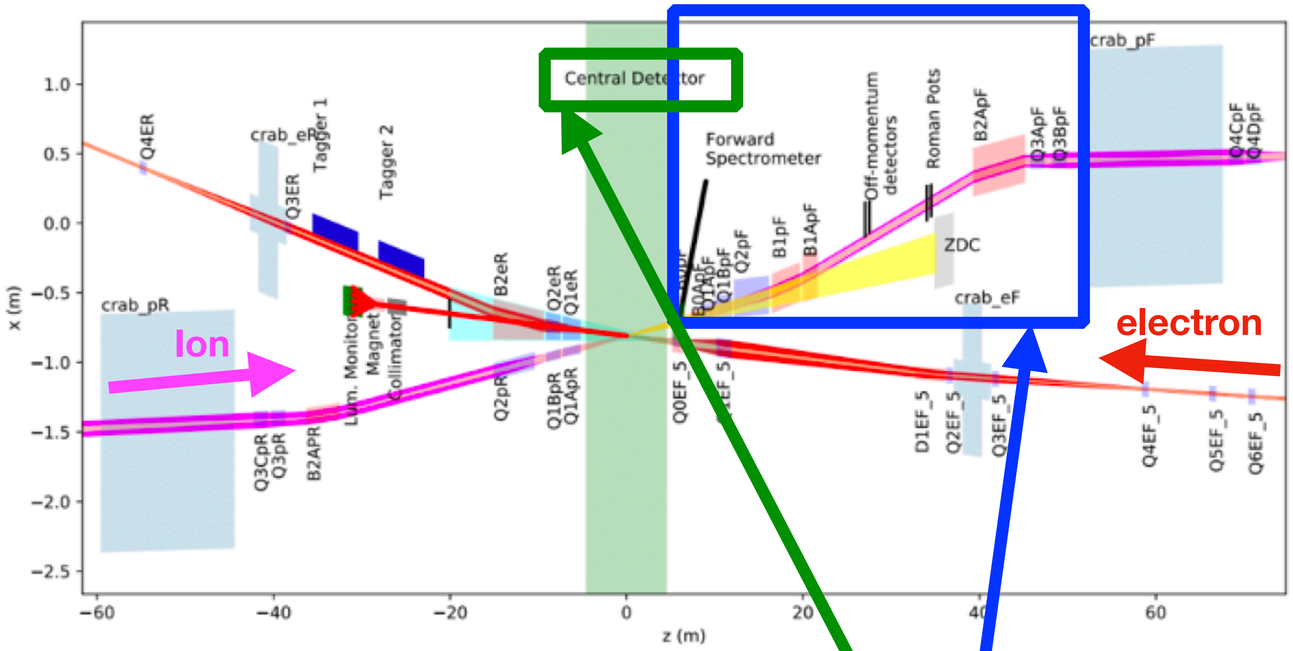
T. Frederico (Instituto Tecnologico de Aeronautica)
E. Ydrefors (Chinese Academy of Sciences)

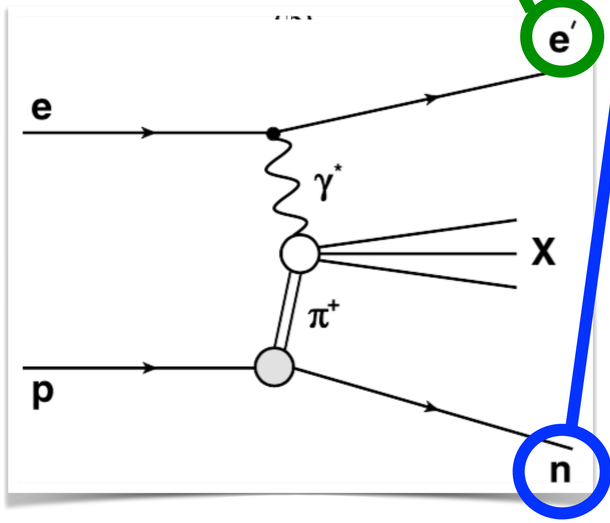
Plots: D. Dutta (MSU), C. Ayerbe (W&M)



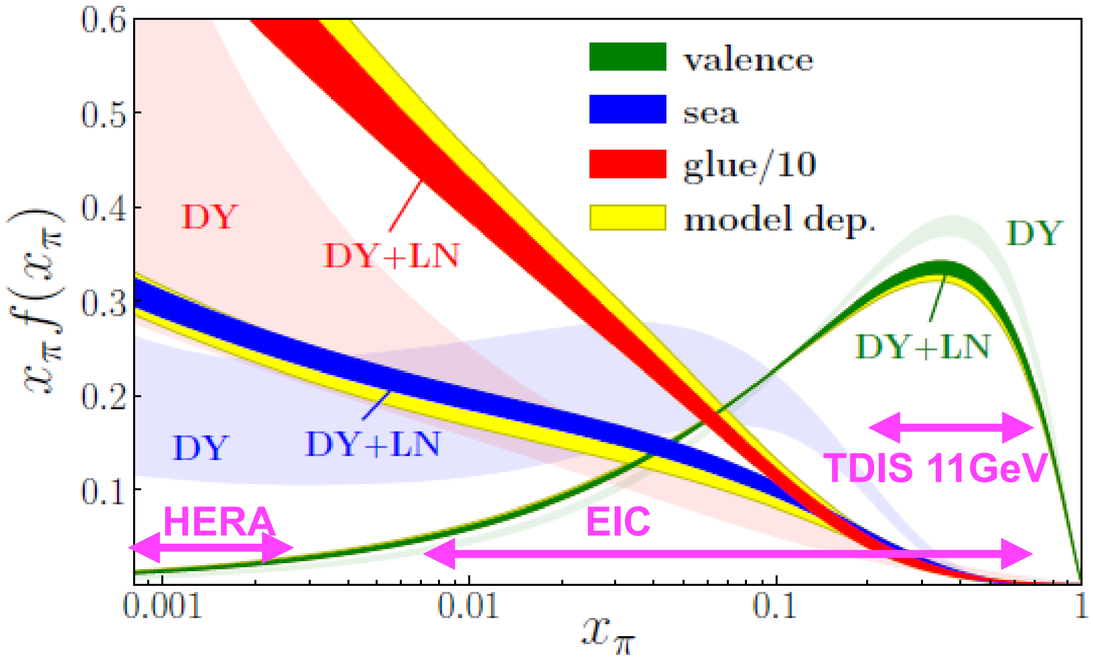
HERMES results: A. Airapetian et al. (HERMES Collaboration), Phys. Rev. D 87, 074029

Gateway to Spectator Tagging at EIC





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

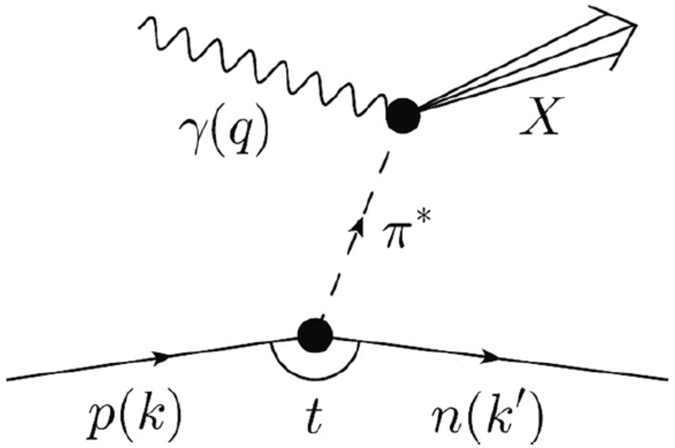


- Meson SF accessible via Sullivan at EIC
- High luminosity ($\mathcal{L}$=10^{34}Hz/cm^2 = 1000 * $\mathcal{L}_{HERA}$)
- Full acceptance
- Bridge HERA low x and JLab valence regime
- Uncertainties increase for SF at EIC as $x_\pi \rightarrow 1$
  - JLab TDIS is crucial for mid to high x_π range!

- 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

Summary

- Meson structure - crucial component in nucleon's structure
- Comparing π/K - experimental insights into EHM
- Experimental data for π/K SF **extremely sparse**



✓ TDIS at JLab: **unique** opportunity
- Broad physics program
- Understand nucleon & meson structure on deeper level
- Add to sparse world data set for meson SF in mid to high x_π range!
  - Universality in valence regime for pion PDF
  - Kaon SF - almost empty world data!
- TDIS 11GeV very important gateway for range of future programs
  - Future EIC and proposed EicC
  - Potential TDIS at 22GeV JLab
  - e.g. TDIS 11GeV key for realising:
    - meson tagging techniques, challenging novel instrumentation, improving models/predictions…

✓TDIS at JLab: status
- C12-15-006 up for jeopardy this year (PAC51)
- Lots of exciting developments to report on, examples:
  - design, technical, software, theory
  - expansion of TDIS program (kaon, neutron);
  - increased demand for TDIS data in community wrt theory and future experiments…

Thank you

And thank you to collaborators for input