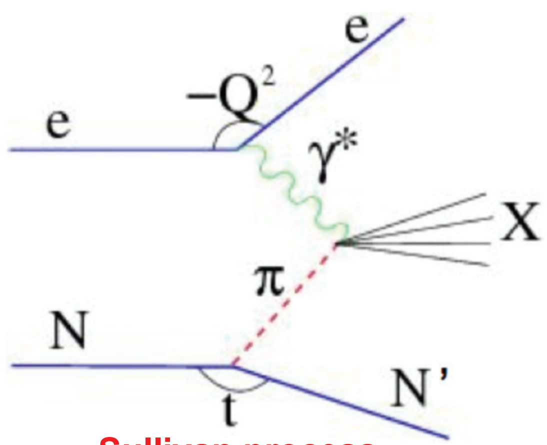
R.A. Montgomery,
on behalf of the TDIS and the Hall A SBS Collaborations

Workshop on Pion and Kaon Structure at an Electron Ion Collider
The Catholic University of America, Washington D.C.
24/05/18

Outline:

- History/Current Status
- Some motivation
- Hall A TDIS Method
- Experimental Setup and Activities
- Novel mTPC and Streaming Readout Concept
- Projections
- Summary

JLab Hall A TDIS Introduction/History



Sullivan process in N(e,e'N')X

https://www.jlab.org/12-gev-upgrade

Now in the 12GeV era!

- Upcoming TDIS measurements in JLab's Hall A
  - Tag nucleon's mesonic content directly via Sullivan process
  - Extract **both pion and kaon structure functions** (SF)

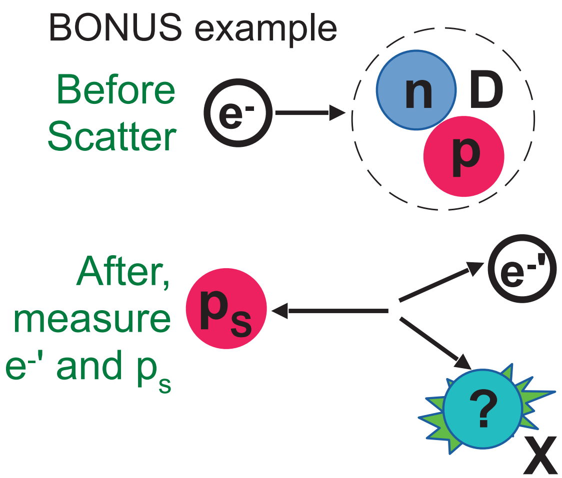
- JLab PR12-15-006 Measurement of Tagged Deep Inelastic Scattering
- **Pion TDIS**
- PAC43 approved (July 2015)
- C1 technical review - significant progress has been made
- All 27 days requested beam time awarded
- High scientific rating (A-), excitement about physics possibilities

- JLab C12-15-006 Measurement of kaon SF through TDIS
- **Kaon TDIS**
- PAC45 approved (July 2017) run group addition to PR12-15-006
- No additional beam time/detectors required

- Independent pion TDIS measurements in valence regime with both proton and neutron targets
- World-first direct extraction of kaon SF

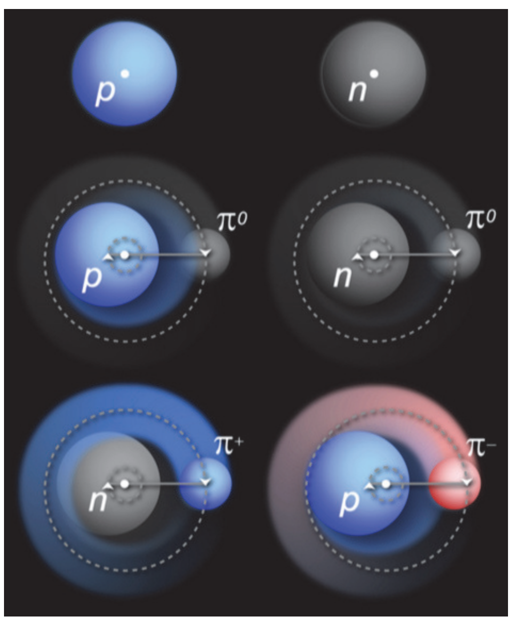
- One of a suite of experiments to utilise Super BigBite Spectrometer (SBS) in upgraded 12GeV JLab era

Spectator Tagging, TDIS, Some Motivation



- Spectator tagging extremely powerful to explore e.g.:
  - partonic structure mesons/nucleons; short-range NN correlations; nuclear modification of quark/gluon densities…
- E.g. JLab Hall B BONUS - spectator proton to tag e^- scattered from "free" neutron in Deuterium ($eD \rightarrow ep_S X$) → neutron SF (F_2^n)

- Proton SF known with high precision experimentally
- **Light meson structure largely unknown, yet basic building blocks of matter**



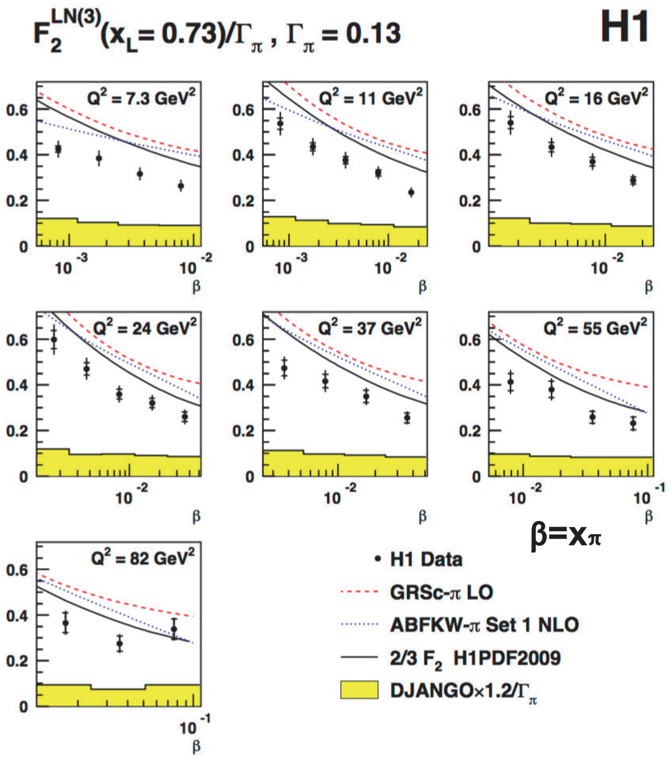
J. Arrington, arXiv:1208.4047

- Nucleon's pion content key role in nucleon/nuclear structure
  - long range nucleon-nucleon interaction; simplest QCD state; dynamical chiral symmetry breaking/goldstone boson; nucleon/nuclear PDFs, up/down sea-antiquark asymmetry…
- Kaon content:
  - access to momentum fractions carried by sea/glue, important to combine with valence quark info for PDF evolution

- Substantial theoretical work, but **experimental data sparse**
  - **TDIS probe mesonic content directly**

Example Previous Data for Extracting Pion/Kaon Structure Information

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



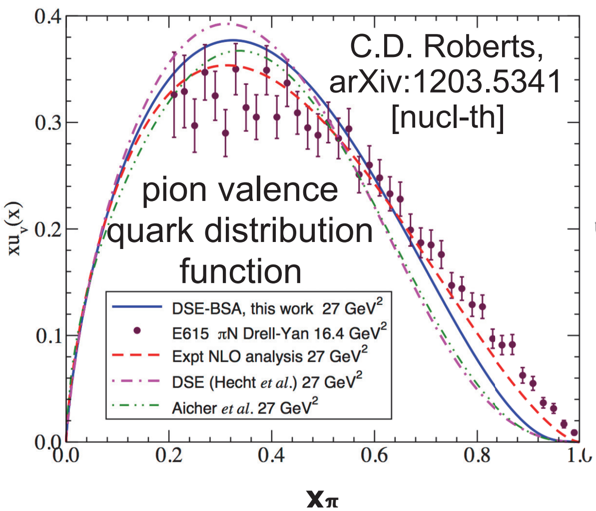
Tagged DIS performed at HERA

- Meson cloud as virtual pion target
- Leading proton/neutron tagged in **ep → eXN**

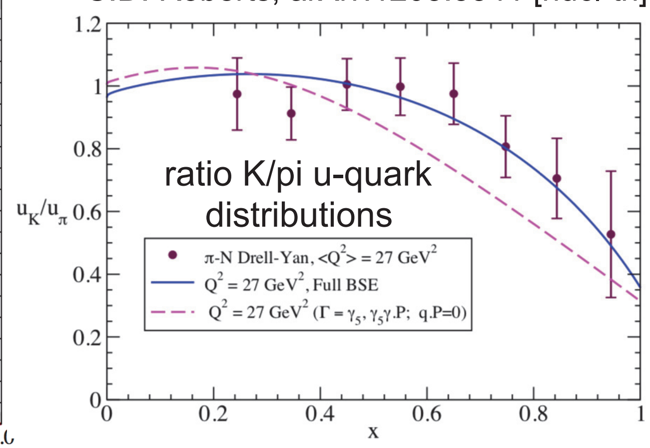
- Pion sea region, low Bjorken x and high Q^2
- $6<Q^2<100\,\text{GeV}^2$; $1.5e^{-4}<x<3.0e^{-2}$
- DIS events with forward going neutrons in coincidence dominated by one pion exchange
- Pion structure function extracted from neutron data

TDIS

- **Higher x, lower Q^2** → allow to study evolution between kinematics



C.D. Roberts, arXiv:1203.5341 [nucl-th]

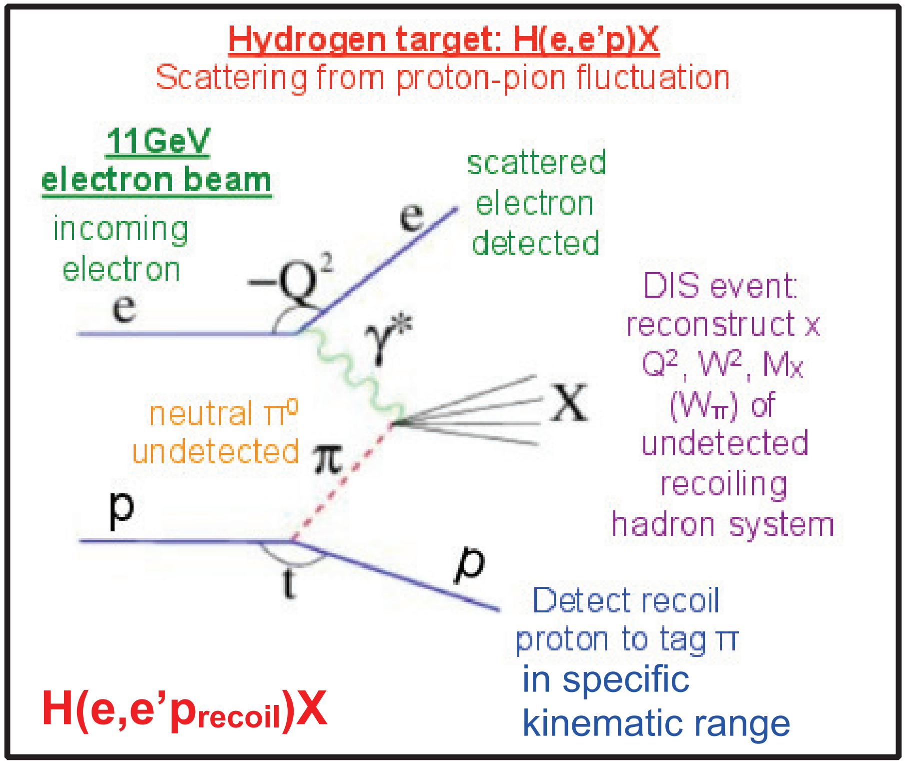


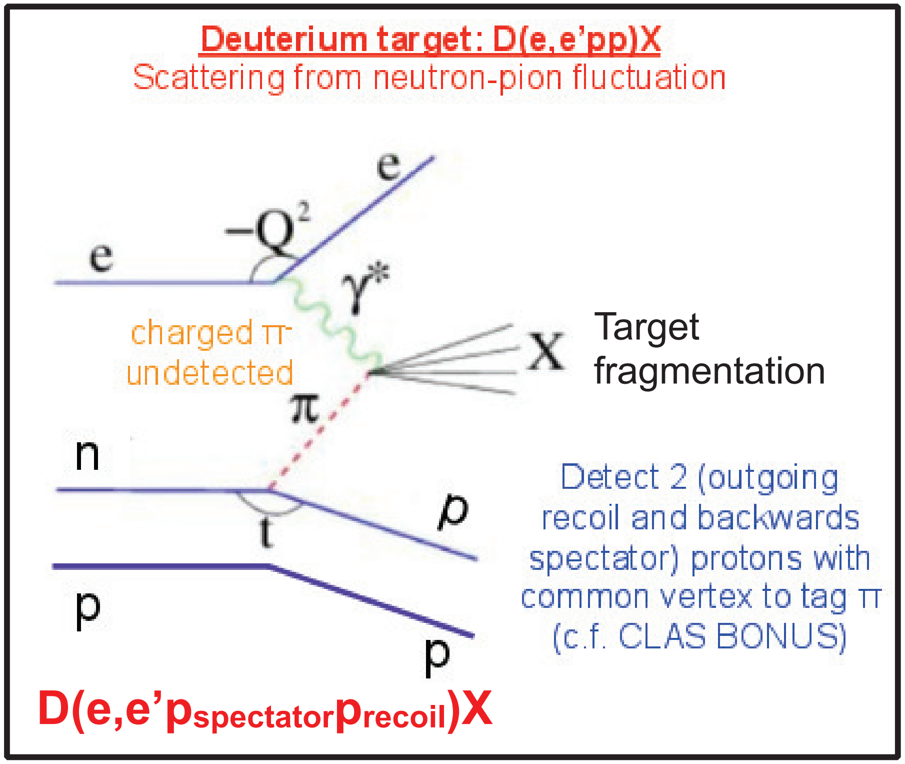
Valence region - Drell Yan Data

- e.g. CERN NA3, or FNAL E615 $\pi^-+N\rightarrow\mu^++\mu^-+X$ data
- Theoretical models tend to disagree at high x

TDIS

- **Independent cross-check** of various models at these kinematics
- Extend measurement to **neutral pions**

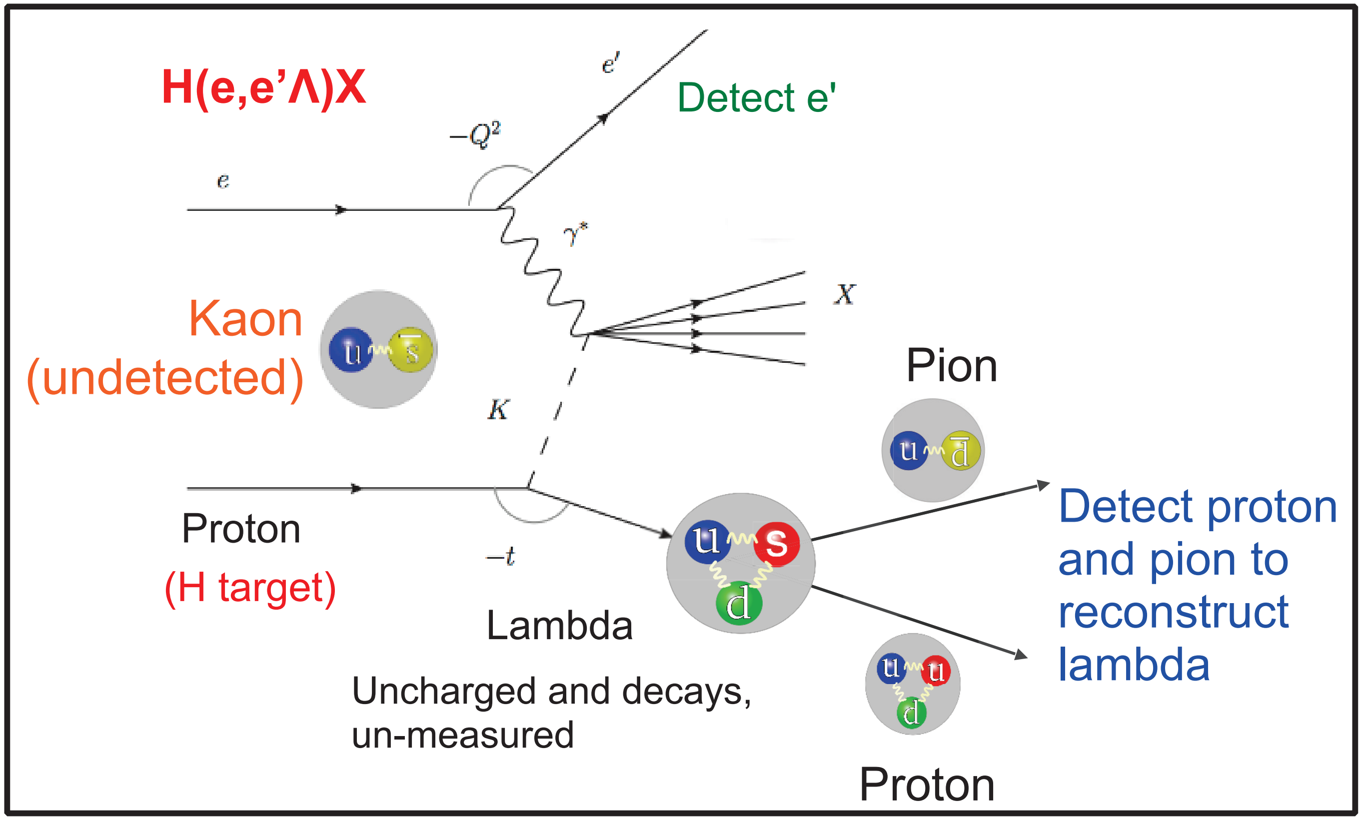


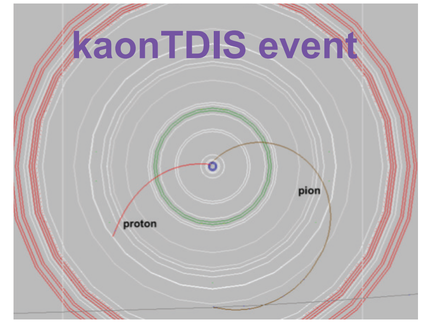


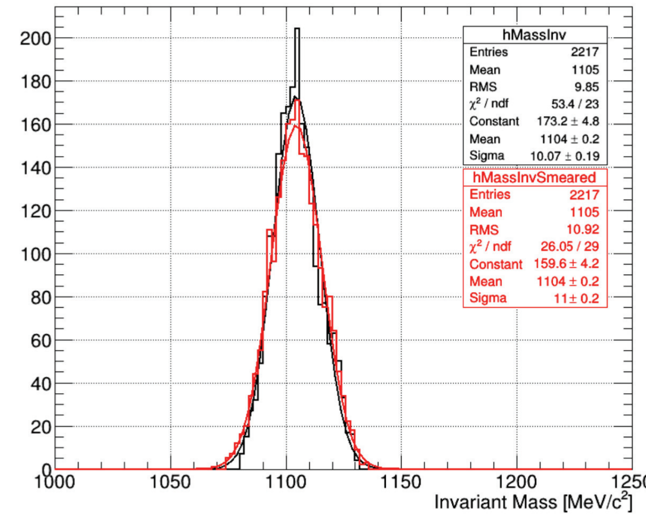
- W^2 invariant mass squared, Q^2 virtuality exchanged photon, x Bjorken x
- t = 4-mom transfer squared at nucleon vertex = $k^2 = (p-p')^2$; p,p' initial,final proton momenta
- t must be small to extrapolate to pole ($|t| < 0.2(\text{GeV/c})^2$)
- **The detected protons are low momentum (60MeV/c - 400MeV/c)**
- **Access to both neutral and charged meson clouds**

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

Kaon TDIS Measurement in Hall A







- Lambda reconstructed from $p\pi^-$ invariant mass and track/vertex
- Proton and pion mostly emitted back to back, with angular and time correlation
- Protons, pions again low momentum in similar range as pion TDIS
- Kaon TDIS also background to pion TDIS (also e.g. $\Delta^0 \rightarrow p\pi^-$ and $\Sigma^0 \rightarrow \Lambda^0\gamma \rightarrow p\pi^-$ etc in pion exchange model) - would be useful to study
- Event generator written for kaon TDIS using chiral effective theory for strange quark asymmetry (arXiv:1610.03333 (2016)), splitting functions, all Feynman diagram contributions to s(bar) PDF in nucleon (K. Park, see proposal for details)

Phenomenological Pion Cloud Model and Pion TDIS

- Theoretical work used to study expected rates, required beam time, projected results etc, as presented in proposal
  - 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 F_2 structure function of nucleon from scattering off virtual pion emitted by nucleon:

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

(z = k+/p+, light cone momentum fraction of initial nucleon carried by pion)

- Unintegrated distribution function (light-cone momentum distribution of pions 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 structure function (i.e. by tagging protons) given by un-integrated product:

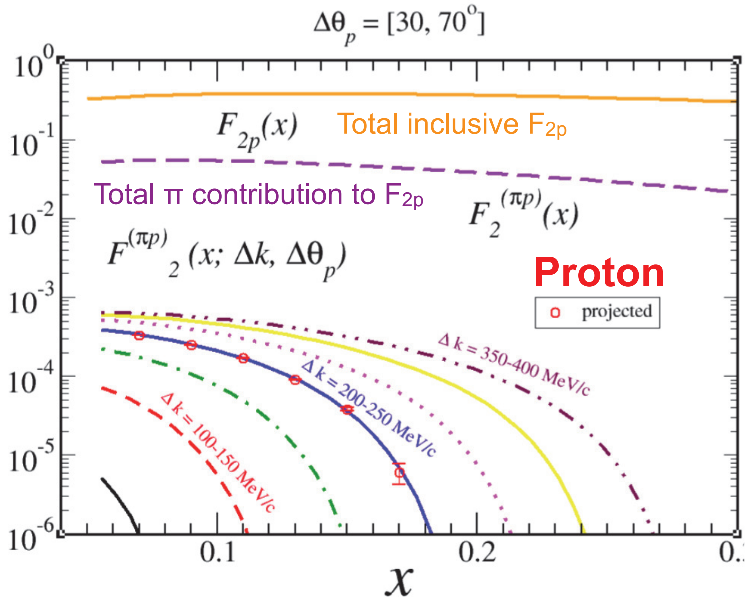
$$F_2^{(\pi N)}(x, z, k_\perp) = f_{\pi N}(z, k_\perp)\, F_{2\pi}\left(\frac{x}{z}\right)$$

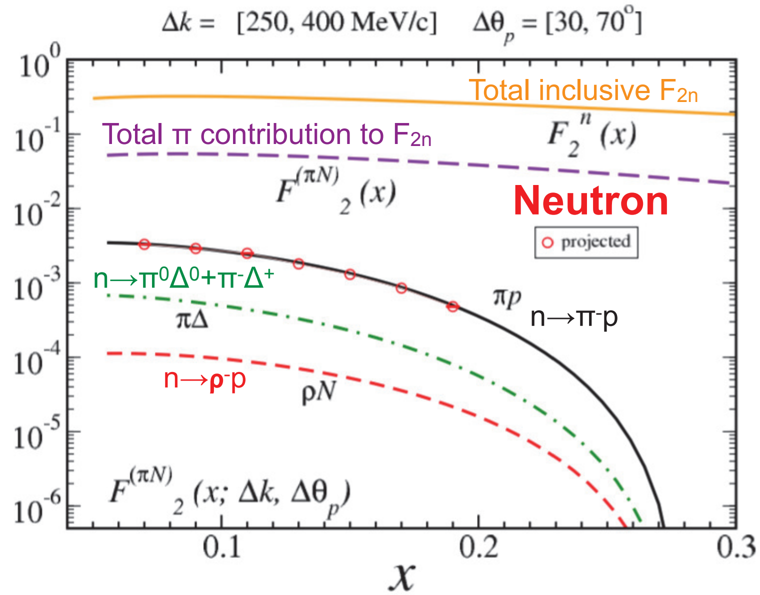
Pion "flux" Pion SF

- Seek to measure low-momentum region where pseudo scalar production dominates
- Region of interest $z \lesssim 0.2$; $x<z \rightarrow$ defines maximum x and Q^2 (given beam energy 11GeV)

Example projections of kinematic dependence of structure functions (from pion TDIS proposal)

Will bin in x and tagged proton momenta integration ranges Δ|k| [MeV]





Assume pion to be dominant but other Contributions ($\pi^- p$) ($\rho^- p$) ($\pi^0\Delta^0+\pi^-\Delta^+$)

- Total inclusive F_{2p} proton structure function
- Total integrated πp contribution to F_{2p}
- Tagged semi-inclusive structure functions

- Total inclusive F_{2n} neutron structure function
- Total integrated $\pi^- p$ contribution to F_{2n}
- Tagged semi-inclusive structure functions

- **Tagged signal is orders of magnitude smaller than DIS signal → high luminosity**

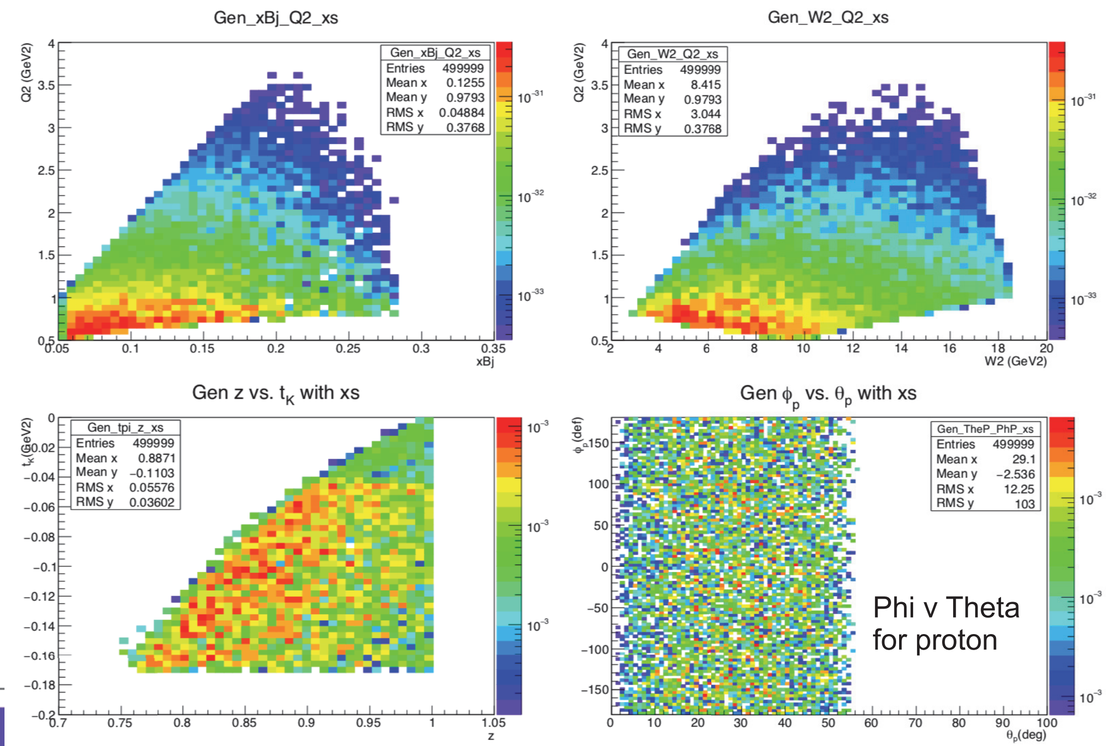
- **Extraction of tagged SF $F_2^T(x,Q^2,z,t)$: form ratio of tagged F_2^T to DIS F_2^p cross-sections**

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

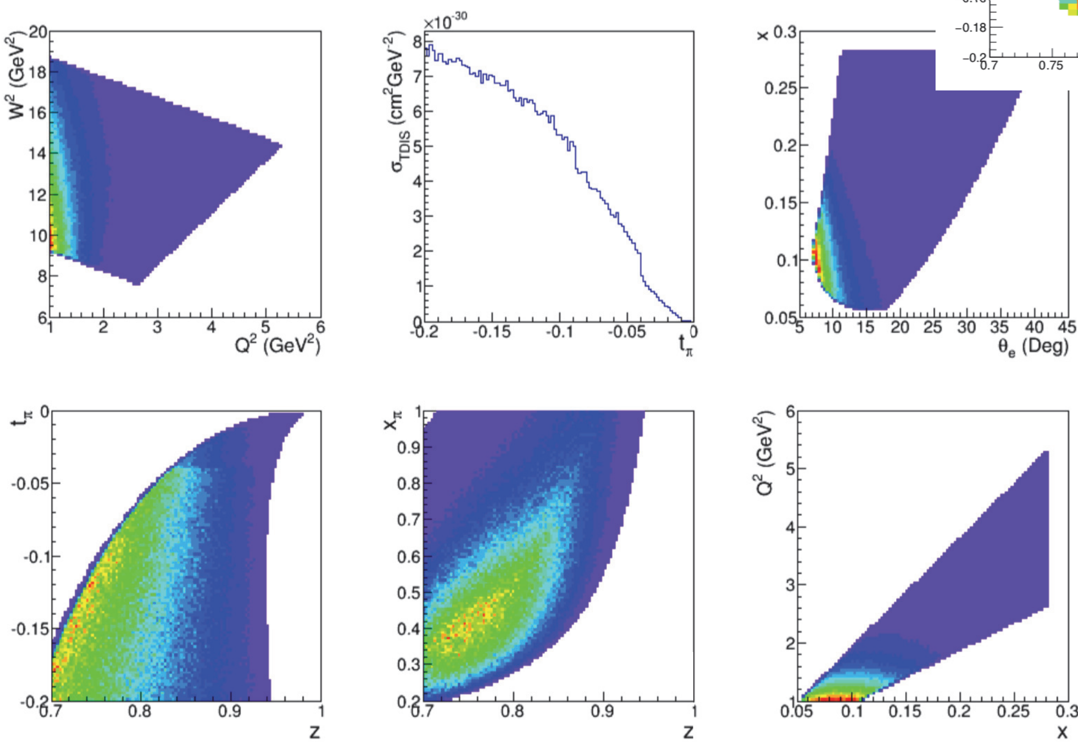
$$F_2^T(x,Q^2,z,t) = \frac{R^T}{\Delta z \Delta t} F_2^p(x,Q^2)$$

- Reduces systematic uncertainties (luminosity, electron trigger efficiency…)
- Same/analogous technique for kaon TDIS

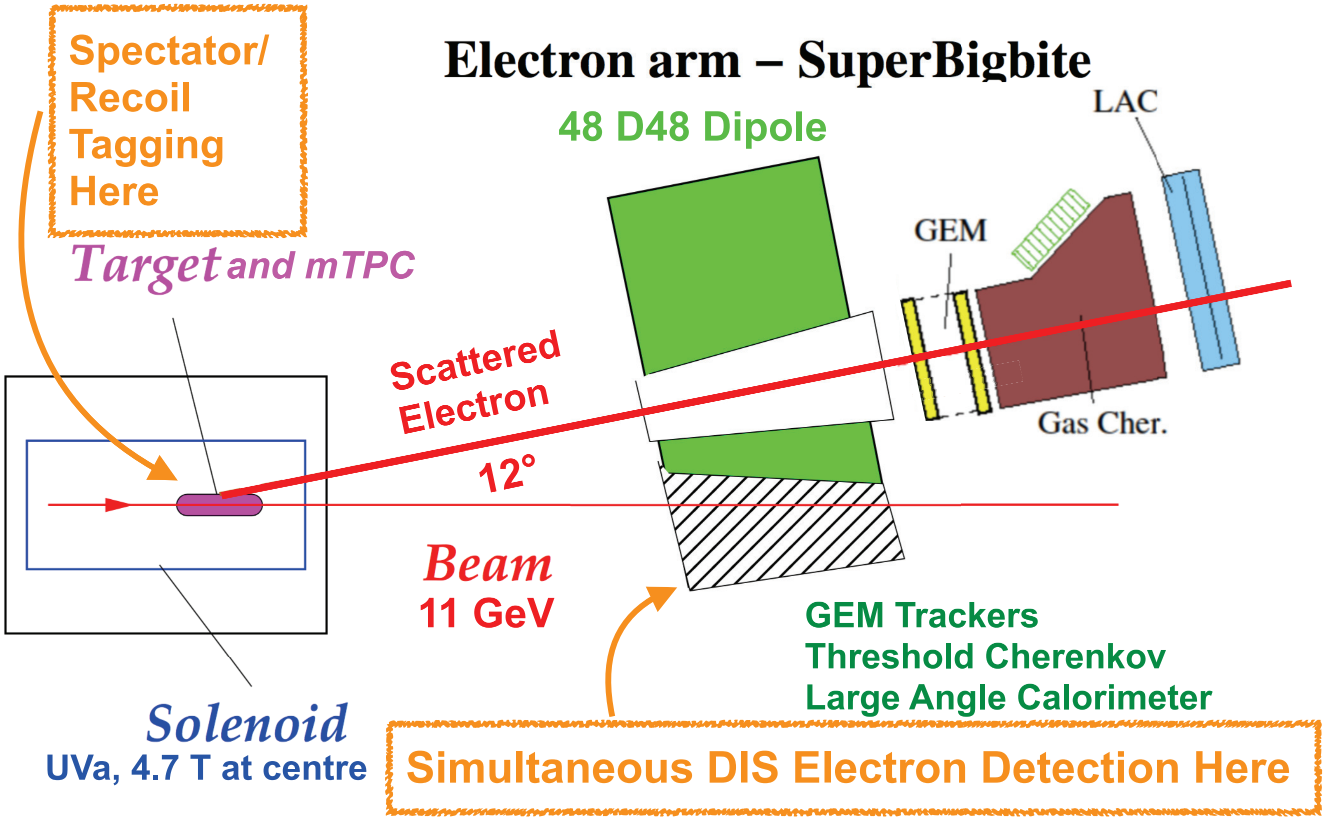
TDIS Kinematic Reach in Hall A



- Right, kaon TDIS proposal
- Event generator and kaon TDIS cross-section weighting



- Left, pion TDIS proposal
- H target; weighted by pion TDIS cross-section from phenomenological model; inclusive DIS cross-section from Cernlib PDF
- x-range~0.1
- After x-range optimised Q^2 reach fixed by limitation of 11GeV beam
- W^2 indicates DIS regime

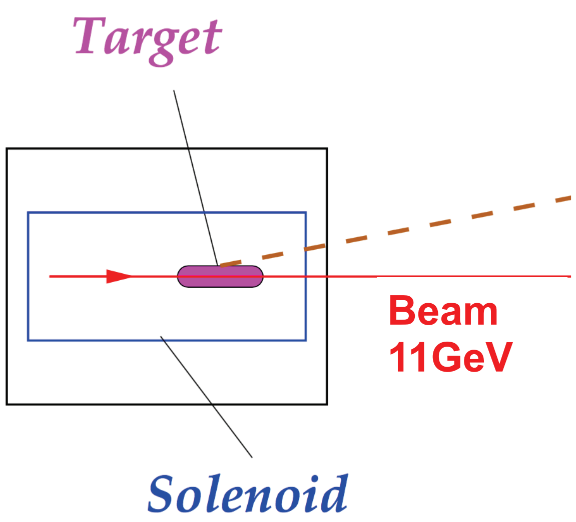


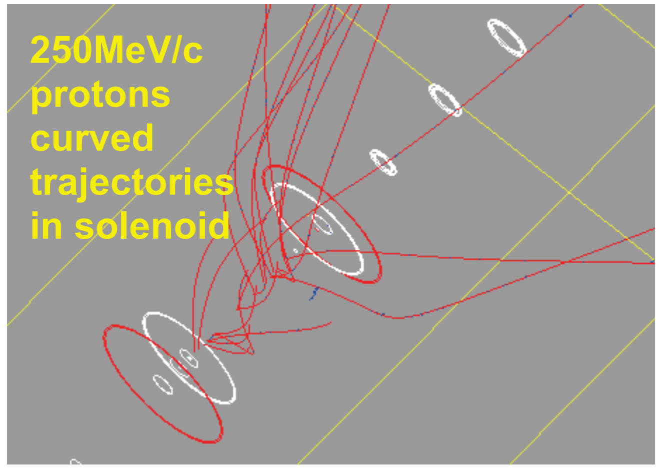
Lots of exciting activities and R&D for TDIS components on-going and ramping up

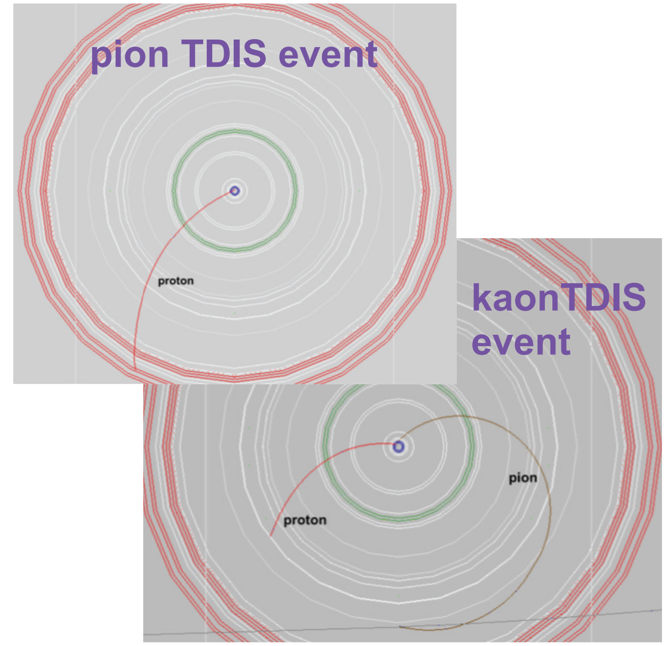
Includes: simulations, testing, prototyping, refurbishments, construction

- 11 GeV e^- beam, 50μA, **high luminosity** $3x10^{36}cm^2/s^{-1}$!
- Cold gas straw target; **H_2/D_2; 40cm length**; 1cm diameter (final config under study)
- Multiple Time Projection Chamber **(mTPC) for proton/pion detection**
- **Solenoid** for momentum analysis of proton/pions
- **Super BigBite Spectrometer (SBS) configured for e- detection**

Experimental Set up - Solenoid and Target

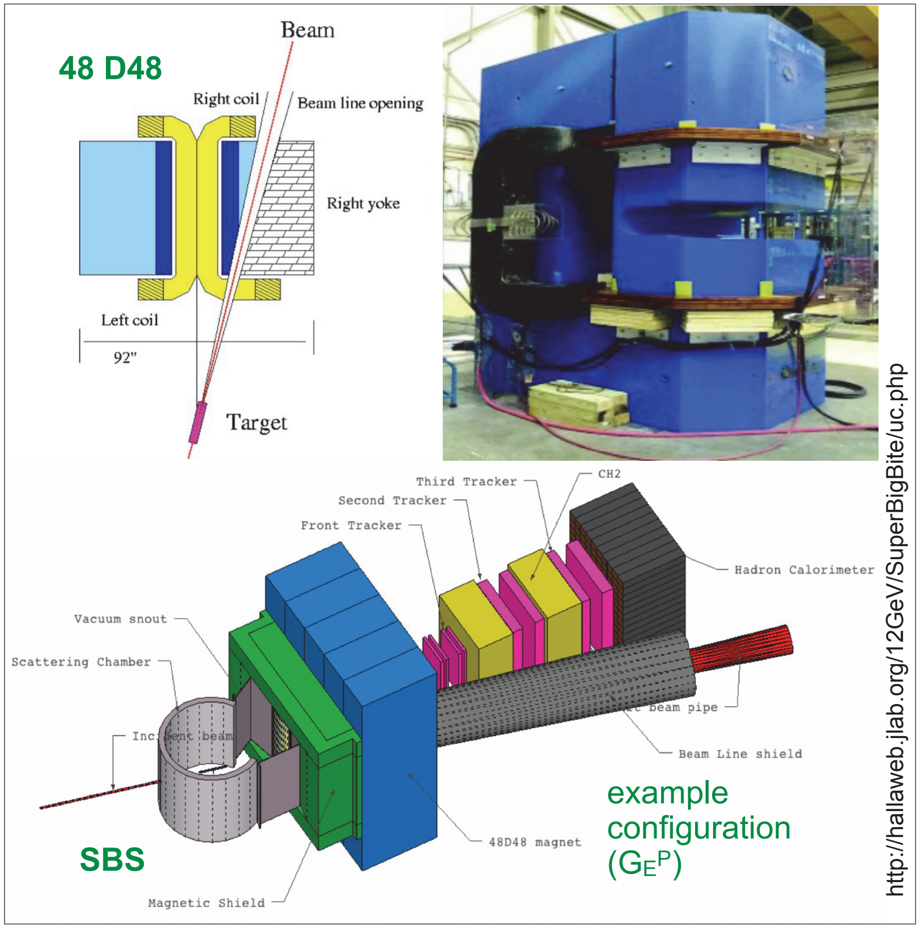






- **Solenoid**
  - Superconducting, 4.7T, from UVa, now housed at JLab
  - Curvature of nucleon tracks - momentum analysis ($p_{\perp} = 0.3B\rho$)
- **Target**
  - Rare TDIS process requires high luminosity, high target density
  - 1cm diam, 40cm length, H_2/D_2, originally 10μm Al walls, 77K, 1atm
  - To minimise challenging cold gas operation of surrounding recoil detector, studying increased temps/pressures and different kapton wall thicknesses
  - Want to minimise material to enhance low momentum reach
  - Prototyping stand in set up (D. Dutta et al., MSU)

Experimental Set up - SBS and Electron Arm

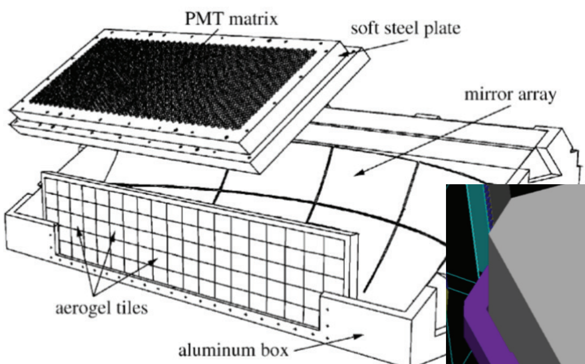


SBS:
- ΔΩ: 76msr @ 15°, 5msr @ 3.5° (forward/small angle hadrons detected)
- Δp: 2-10GeV/c
- σ_p/p: ~1x10^{-3}p[GeV/c]
- Angular resolution 0.5mrad

SBS spectrometer (JLab Hall A 12GeV era):
- Open-geometry magnet
- 48D48, 46cm gap, 2.5T*m
- Cut-out, very close to target
- Higher luminosities (up to 8x10^{38}cm^{-2}s^{-1})
- Increased acceptance (~70msr)

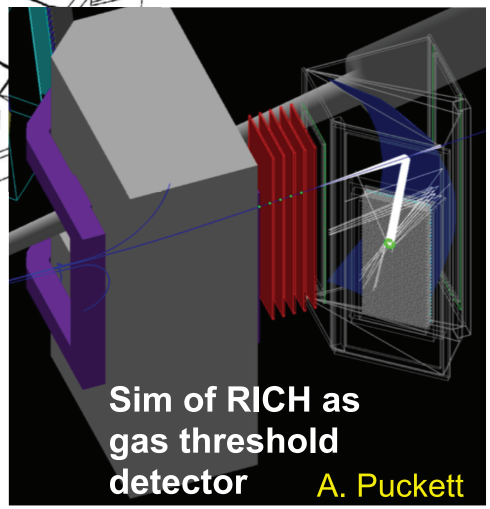
TDIS:
- **SBS configured for e- detection**
- 12° scattering angle; acceptance ~50msr
- 5 GEM tracker planes (70µm resolution)
  - GEM construction, commissioning, testing on-going at JLab (INFN, UVa)
- Threshold gas Cherenkov
- Large angle calorimeter (LAC)
- e^- PID and trigger (L2) = Cherenkov + LAC (combined π rejection factor ~10^4)

Experimental Set up - SBS and Electron Arm



(NIMA 479 (2002) 511)
Rings from aerogel tile/gas imaged by wall of PMTs

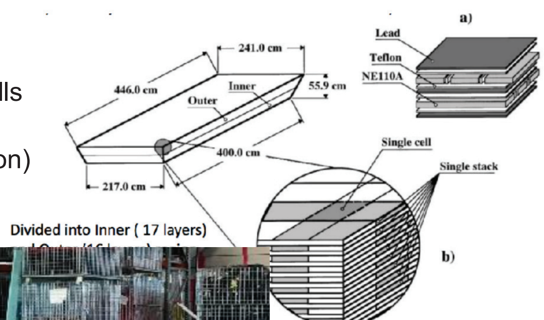
π/K/p PID separation over momentum range suited to SBS



Cherenkov Detector:

- HERMES dual-radiator RICH (aerogel and gas) re-used for SBS semi-inclusive DIS experiment (E12-09-018)
- Currently delivered to JLab from UConn, detector characterisations/tests on-going (PMTs, aerogel) (A. Puckett et al., UConn)
- Modified into threshold gas Cherenkov for e^-/π discrimination for TDIS (remove aerogel, measure photon yield from gas)
- Simulations of gas selection/efficiency on-going

Area 4m x 2.2m
40 x 24 matrix of 10x10cm2cells
PMT readout all 4 sides
2 readout layers (e/π separation)

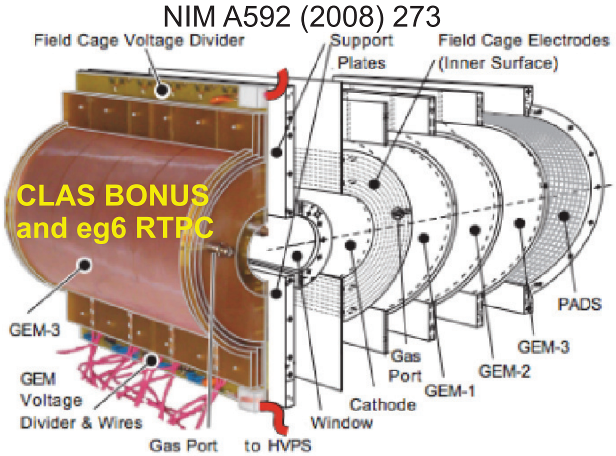


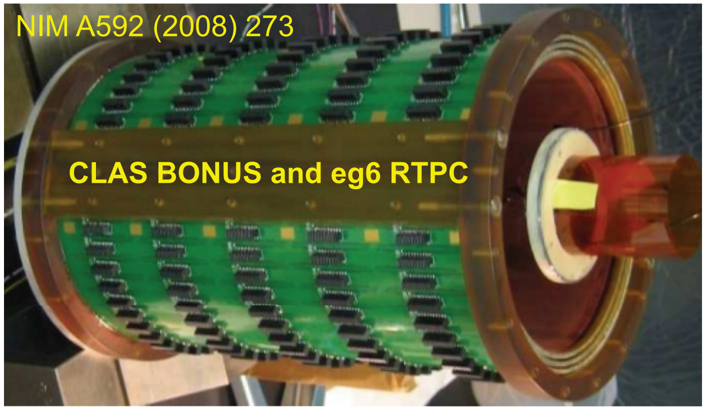
(NIMA 537 (2005) 562)
(NIMA 447 (2000) 424)

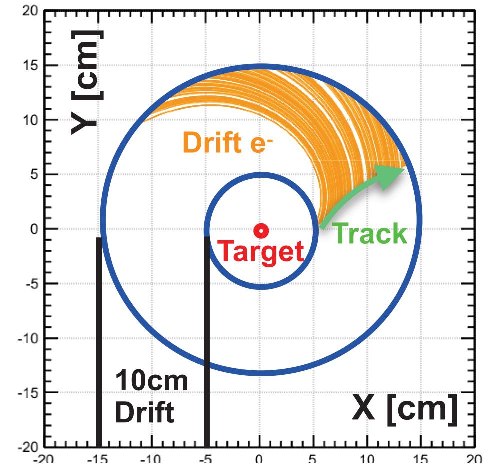
Large Angle Calorimeter (LAC)

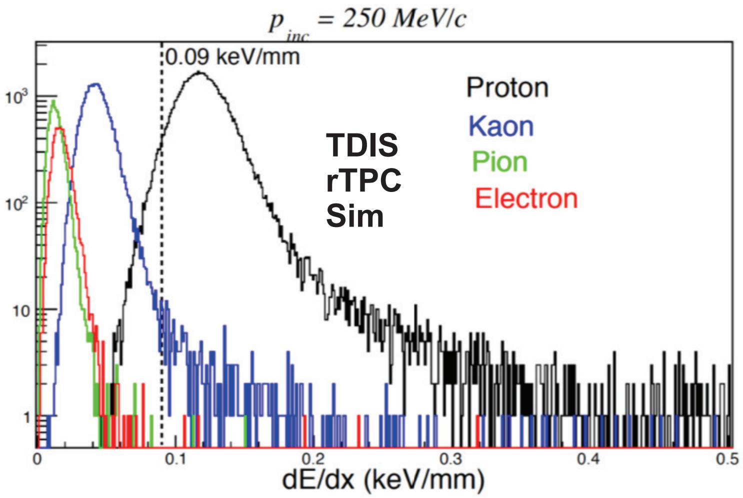
- Refurbished from CLAS (JLab 6GeV era Hall B)
- Lead/scintillator sandwich calorimeter
- Energy resolution 7%@1GeVc
- Position resolution 2.9cm, time resolution 50ps, π rejection factor ~10-20
- Tests on-going at JLab (PMTs tested, repaired, cosmic tests planned) (D. Dutta et al., MSU)

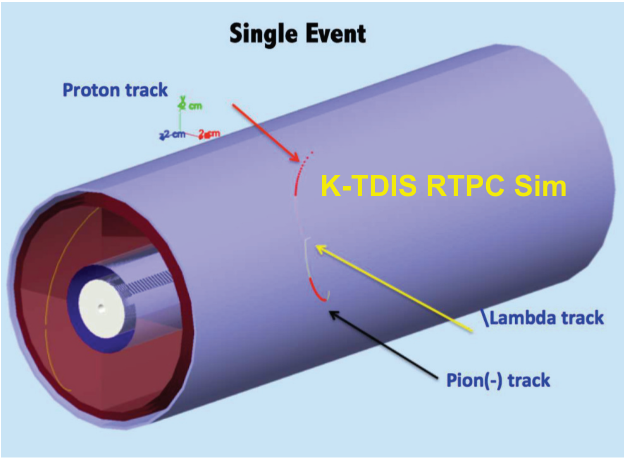
Experimental Set up - Spectator/Recoil Nucleon Detection

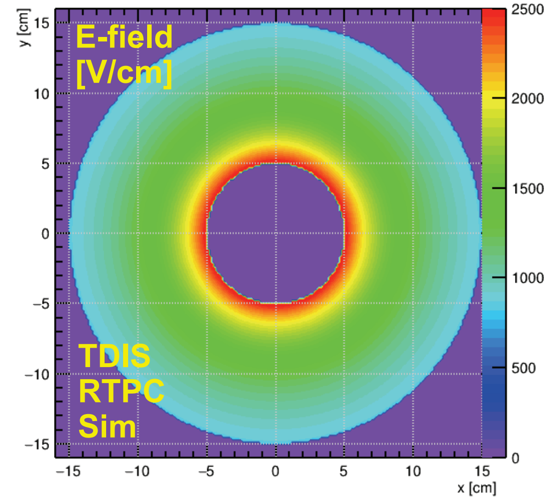






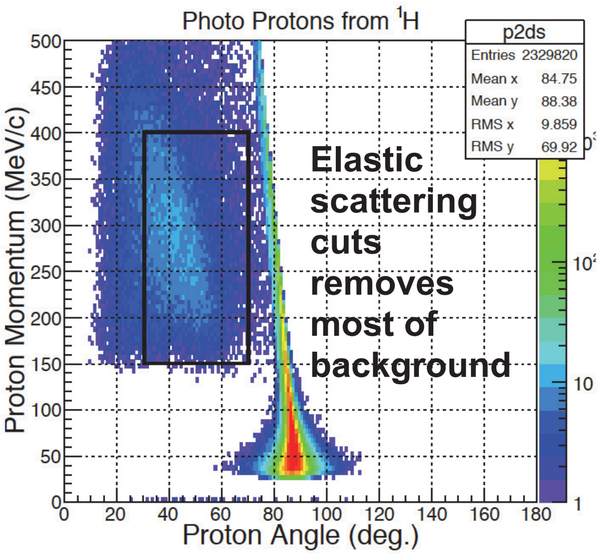


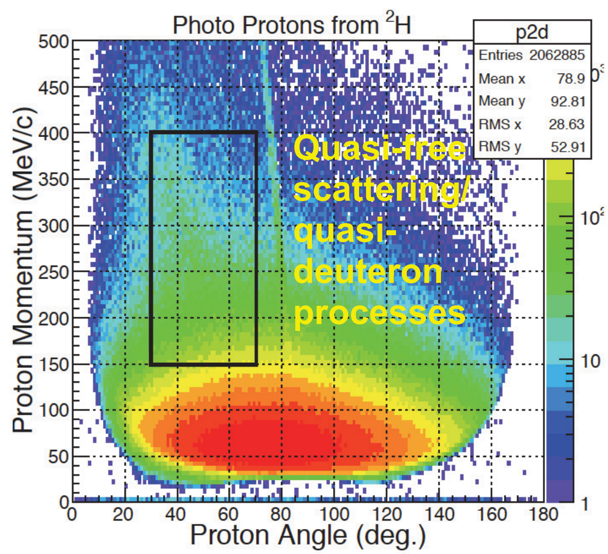




- **Need large angular/kinematic coverage and low momentum reach**
- Original aim: BONUS-style radial time projection chamber (rTPC)
- Filled with low pressure (~0.1atm), cold (matching target) He/CH_4 gas mix
- Ionisation created by charged tracks drifts to triple layer cylindrical GEMS at outer radius
- Inner r=5cm, outer r=15cm, 10cm drift, radii at different potentials (1/r E-field)
- dE/dx for PID
- Tracking → momentum analysis ($\delta p_\perp/p_\perp$<few%), vertex reconstruction with high resolution

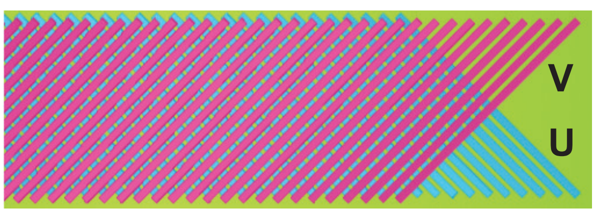
Experimental Set up - Spectator/Recoil Nucleon Detection





Geant4 simulated background proton rates (J. Annand)

Target	θ_p (deg.)	$70 < p_p < 250$ (MHz)	$p_p > 250$ (MHz)	$150 < p_p < 400$ (MHz)
^{1}H	30 - 70	2.3	7.4	6.3
^{2}H	30 - 70	357	20.1	64
^{2}H	100 - 140	204	3.1	–
^{27}Al	30 - 70	0.37	0.0	0.05
^{27}Al	100 - 140	0.10	0.0	–



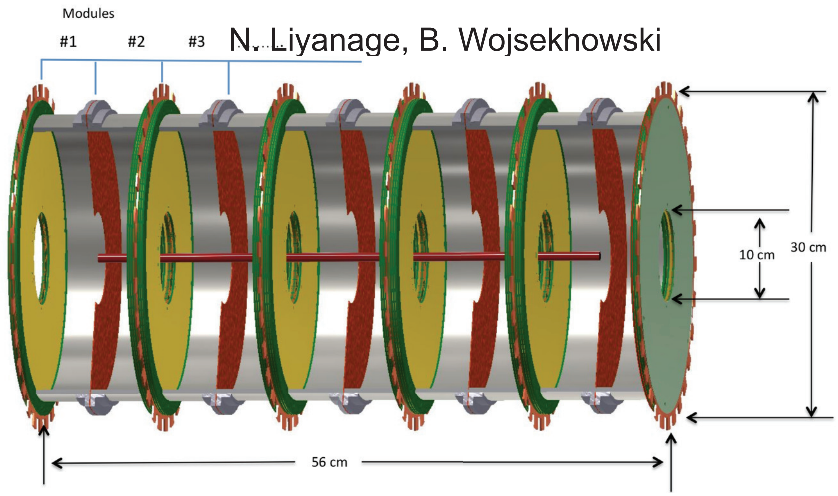
- GEM readout
- Strips UV pattern
- Angular resolution 0.2°; coordinate resolution <1mm; time resolution 10ns

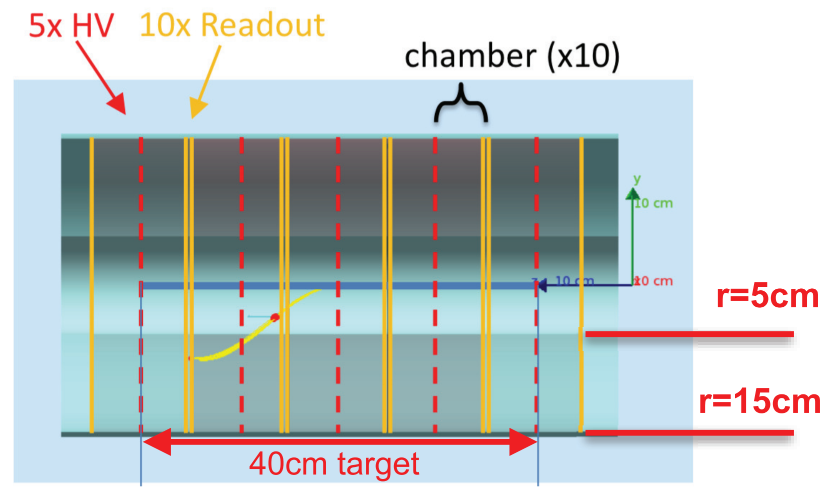
- Very challenging conditions (high luminosity)
- Background rates very high (^{2}H ~ couple 10^{2}MHz)
  - Protons from photo-nuclear processes
- True recoils/spectators separated from accidentals using time and position vertex reconstruction (SBS + TPC)
- Simulated ionisation drift times challenging (tens of μs)
  - Extremely high occupancies in rTPC and readout channels
  - Track "memory"/signal duration in time too long
  - Difficult to find readout electronics to cope

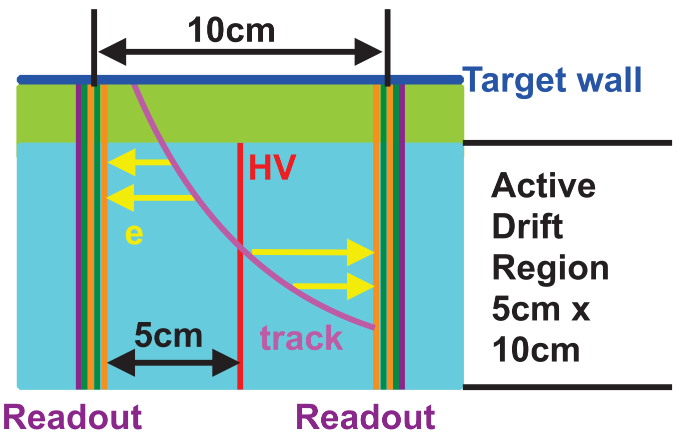
☑ Move to a multiple time projection chamber (mTPC) design

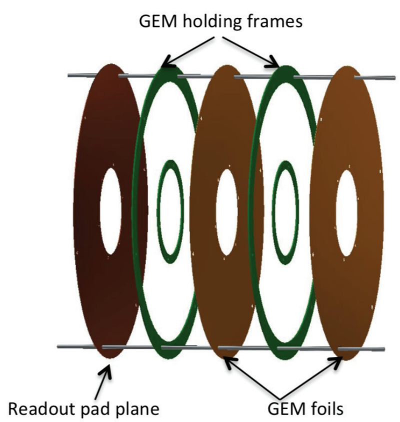
☑ Faster, construction may be easier…

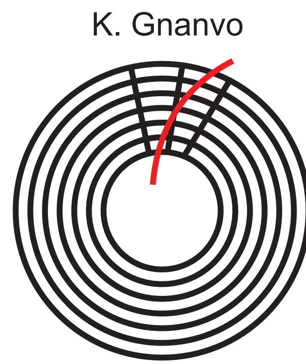
Multiple Time Projection Chamber Concept

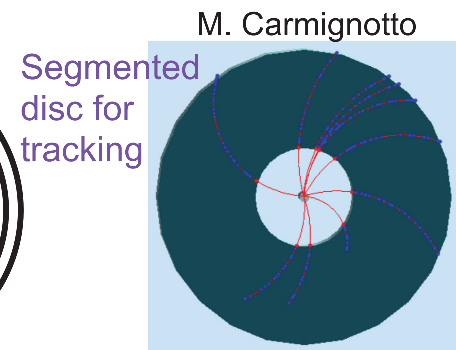




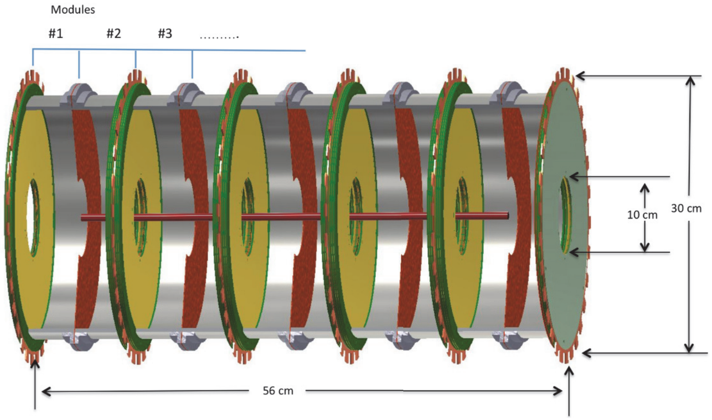




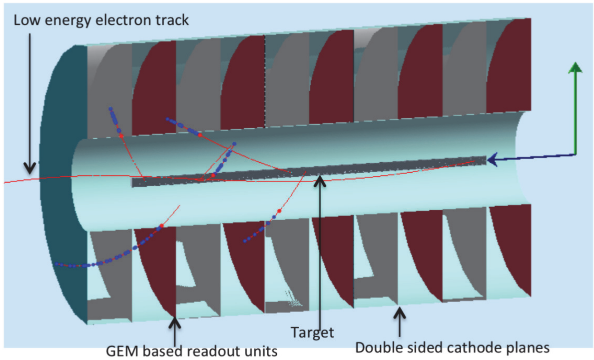


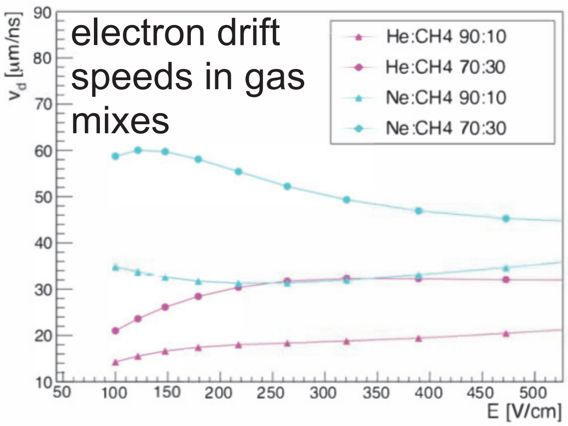


- Modular multiple time projection chamber with 10 separate chambers
- Each chamber has 5cm e^- drift length along beam axis, inner r=5cm, outer r=15cm
- E-field and e^- drift parallel beam-axis (much faster)
- Double layer planar GEM foils for readout of each chamber
- Segmented pad readout disc for track reconstruction, with smaller pad sizes at inner radii for highest rates(e.g. 20rings, 126pads/ring, 2520 pads/plane, pad lengths ~2mm - 7mm)



M. Carmignotto





- **Simulation/prototyping on-going to optimise mTPC design**
  - Geometry, materials, readout electronics, pad design
  - Gas - mix (thickness must be minimised to prevent E-loss/secondaries); low temperature/ pressure; **shorter drift times of couple of μs** now achievable!
  - Preliminary simulations indicate
    - Track efficiencies with required momentum resolution for reconstruction acceptable (initial estimates 50-70% with <10% momentum resolution)
    - **Occupancies** have been significantly optimised (current rate estimates ~70MHz/ charged tracks chamber), and will be **manageable** when combined with proposed readout design
- UVa (N. Liyanage et al.) grant received for prototyping mTPC module/GEMs - many things to learn from these developments
- Feb 2018, NSF major research instrumentation (MRI) proposal submitted, led by UVa (N. Liyanage et al.), with U.Hampton/JLab/TDIS collaborating institutions: Development of an mTPC for Jefferson lab Tagged Deep Inelastic Scattering (TDIS) experimental program

- **Streaming readout test stand** in development at JLab to study readout electronics
  - Proposed start summer 2018 (Ed Jastrzembsky et al, JLab DAQ group)
  - Study feasibility/several features of SAMPA ASIC for TDIS (and for other detectors)
  - Learn about continuous data stream and event synchronisation/linking with data stream from other triggered detectors (these developments will be very interesting for TDIS-related experiments at an EIC)

- SAMPA ASIC
  - Developed by University of Sao Paolo (Brazil) for TPC in ALICE (LHC) upgrade
  - Continuous sampling with high data readout speed up (ideal for high rate applications, can be operated triggered or trigger-less)

Image from SAMPA v3 data sheet

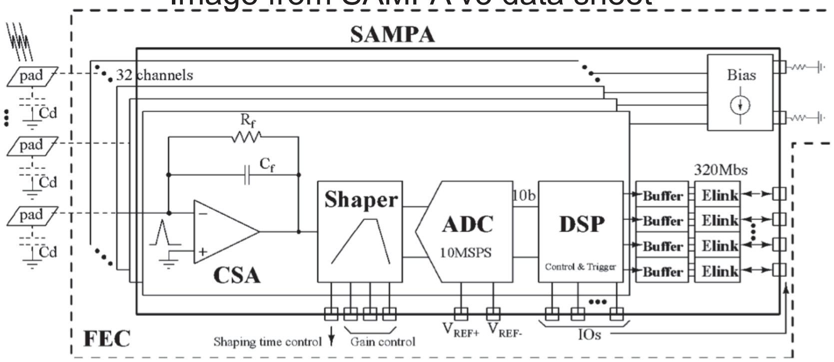


Figure 1: Block diagram for the SAMPA chip.

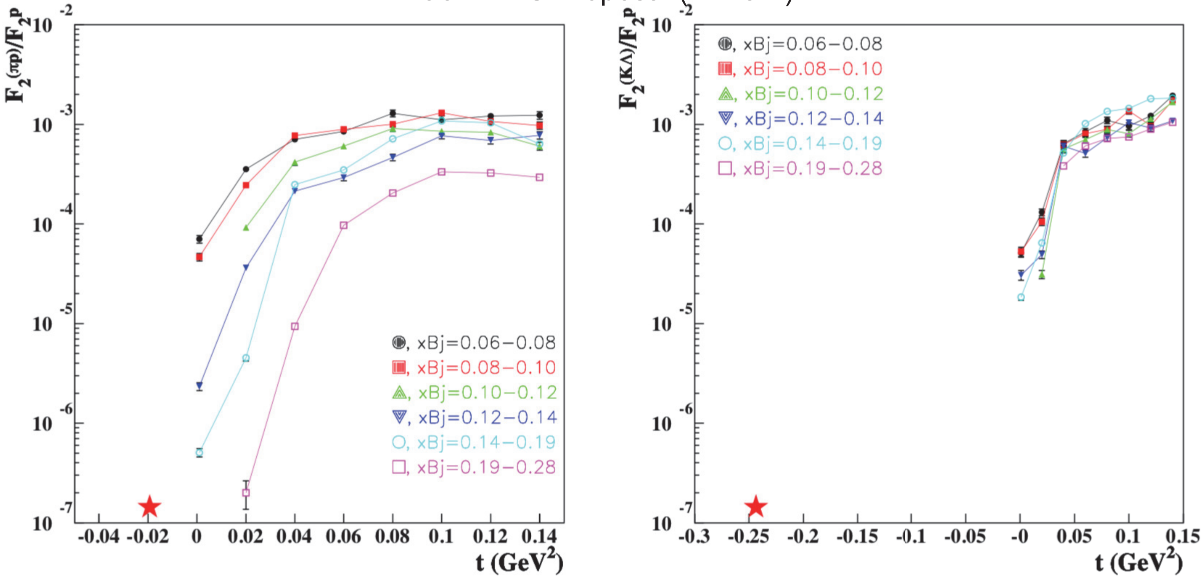
More info: http://iopscience.iop.org/article/10.1088/1748-0221/12/04/C04008/pdf

- SAMPA ASIC has 32chans/chip, 160ns shaping time, 10MSamples/s 10 Bit ADC, baseline correction, zero suppression

- Decision and acquisition of common readout unit parameters to control/readout several SAMPA chips simultaneously in test stand underway

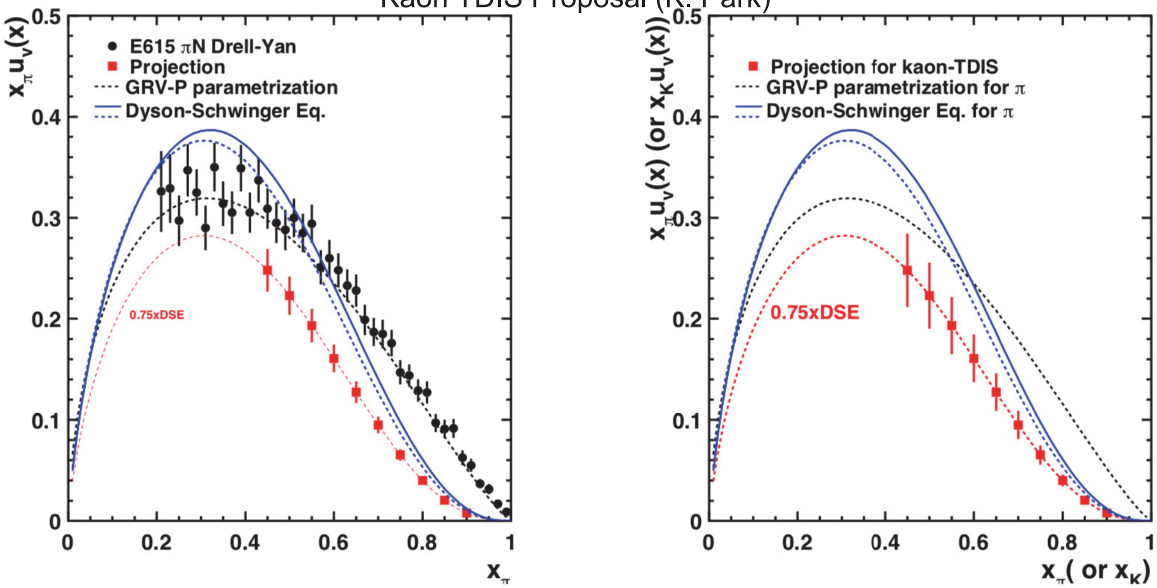
Projected Results

Kaon TDIS Proposal (K. Park)



- t-dependence for different x_{Bj}
- $F_2^{(\pi p)}(t,\Delta x)/F_2^p$ for momentum 100 - 400MeV/c
- $F_2^{(K\Lambda)}(t,\Delta x)/F_2^p$ for momentum <100MeV/c
- Statistical errors included
- As low a momentum reach of mTPC as possible essential for extrapolation to obtain shape of curve

Kaon TDIS Proposal (K. Park)



- Projected valence quark distribution as a function of $x_{\pi/K}$
- Results from Drell Yan E615
- GRV-P parameterisation and DSE for pion only
- 5% systematic uncertainty in pion flux assumed, total systematic uncertainty of 8.4% included

Summary

- Upcoming JLab TDIS measurements will offer an independent, direct probe of mesonic content of nucleon structure in target fragmentation regime

- TDIS will use Hall A SBS to detect DIS electron and novel mTPC to measure recoilis/spectators
  - tag hard scattering events from nucleon's meson cloud
  - pion TDIS will provide access to both charged and neutral meson cloud contributions
  - access both to pion and kaon SF
  - **nucleons and light mesons are building blocks of matter, their SF are important**

- Realisation of experiment possible by **mTPC and streaming readout** for extremely high rates
  - **Developments constantly on-going,** ever-growing collaboration - watch this space!
  - neutron DVCS run group addition currently under study

- TDIS will provide useful gateway for similar measurements at EIC, experimentally and theoretically:
  - Extraction of the SF will be model-dependent
  - TDIS will improve accuracy of pion PDFs in valence regime, help resolve any tensions between DY and HERA data; shed some light on d(bar)-u(bar) asymmetry; constrain kaon PDFs (since almost no data exists)