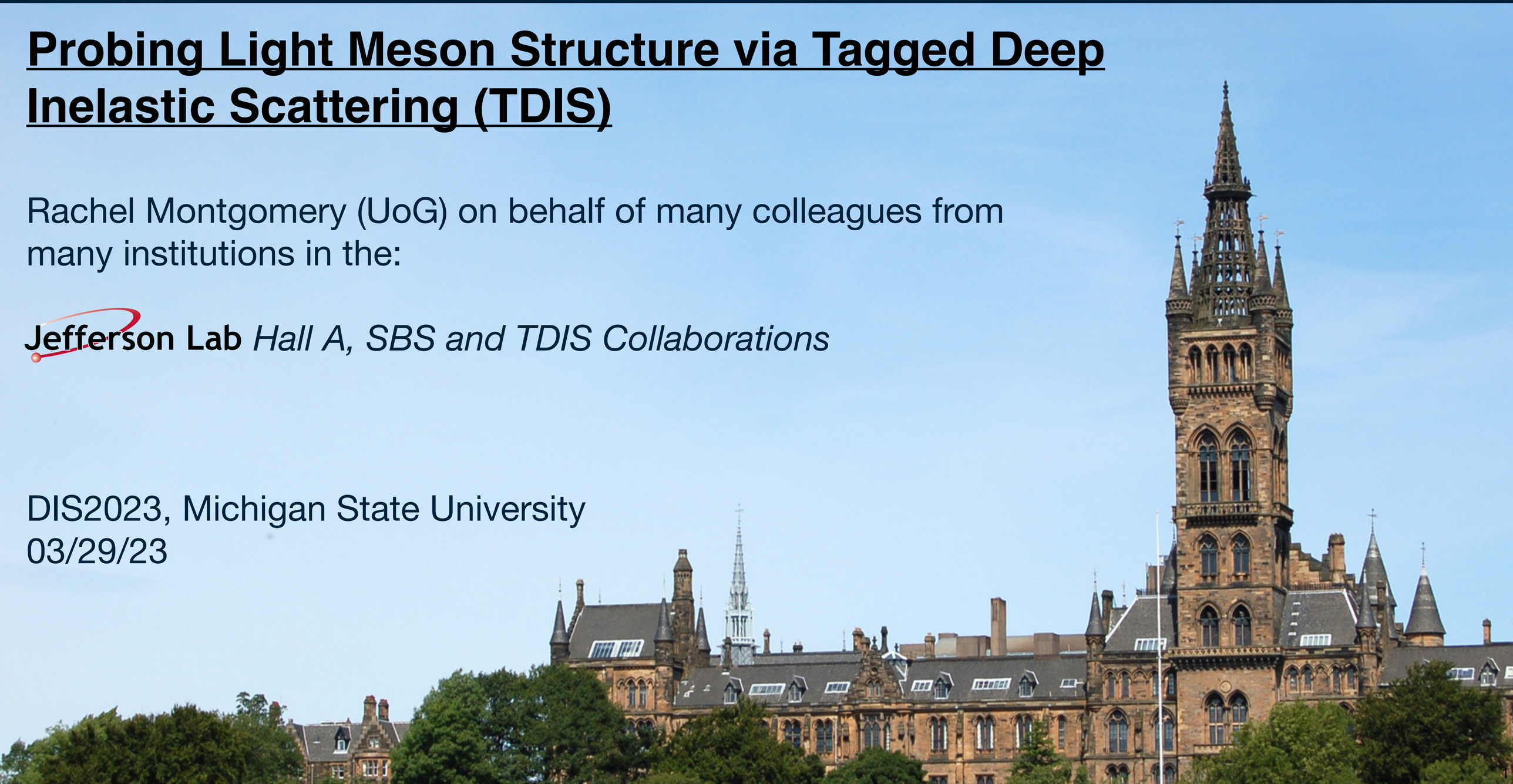
University of Glasgow

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

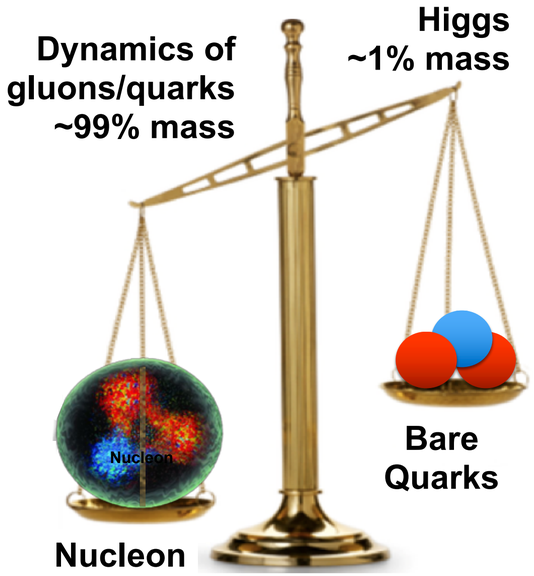
Rachel Montgomery (UoG) on behalf of many colleagues from many institutions in the:

Jefferson Lab *Hall A, SBS and TDIS Collaborations*

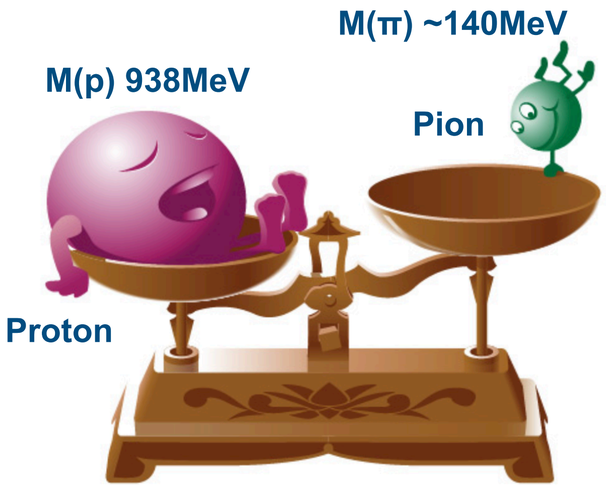
DIS2023, Michigan State University
03/29/23



Why Meson Structure?



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

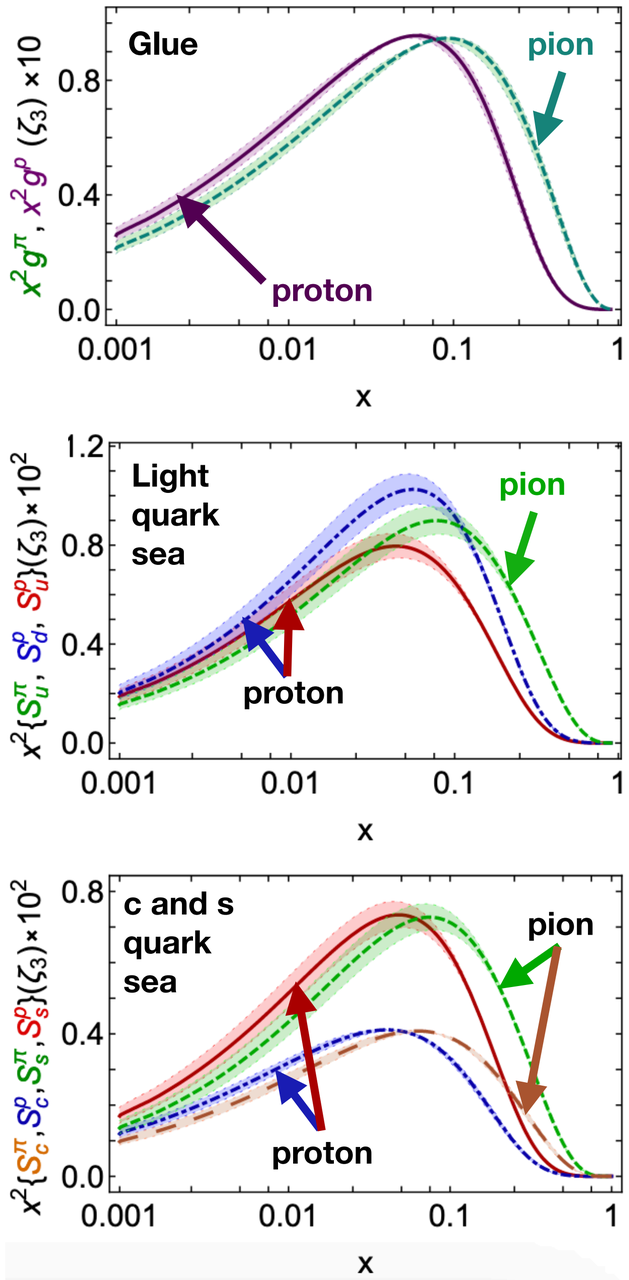


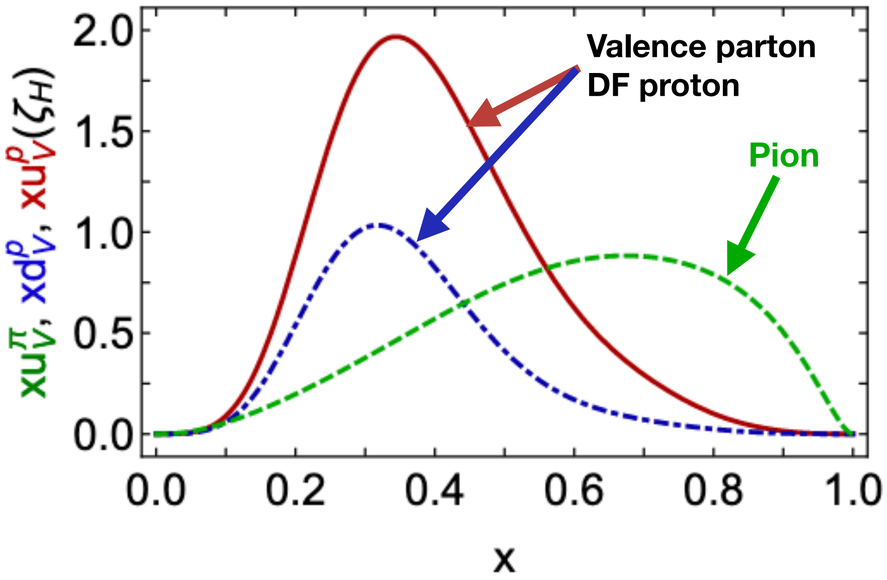
https://www.nobelprize.org/prizes/physics/2008/illustrated-information/

- Several motivations for π/K
  - nucleon/nuclear structure; mesonic content; NN interaction; access to strangeness… …
- Dynamics of strong interactions in QCD ~99% nucleon mass
  - emergent hadronic mass (EHM)
- Theoretical mass budgets for **light π/K** (Goldstone bosons) vastly different from **heavy nucleon,** and **each other (different gluon contents?)**
- Comparing distributions of light quarks versus strange quarks within mesons
  - → measurable signals of EHM
- π/K structure not well known experimentally
- Substantial theoretical work…need data
- Interesting implications for PDFs

Pion vs Proton Valence PDF

From arxiv: 2203.00753 [hep-ph]





From C. Roberts (INP)

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

- Marked difference between pion and proton valence PDF
- Differences translate into sea and glue DF
- “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?”

Accessing Pions/Kaons

Sullivan Process

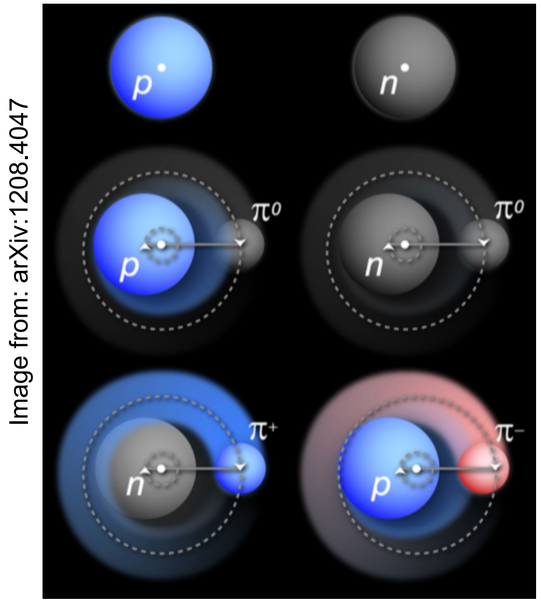
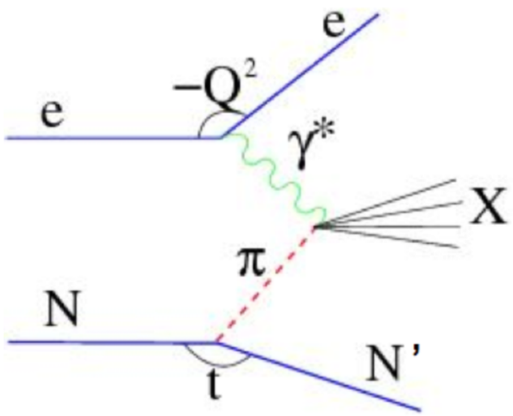
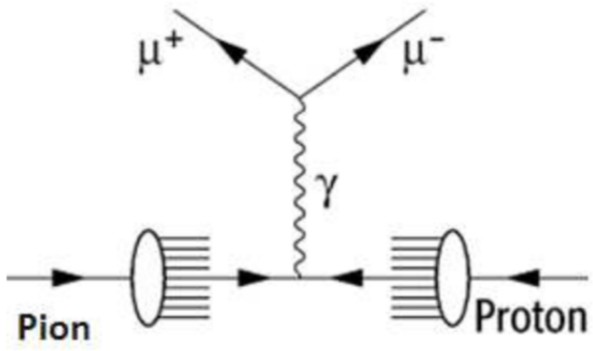


Image from: arXiv:1208.4047

Hard scattering from virtual meson cloud of nucleon



Drell-Yan

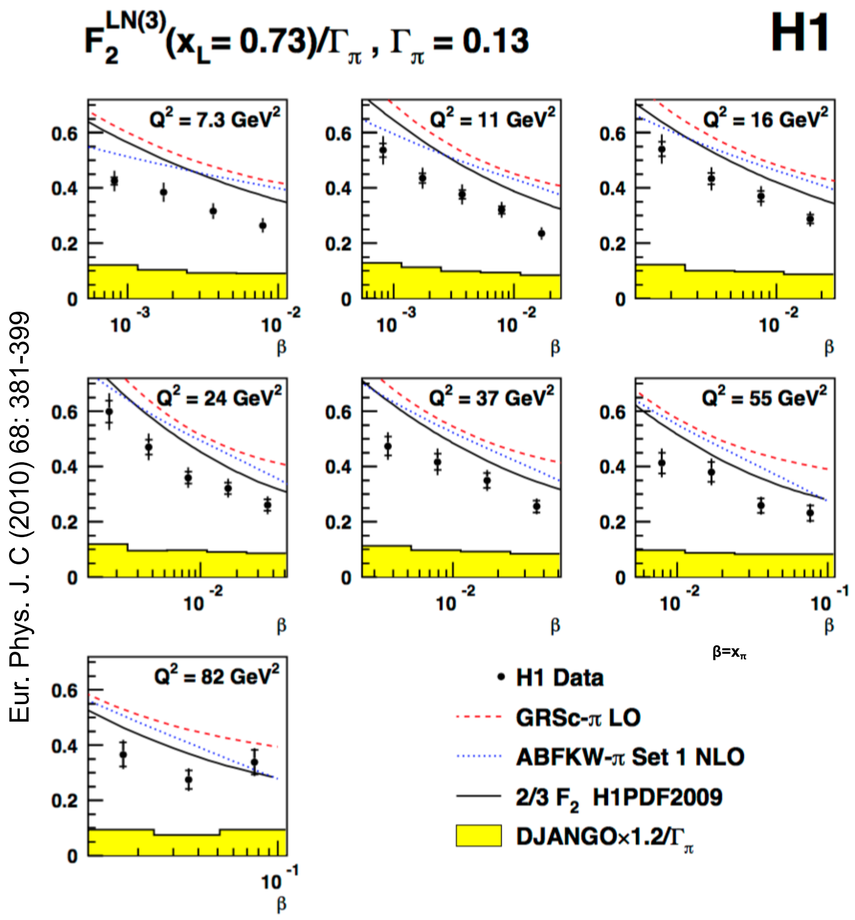


e.g. quark of pion annihilates with anti-quark of proton, virtual photon decays into lepton pair

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

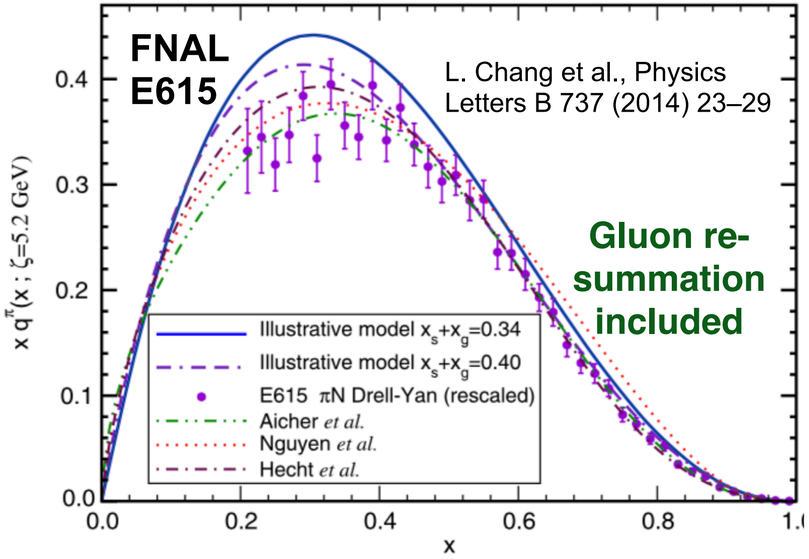
$$\frac{d^2\sigma}{d\Omega dE'} = \frac{\alpha^2}{4E^2{}_0 \sin^4\frac{\theta}{2}} \cos^2\frac{\theta}{2}\left[\frac{1}{\nu}\underline{F_2(x,Q^2)} + \frac{2}{M}F_1(x,Q^2)\tan^2\frac{\theta}{2}\right]$$

Example Previous Data

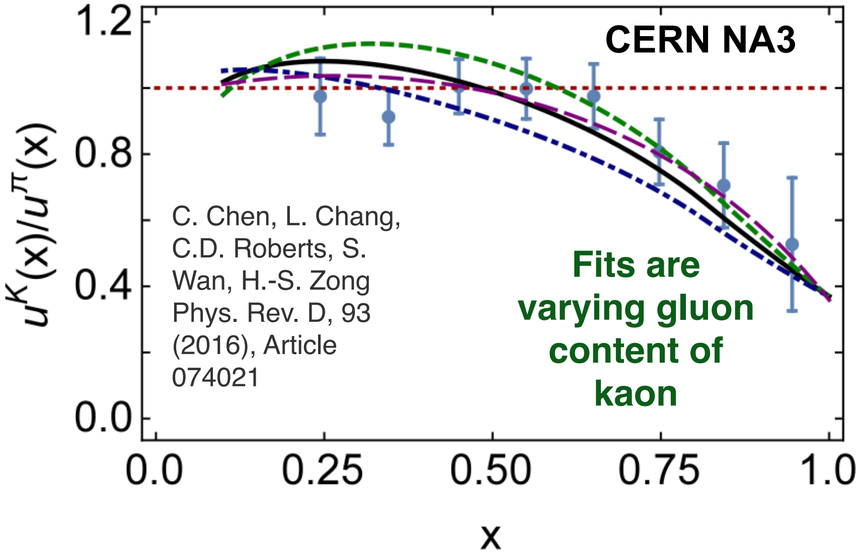


Eur. Phys. J. C (2010) 68: 381-399

Pion valence quark distribution function



Ratio K/pi u-quark distributions



Sullivan Process at HERA:

- Leading neutron tagged in ep → eXN
- 6 <Q^2 < 100GeV^2; 1.5e^{-4} < x < 3.0e^{-2}

JLab TDIS:

- Higher x, lower Q^2
- Study evolution between kinematics

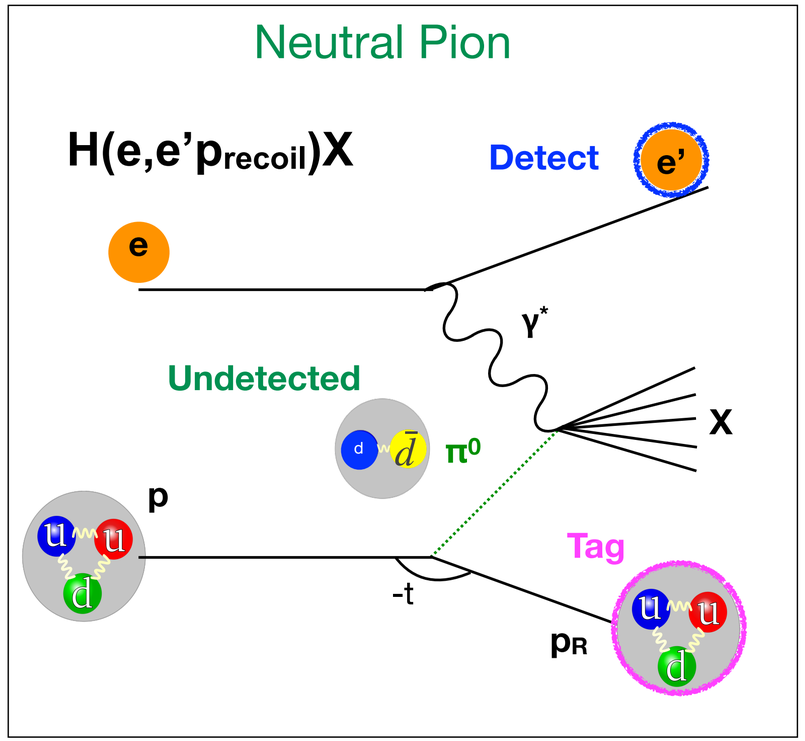
Valence region - DY at CERN and FNAL:

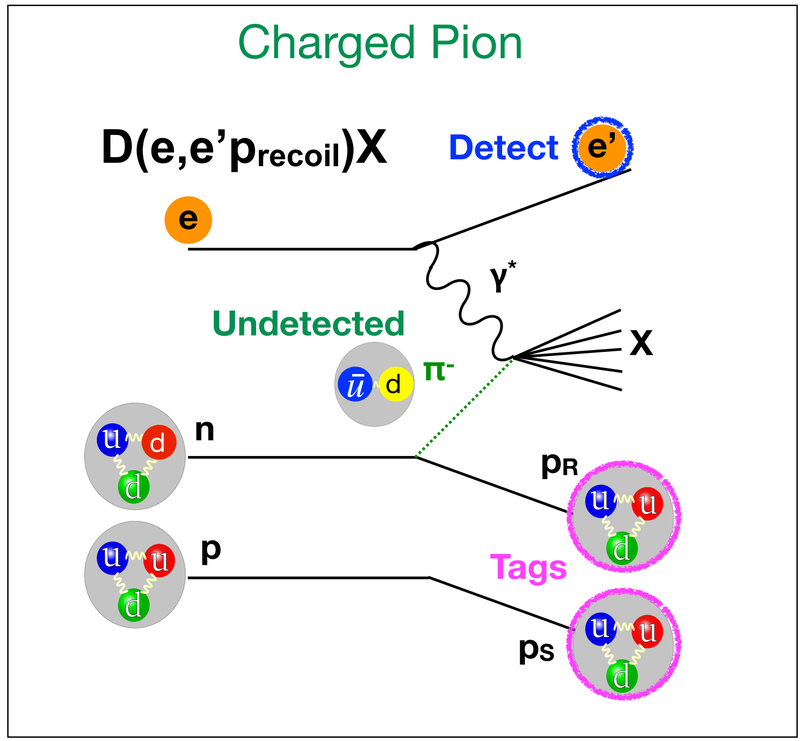
- Large-x region interesting - substantial theory, pQCD, DSE, light-front, …, NLO, gluon re-summation
- **More data needed for reducing uncertainties in global PDF fits**
- More DY data coming from AMBER at CERN - complementarity

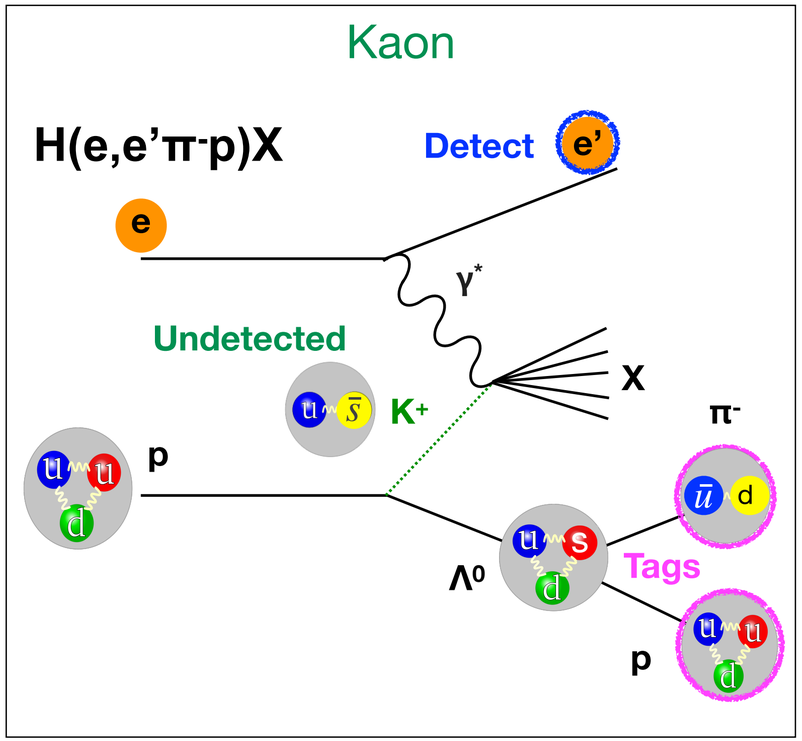
JLab TDIS:

- Independent cross-check, test of universality
- Extend to neutral pions and **improve kaon situation (!!!)**

TDIS Measurements







8 < W² < 18 GeV²
1 < Q² < 3 GeV²
0.05 < x < 0.2

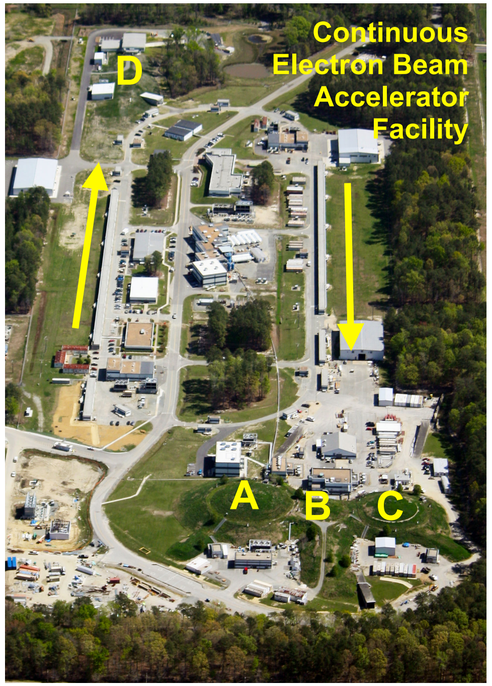
- Ratio of tagged to total inclusive cross-sections
- Tagged signal orders of magnitude smaller → need high luminosity

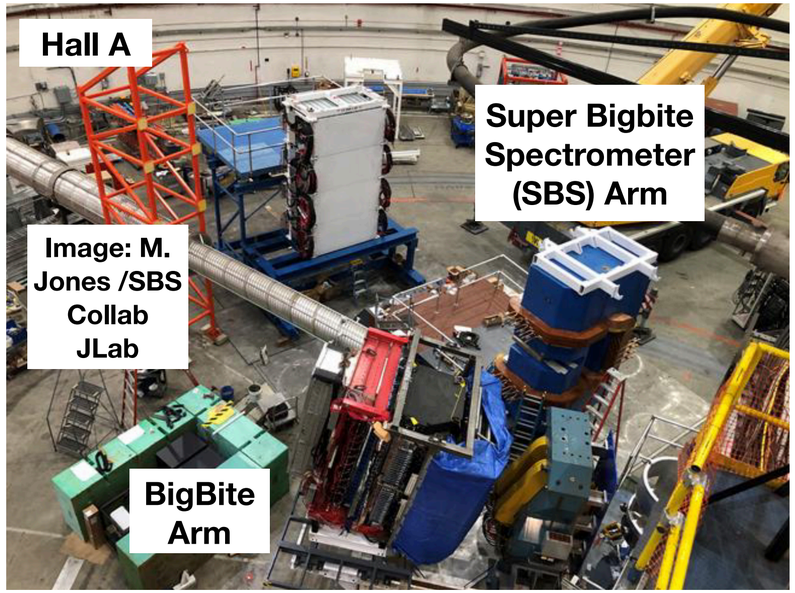
$$R^T = \frac{d^4\sigma(ep \to e' X p')}{dx dQ^2 dz dt} \Big/ \frac{d^2\sigma(ep \to e' X)}{dx dQ^2} \Delta z \Delta t \sim \frac{F_2^T(x, Q^2, z, t)}{F_2^p(x, Q^2)} \Delta z \Delta t$$

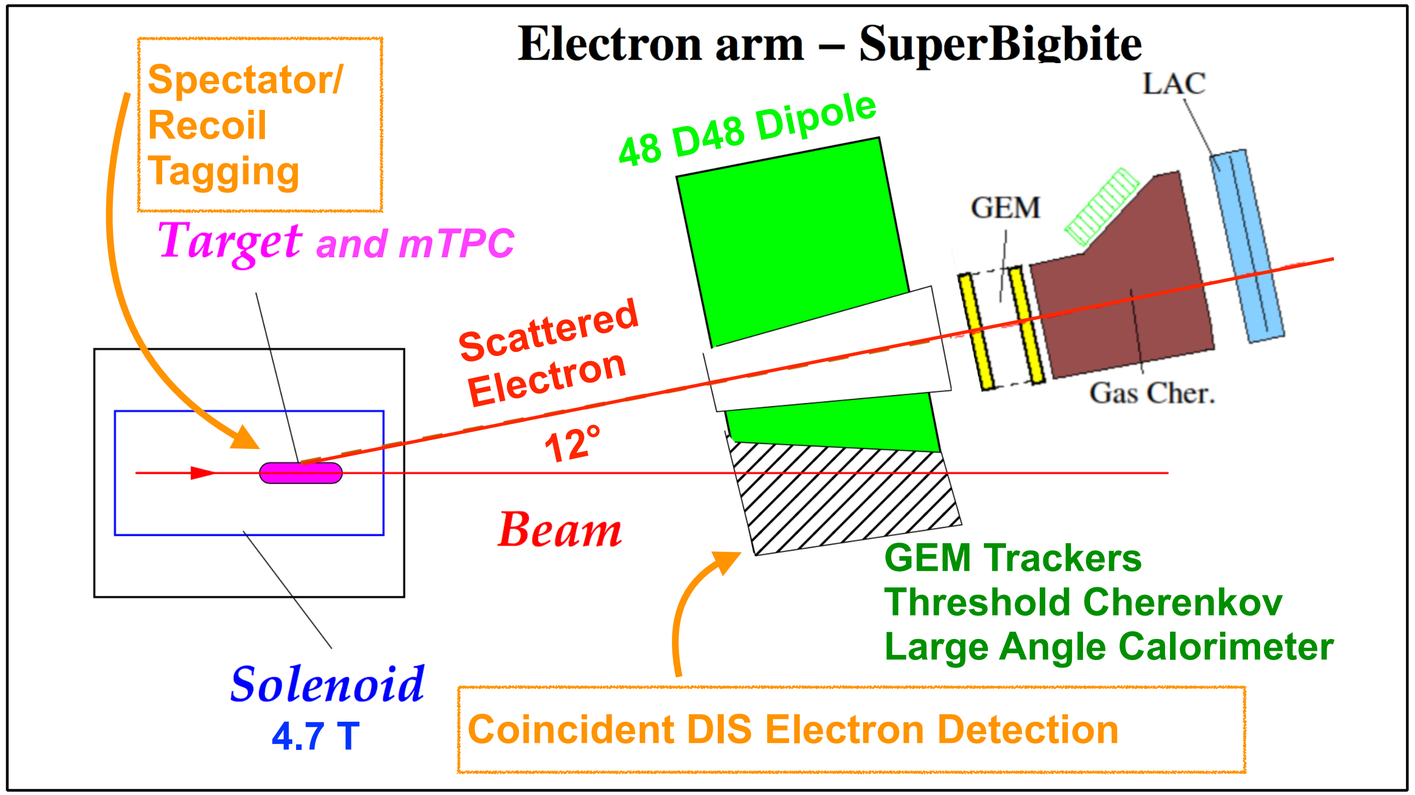
- Small -t
- Very low momentum recoiling hadrons (60 - 400 MeV/c) → need novel detector

TDIS Measurements

JLab high current Halls (A/C) ideal for rare TDIS process

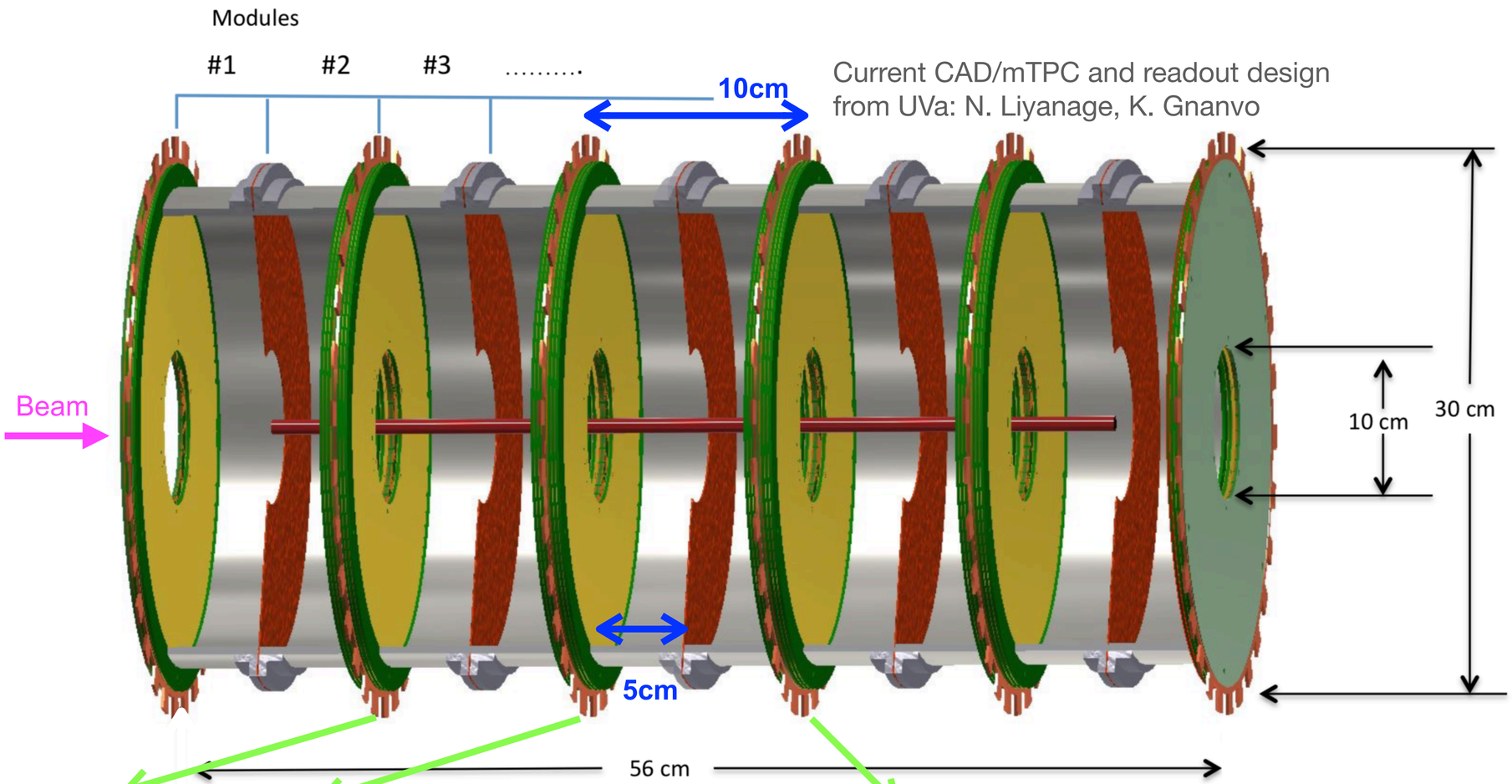


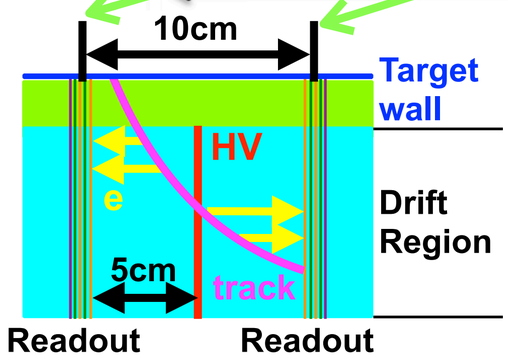


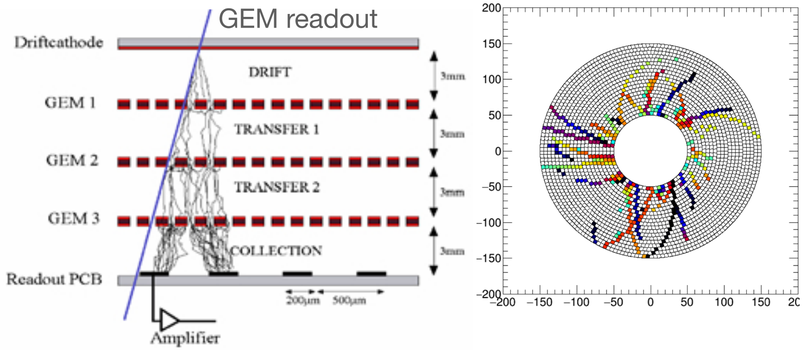


- 50μA 11 GeV e^- beam on high density fixed target
  - H/D gas; 40 cm length; 1 cm diameter; 25 μm walls; 3 - 4 atm; room temp
  - → high luminosity 2.9 x 10^{36} $cm^{-2}s^{-1}$
- e' detection in reconfigured Super Bigbite Spectrometer
  - Current use: SBS program of nucleon E/M FF at highest ever Q^2
  - Electron PID and (L2) trigger, tracking and π rejection (~10^{-4})
- High rate multiple time projection chamber (mTPC) for tagging

High Rate mTPC







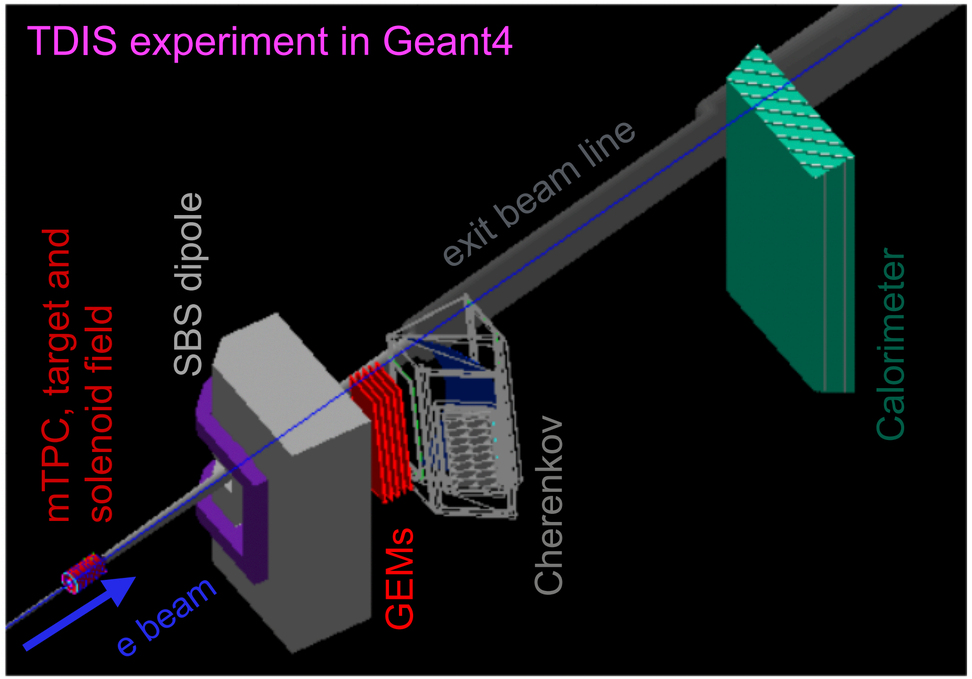
- Division of volume into chambers
- Reduces background rates

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

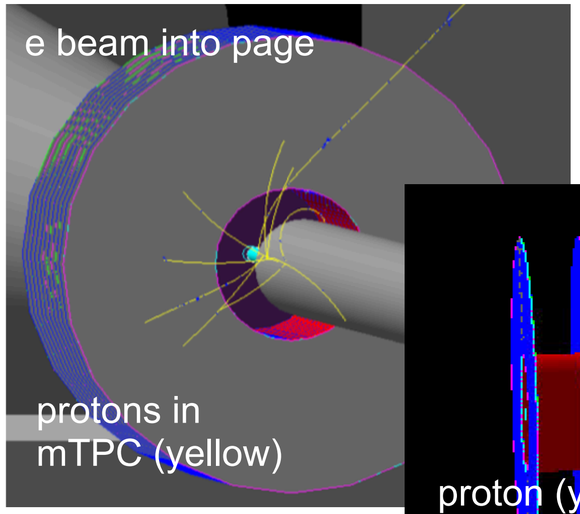
- Readout planes
  - Multi layer GEM foils
  - Segmented readout pads

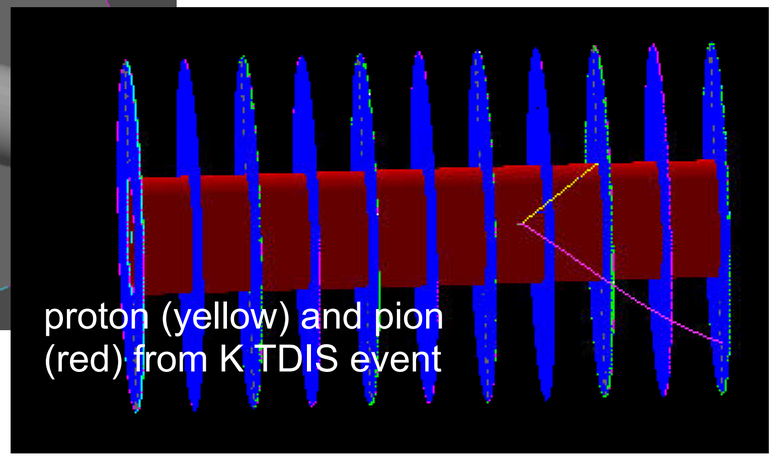
- Tag recoils/spectators
  - Vertex tracking
  - Momentum reconstruction (solenoid)
  - PID by dE/dx

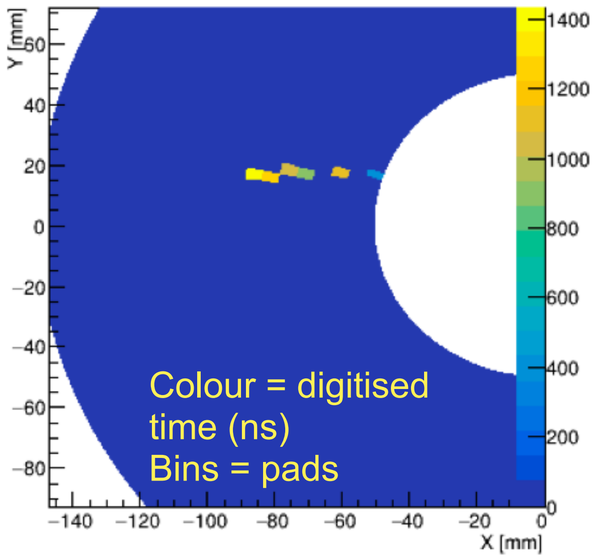
Simulation

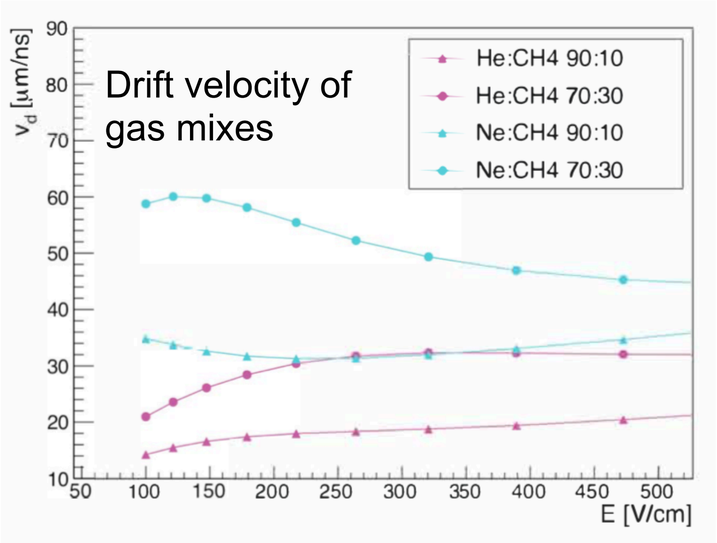


- In-depths studies within SBS collaboration's Geant4 framework
  - *Team* of contributors (e.g. C. Ayerbe, E. Fuchey, S. Wood, A. Tadepalli, D. Dutta, R. Montgomery, A. Puckett, M. Carmingotto…and more!)
- mTPC also simulated using CERN's magboltz/garfield
  - Gas mixtures; electric field…
- Updates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

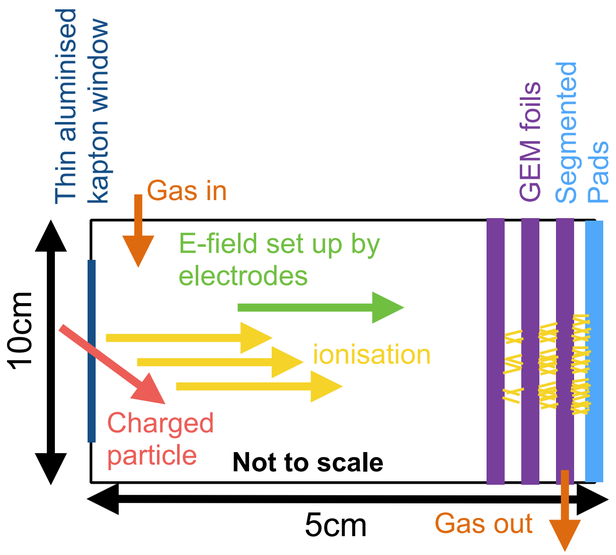




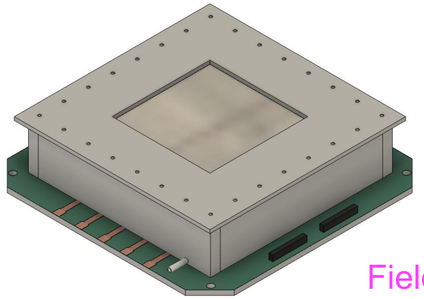


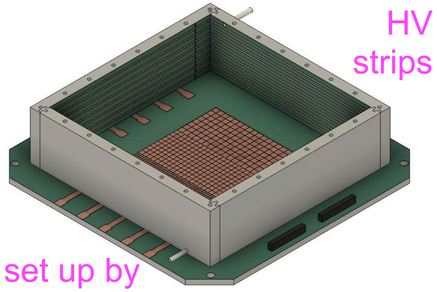


mTPC Prototyping



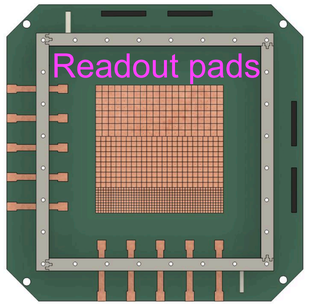
- University of Virginia constructing 1st prototype mTPC chamber (N. Liyanage, H. Nguyen, S. Ali)
  - 10 x 10 cm^2 square active area
  - Entrance window → cathode → 4.7cmcm drift in field cage → triple GEM (2mm between foils) → segmented anode (PCB) → Panasonic connectors
- JLab/Mississippi State (E. Christy, C. Cuevas, A. Nadeeshani) preparing HV divider
- Expect start of tests ~ April
- Aims: tune simulation and tracking, test design





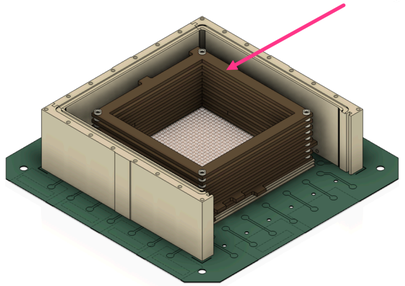
Field set up by electrode strips

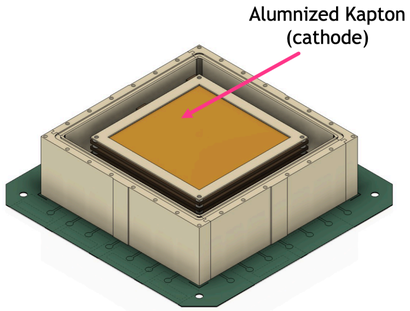
HV strips

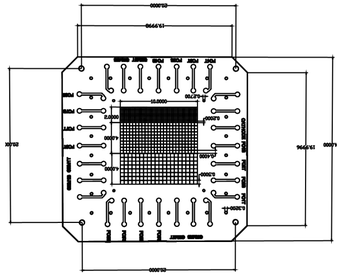


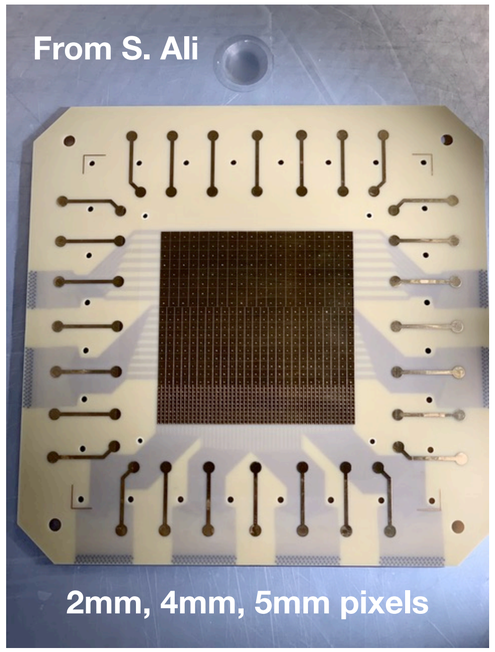
Different sized pads

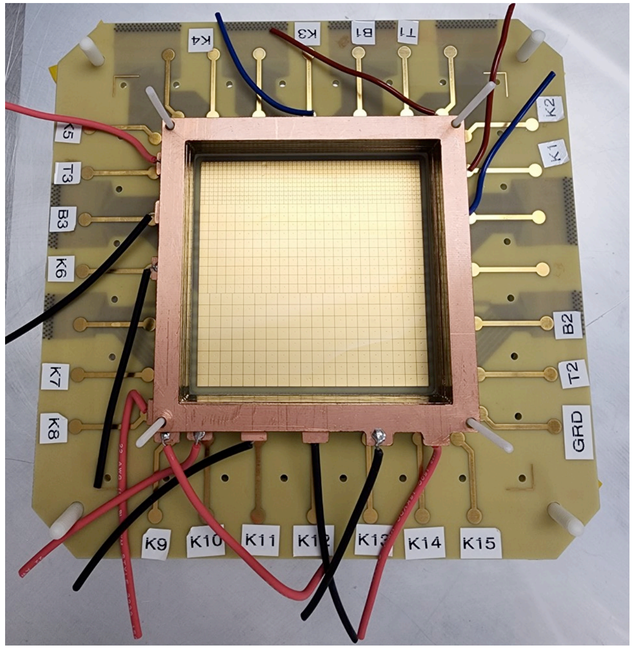
CAD model: S. Ali





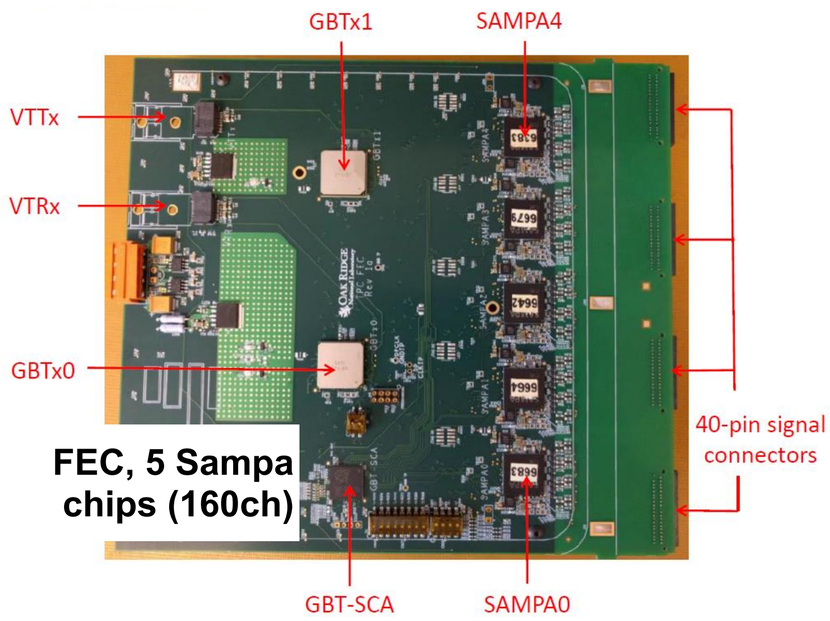


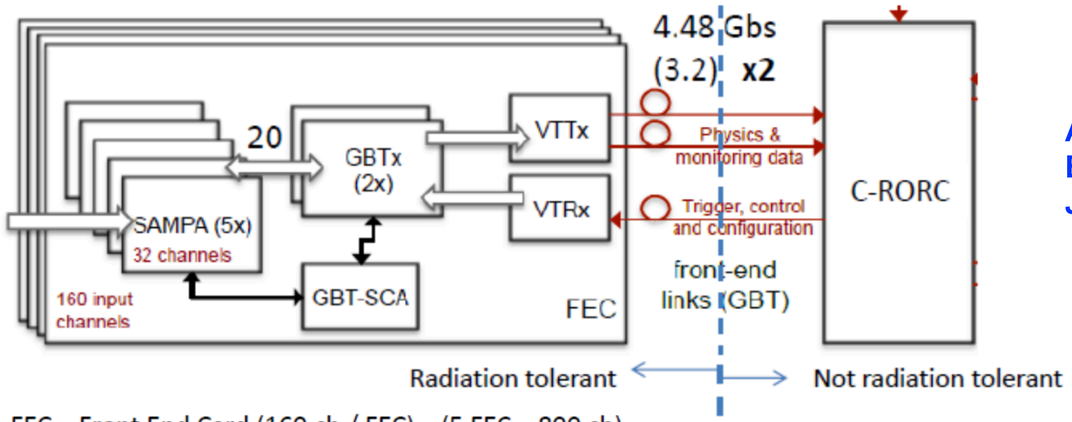




Construction/image: Huang Nguyen

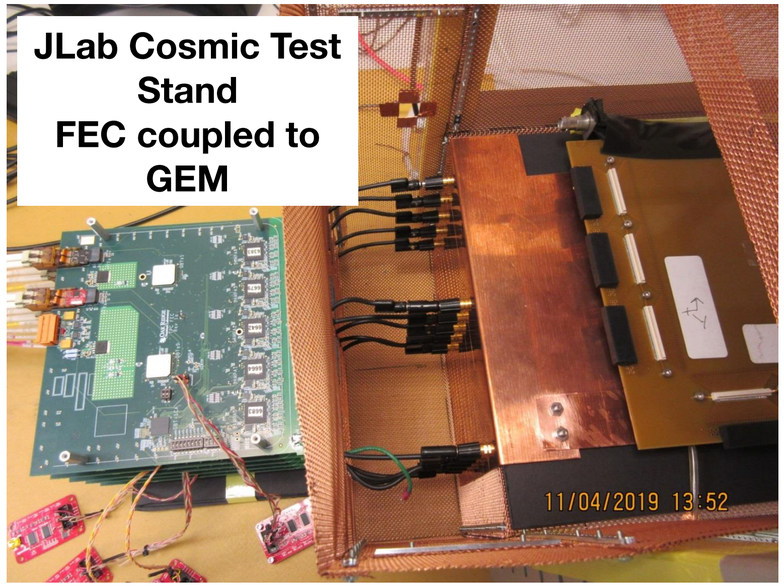
Triggerless Readout at JLab





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

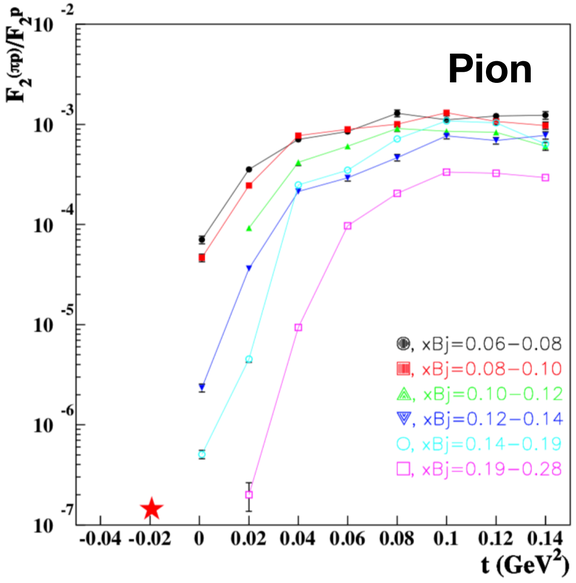


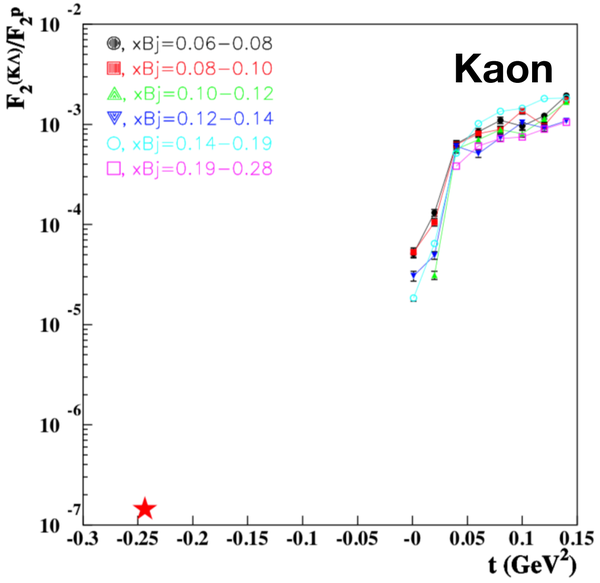
JLab Cosmic Test Stand
FEC coupled to GEM

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

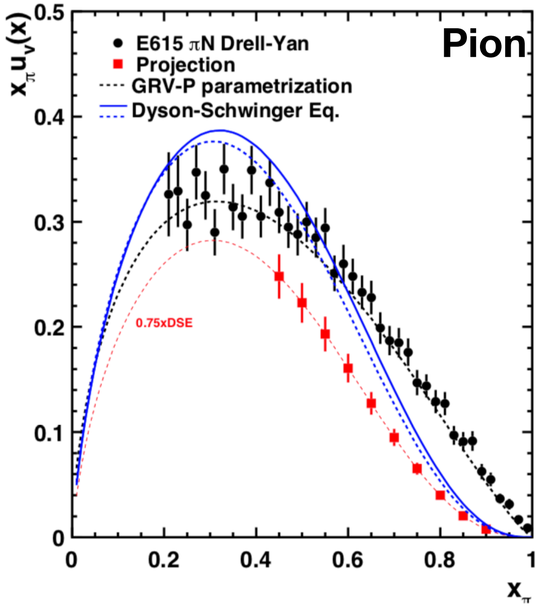
- Prototyping at JLab (E. Jastrzembski, G. Heyes, et al.)
- Using Oak Ridge SAMPA FEC for the ALICE TPC
- SAMPA ASIC: pre-amp, ADC, zero-suppression… (M. Bregant, Sao Paolo)
- Continuous sampling w/ high readout speed (~1TB/s post zero-supp for ~35k chan)
- Awaiting delivery of chips; rad hard components under procurement

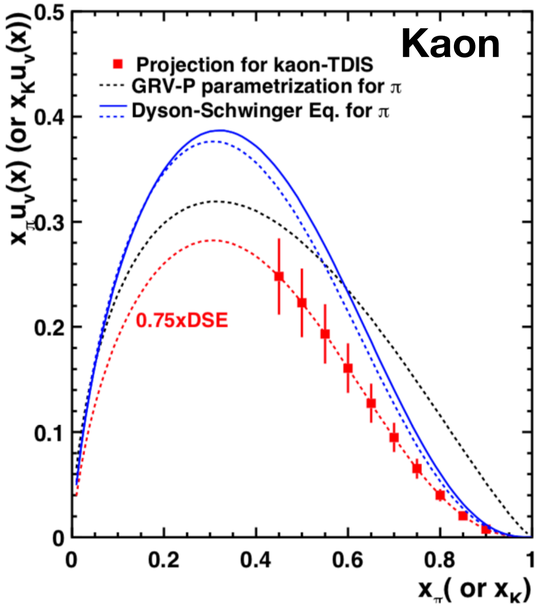
Example Projected Results





- 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

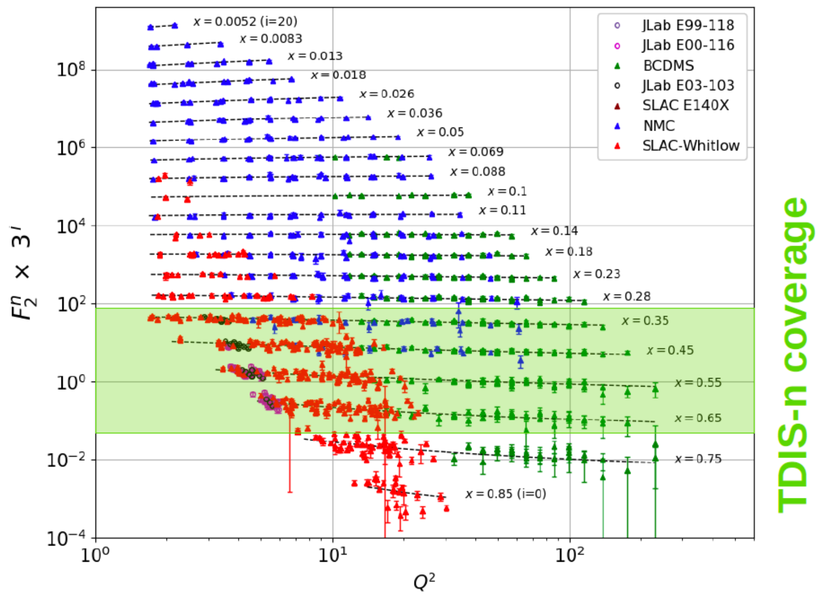




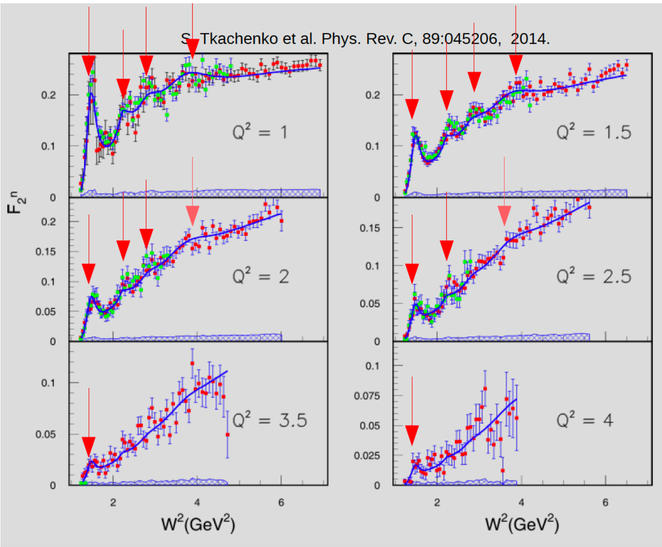
- Projected range of coverage for input to valence quark distribution analyses
- For more discussion on impact for global PDF fits see:
  - Patrick Barry's talk
  - 03/30; 12:10pm, WG6

Also…TDISn

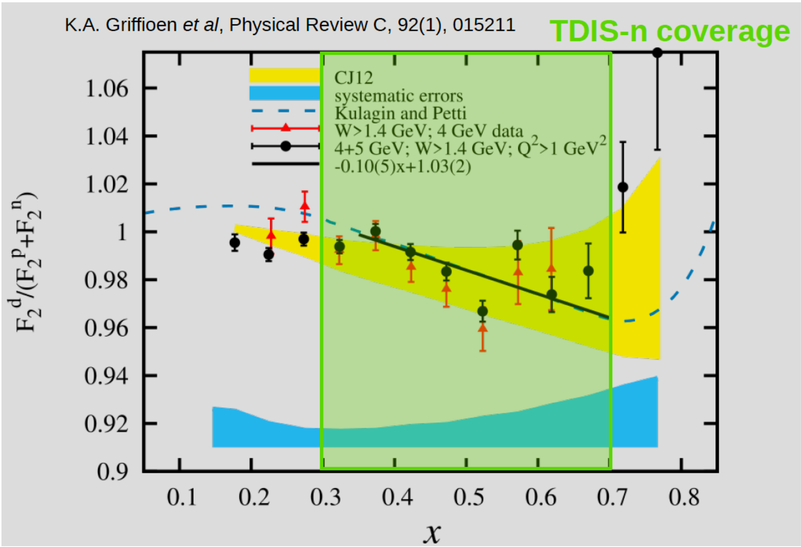
Neutron F_2 SF



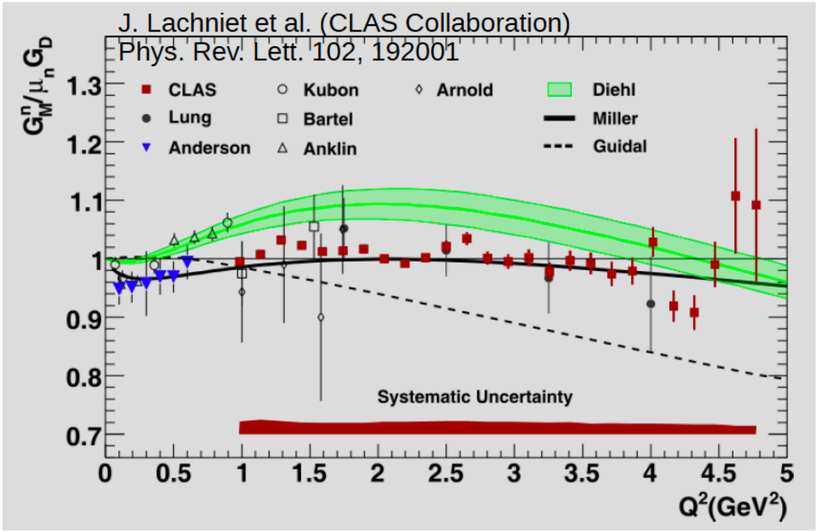
Resonance Region SF



EMC effect in deuteron

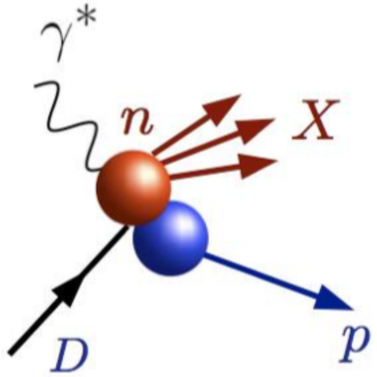


Elastic e-n scattering and EM form factor G_M^n



- Tagged DIS measurement of neutron SF
- Plus other topics

- (c.f. JLab BoNuS, BoNuS12, MARATHON)
- Cross-checks of systematics
- Increased statistics
- Calibrate mTPC acceptance and efficiency
- → Independent normalisation check of tagging method

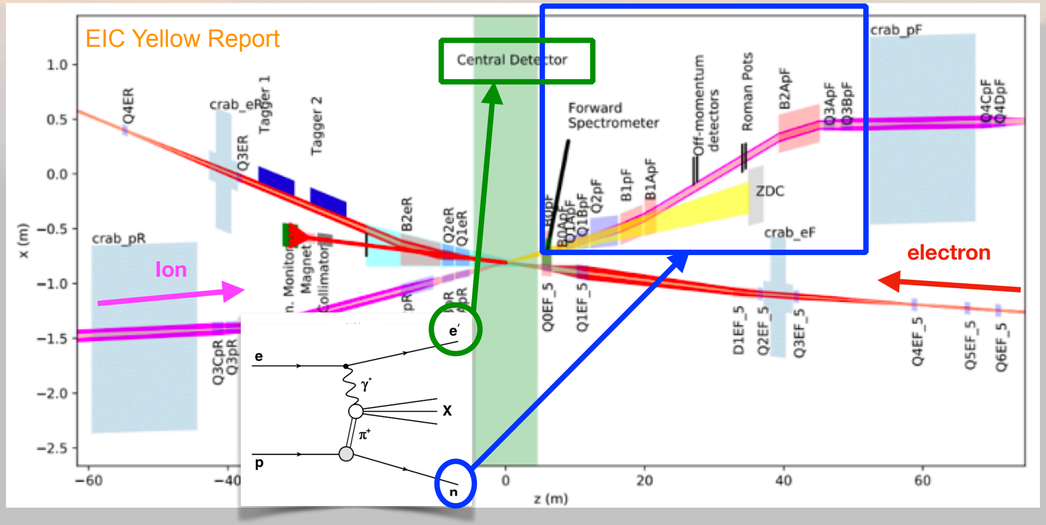


Summary

- Meson structure important for understanding nucleon's fundamental structure
- Comparing π/K structure can offer insights into mass enigma

- Experimental data for π/K structure functions extremely sparse

✓ TDIS at JLab:
  - New data - test of universality in valence regime for PDF
  - Understand nucleon & meson structure on deeper level
  - Kaon SF extraction - almost empty world data set!
  - First prototyping underway…
  - Important precursor for meson structure via spectator tagging at EIC



- EIC Meson Structure Function Working Group:

Aguilar *et al*, Eur. Phys. J. A. (2019) **55** 190
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