Pion and Kaon Tagged DIS at JLab 12-GeV

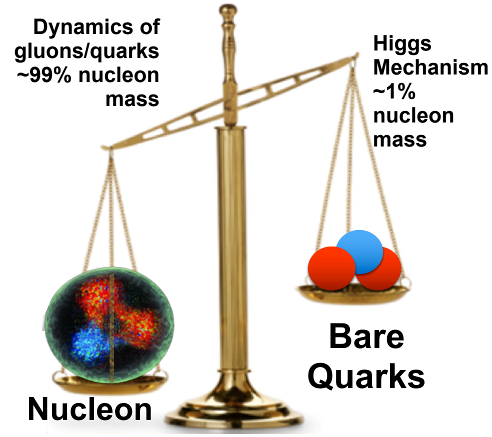
R.A. Montgomery,
on behalf of the Jefferson Lab Hall A and SBS
TDIS Collaboration

Workshop on Pion and Kaon Structure
Functions at the EIC
2nd - 5th June 2020

Upcoming JLab Hall A TDIS Experiment: Motivation

- Light mesons building blocks of universe
- Important to know their structure - data sparse (lack of stable targets)!

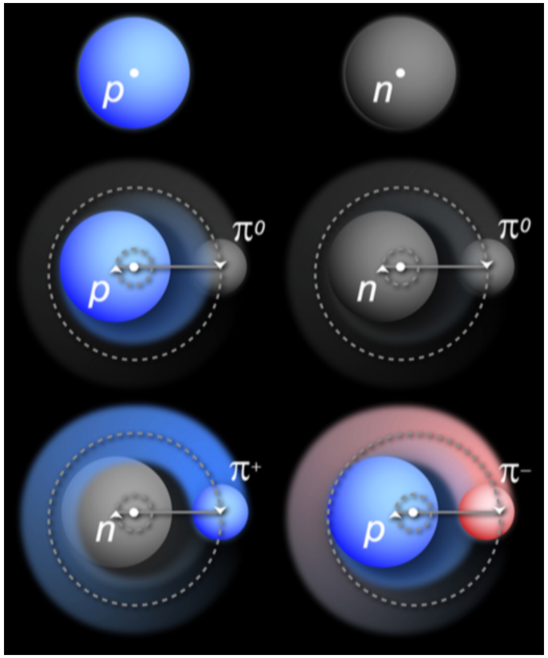
- Test-beds for QCD
  - Simpler $q\bar{q}$ system than nucleon, yet highly complex QCD sates e.g. roles in hadron mass emergence, see C. Roberts, J. Qiu talks June 2nd



- Nucleon's pion content key in nucleon/nuclear structure
  - long range nucleon-nucleon interaction; nucleon/nuclear PDFs, up/down sea-antiquark asymmetry…
- Kaon content also important:
  - access momentum fractions carried by sea/glue, differences in glue content of kaon and pion, combine with valence quark info for PDF evolution

- Important to combine data with substantial phenomenological/ theoretical developments e.g.
  - Provide constraints for PDF/input to global fits
  - Magnitude nucleon's mesonic content unknown
  - How does mesonic content affect nucleon's SF, PDF?

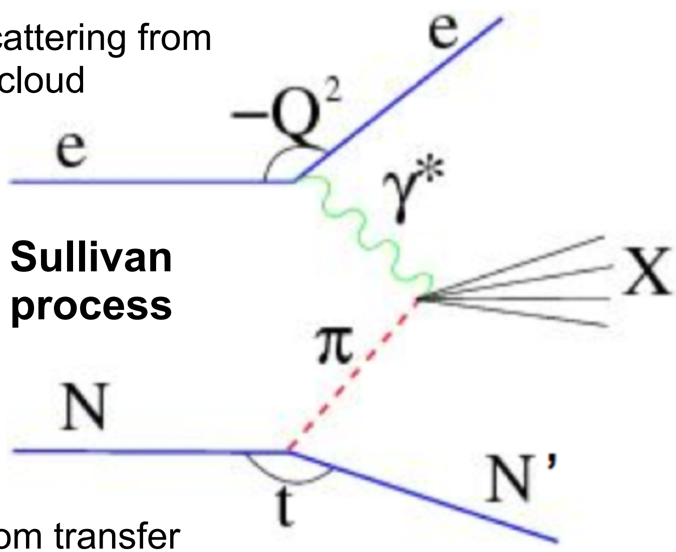
- TDIS: DIS from nucleon+meson fluctuations
- Experimental evidence for mesonic content of nucleon
  - nucleon charge densities; pion/kaon form factor data



J. Arrington, arXiv:1208.4047

TDIS and the Sullivan Process

Hard scattering from meson cloud



Sullivan process

t = 4-mom transfer squared at nucleon vertex

- Tag nucleon's mesonic content directly via Sullivan process in N(e,e'N')X
- Tagging → effective free targets not easily found in nature

- Novel probe of meson partonic structure
- Valence regime pion and kaon structure function (SF) extractions (model-dependent)

<u>Sullivan process - T. Horn and R. Trotta talks (June 2nd)</u>

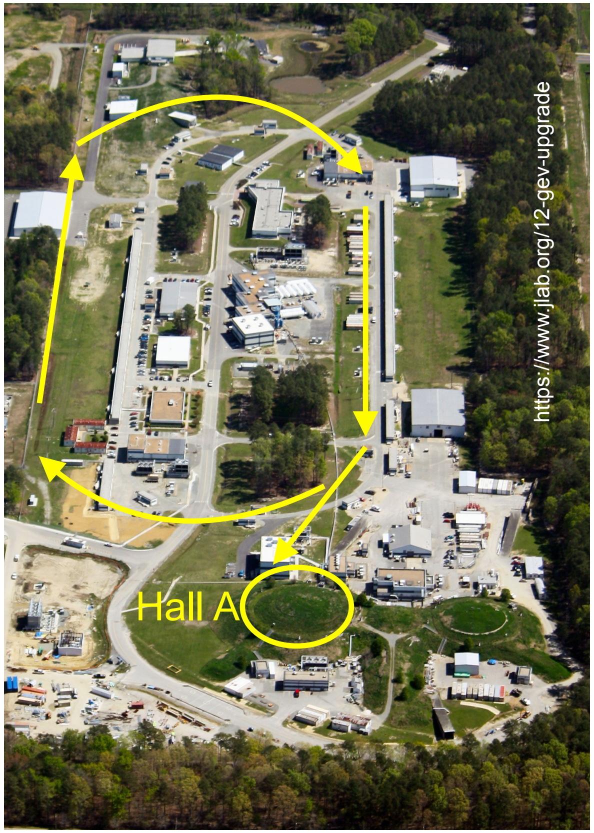
- Small -t: cross-section behaviour characteristic of meson pole dominance
- "Reliable access to meson target as t becomes space like if pole associated with meson remains dominant feature of reaction, and structure of related correlation evolves slowly/smoothly with virtuality" (S-X Qin, C. Chen, C. Mezrag, C.D. Roberts, Phys. Rev. C 97 (2018) 015203) → pion $-t \leq 0.6 \text{GeV}^2$, kaon $-t \leq 0.9 \text{GeV}^2$
- Can be checked empirically - data taking at range of t-values
- Experiments: electroproduction for physical pion form factor

T. Horn, C.D. Roberts, J. Phys. G43 (2016) no.7, 073001
G. Huber et al, PRL 112 (2014) 182501
R.J. Perry et al, PRC 100 (2019) 2, 025206

TDIS Overview/History

- Collaboration of experimentalists and theorists

- **Pion TDIS**
- JLab PR12-15-006 Measurement of Tagged Deep Inelastic Scattering
- PAC43 approved (July 2015) (awarded requested beamtime)
- High scientific rating (A-), excitement about physics



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

- Pi/K SF (model-dependent) extractions in valence regime
- Sullivan process pion measurements
  - First with both proton/neutron targets
- First Sullivan process extraction of kaon SF

- One of suite of experiments utilising Super BigBite Spectrometer (SBS) in upgraded 12GeV JLab Hall A
- High luminosities ⇢ pioneering DIS technique

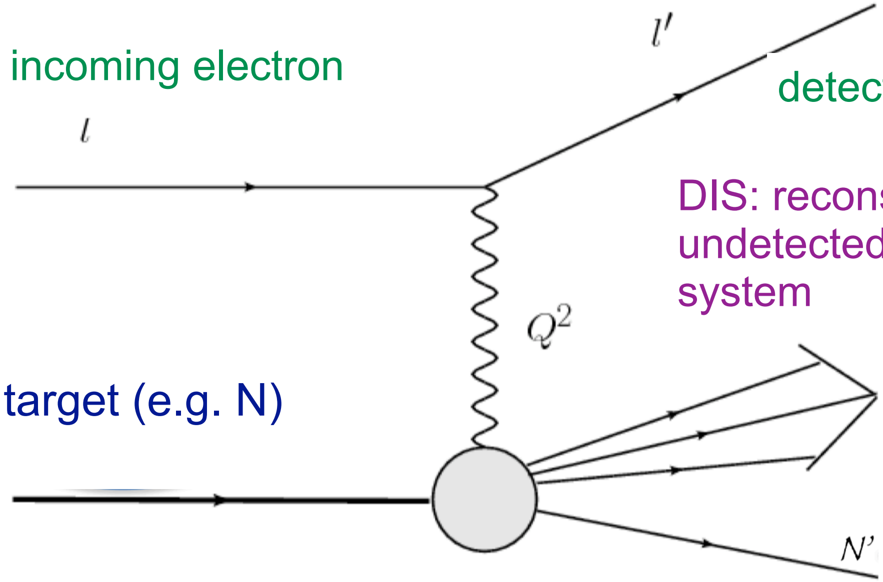
Basic Experimental Approach

incoming electron

detect DIS electron

DIS: reconstruct W and M_x of undetected recoiling hadronic system

target (e.g. N)



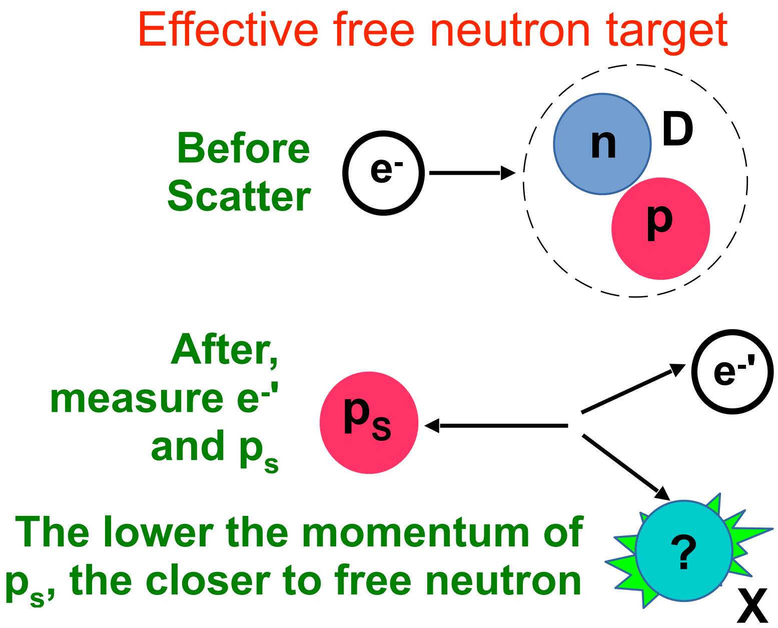
detect recoiling target to tag process

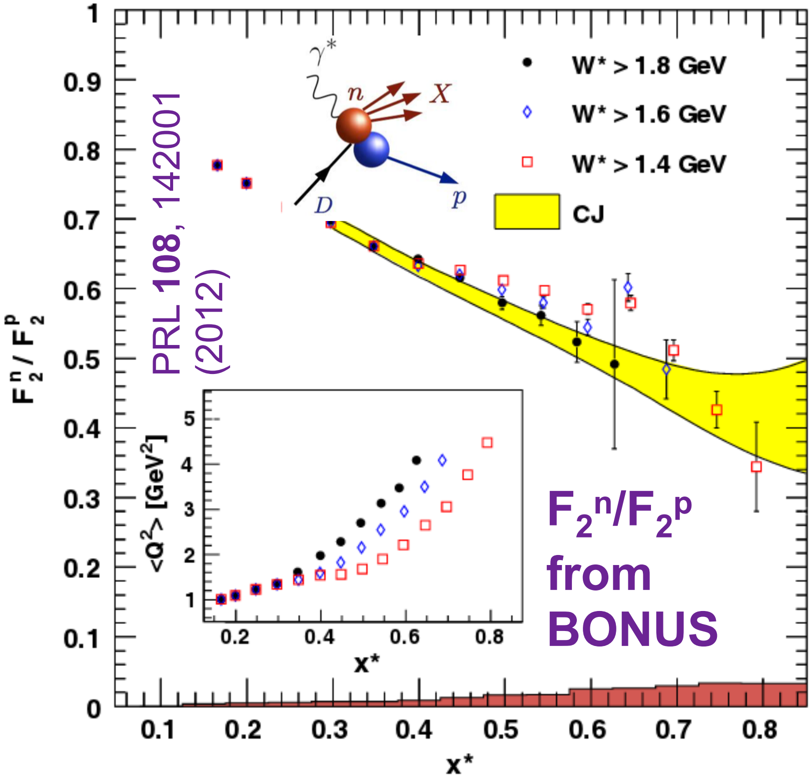
DIS variables: x_{Bj}, Q^2, W^2, M_x,
t (four-mom transfer squared at nucleon vertex)

- Inclusive DIS cross-section historically powerful to access partonic sub-structure (F_1, F_2 SF)

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

- Spectator tagging to access targets not readily found in nature…

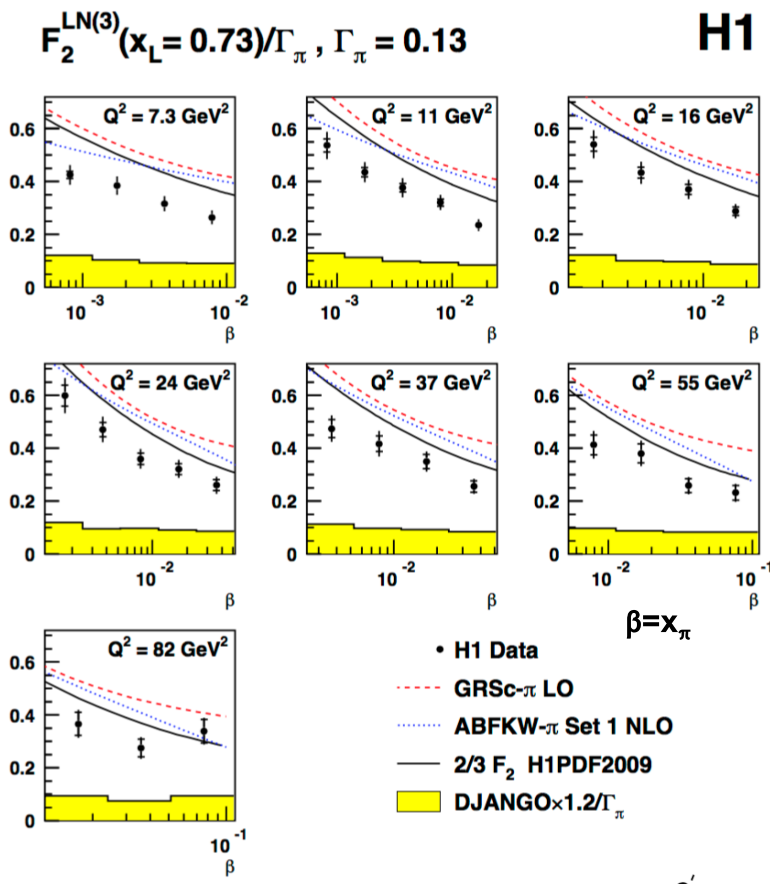




- e.g. BONUS at JLab
- Neutron valence structure (F_2^n), input global PDF fits (https://www.jlab.org/theory/cj/)
- p_s tagged coincident DIS e^- scattered from "free" neutron ($eD \rightarrow ep_sX$)
- Low momentum p_s - neutrons barely off shell
- Very recent/on-going BONUS12 - better precision, higher x, W^2
- Proton SF known very well, but…
- **light meson structure data sparse**

Previous Data for Pion/Kaon Structure

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



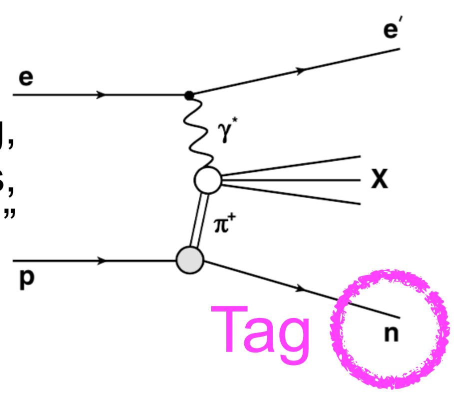
HERA Tagged DIS

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

- Pion sea region, low Bjorken x, high Q^2
- $6<Q^2<100 \text{GeV}^2$; $1.5e^{-4}<x<3.0e^{-2}$

- DIS events with forward going coincident neutrons dominated by one pion exchange
- Charged pion SF extracted

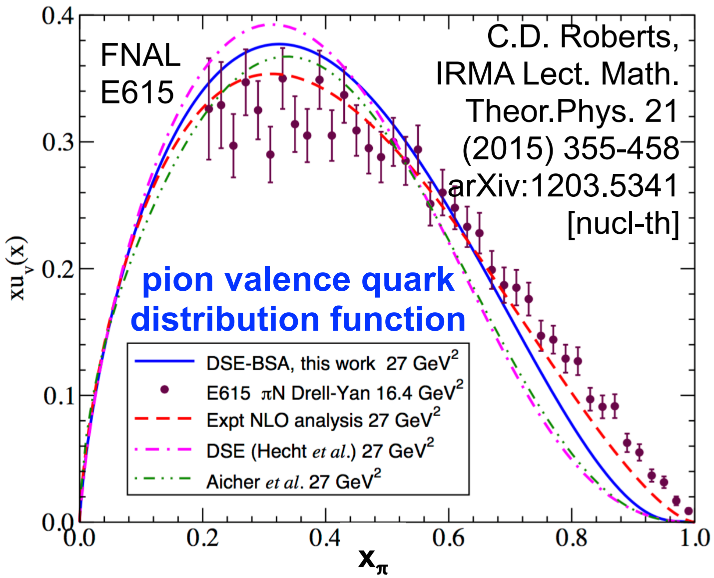
Diffractive scattering,
forward detectors,
Pion "on-shell"



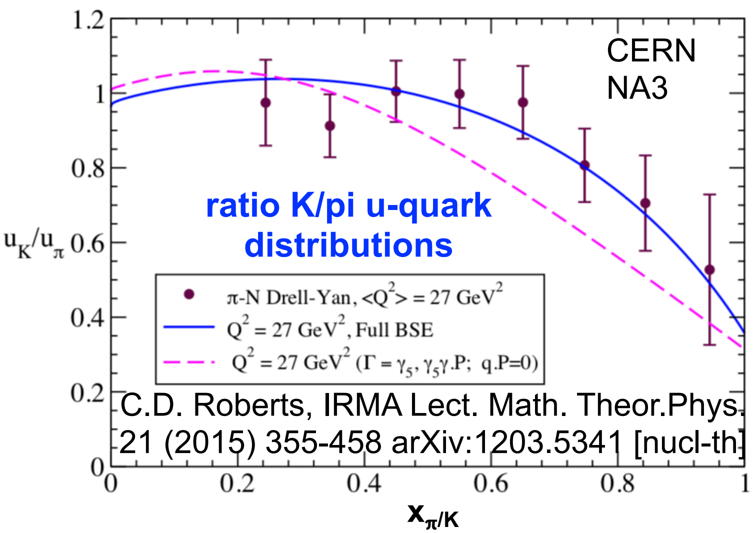
TDIS:

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

Previous Data for Pion/Kaon Structure

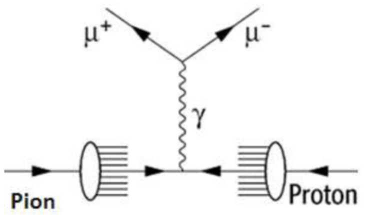


PDF $(1-x_\pi)$ for $x\to1$, pQCD expects $(1-x_\pi)^2$



Valence region - Drell Yan

- e.g. CERN NA3, FNAL E615
- Data sparse
- Practically non-existent for kaon



- Large-x region very interesting (model tensions, pQCD, DSE, light-front…, re-summation effects)
- More data requested for global PDF fits at high x (P. Barry et al. (JAM collaboration), Phys. Rev. Lett. 121, 152001 (2018))
- Basis light front quantisation (BFLQ) technique - agreement in PDF evolution between DY/HERA (Jiangshan Lan et al. (BLFQ Collaboration) Phys. Rev. D **101**, 034024 (2020))

TDIS

- More data essential! More than one data set for PDF extraction (c.f. proton DIS data sets)
- Supplement/synergy COMPASS++/AMBER (see O. Denisov, V. Andrieux talks June 2nd)
- Independent process for cross-checks of models
- Extend to neutral pions!

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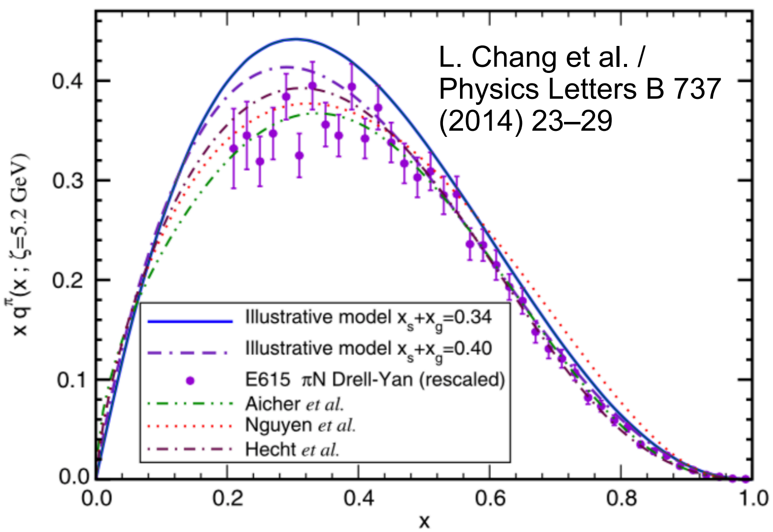

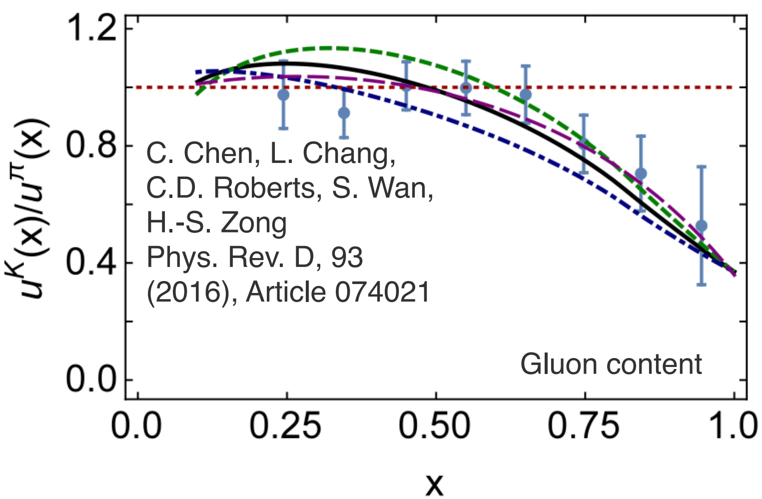

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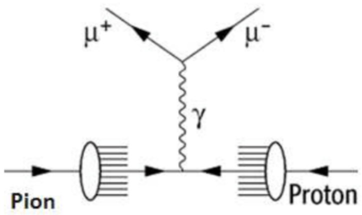

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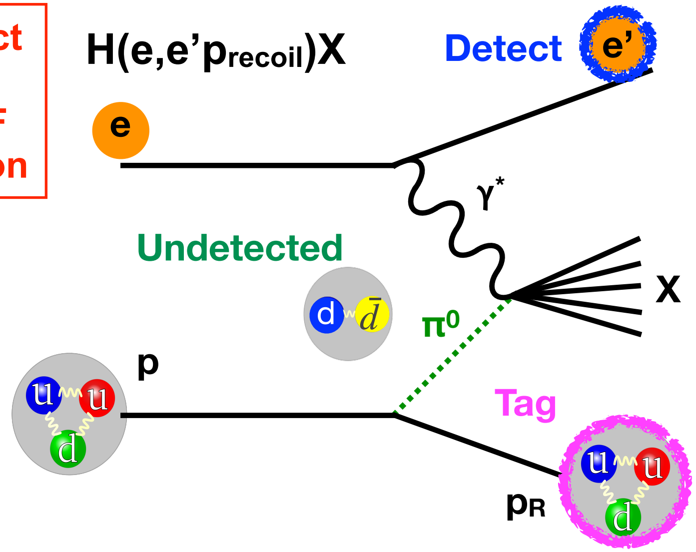
TDIS Measurements

1st direct neutral pion SF extraction



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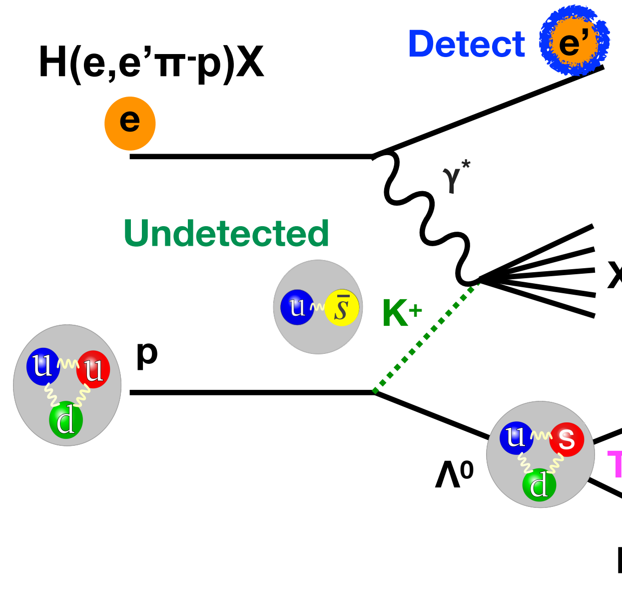
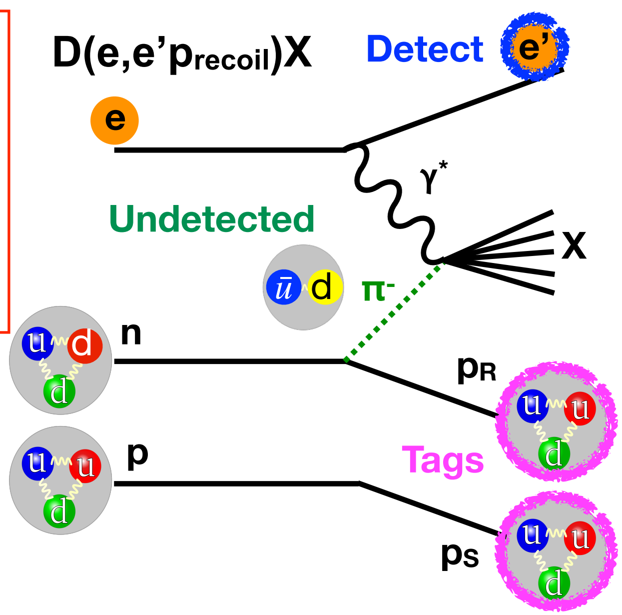


Resolve QCD model tensions for charged pion



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

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

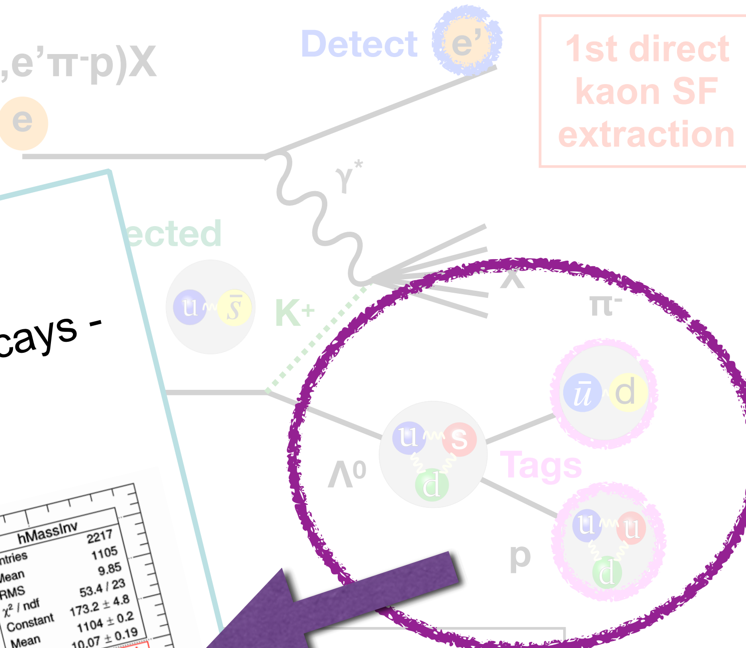
TDIS Measurements

1st direct neutral pion SF extraction

H(e,e'p$_{recoil}$)X

1st direct kaon SF extraction

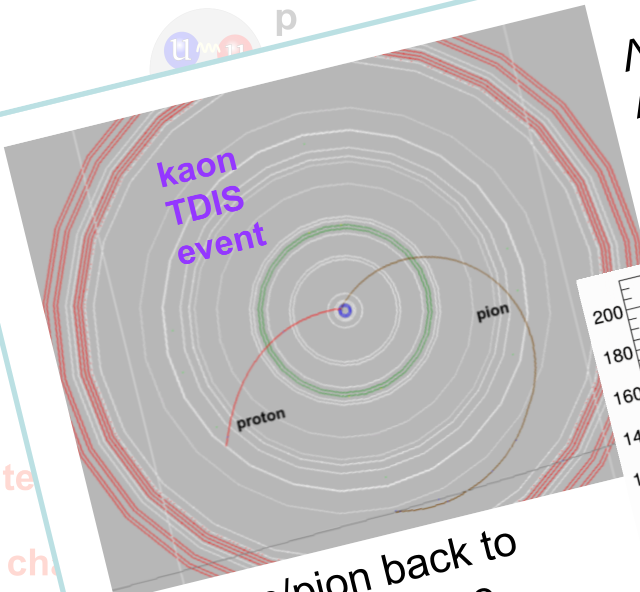
H(e,e'π⁻p)X



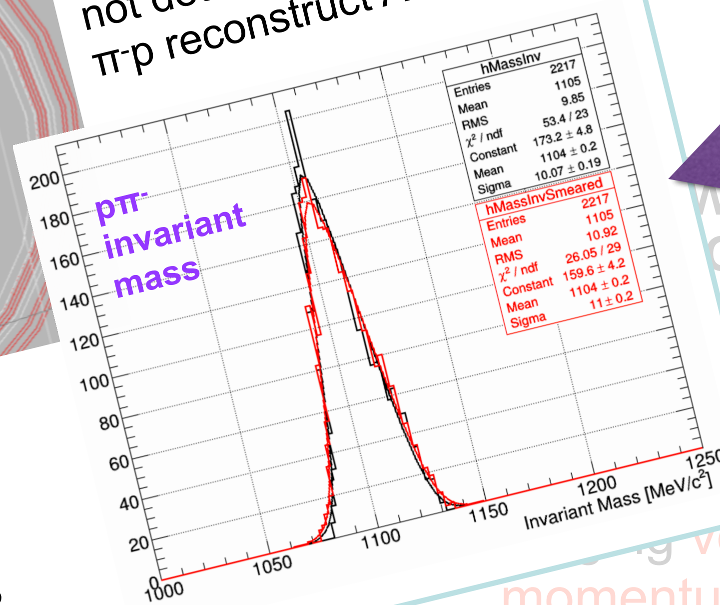
$\Lambda^0 \rightarrow \pi^- p$

Λ^0 uncharged and decays - not detected

$\pi^- p$ reconstruct Λ^0



Proton/pion back to back in CM frame with displaced decay vertex. Momenta similar to pion TDIS protons



W² < 18 GeV²

Q² < 3 GeV²

...5 < x < 0.2

...ctor essential for ... very low momentum recoiling hadrons (60 - 400 MeV/c)

TDIS Measurements

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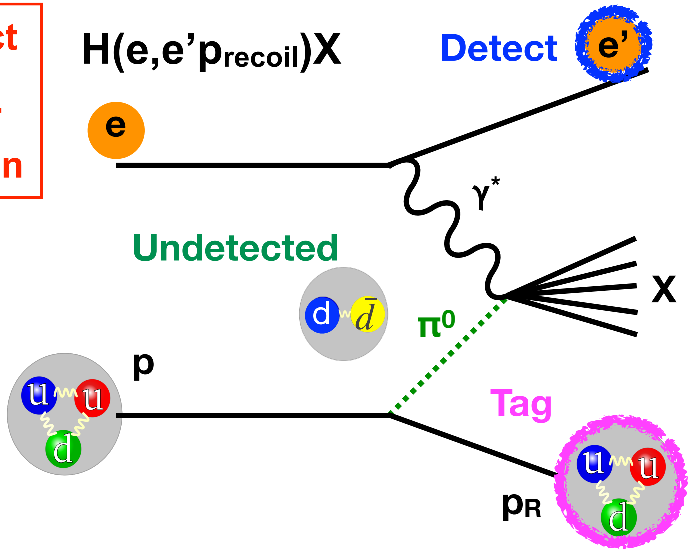

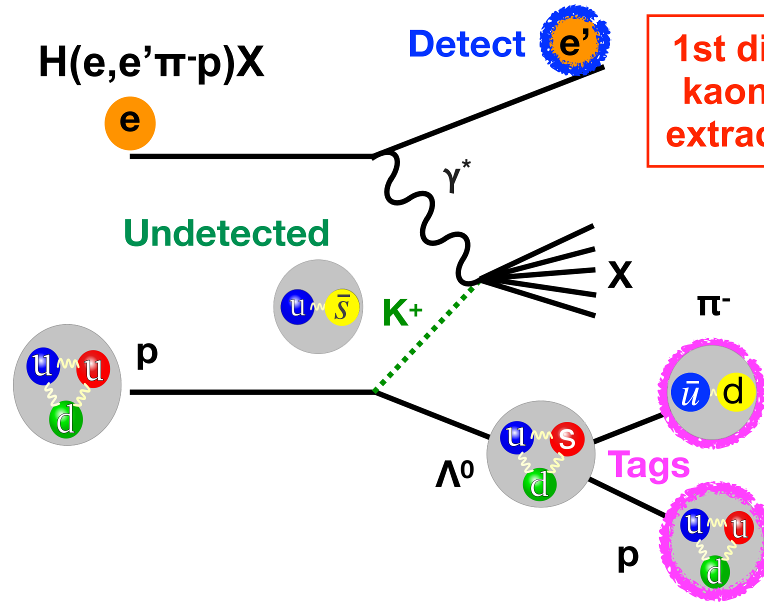

1st direct kaon SF extraction

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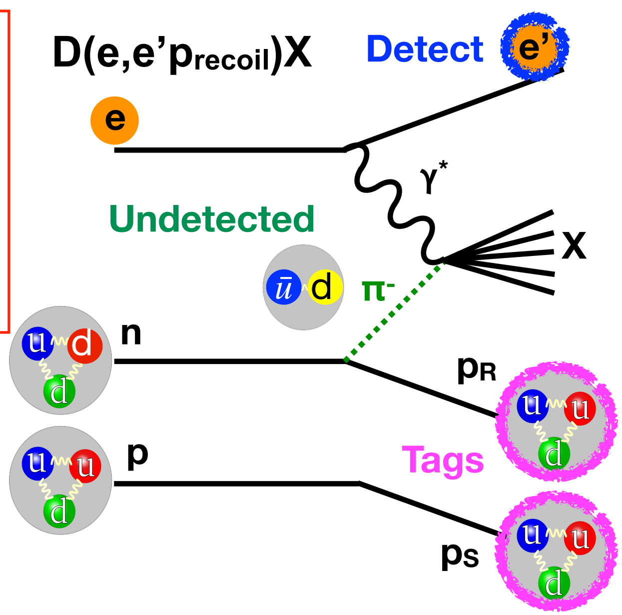

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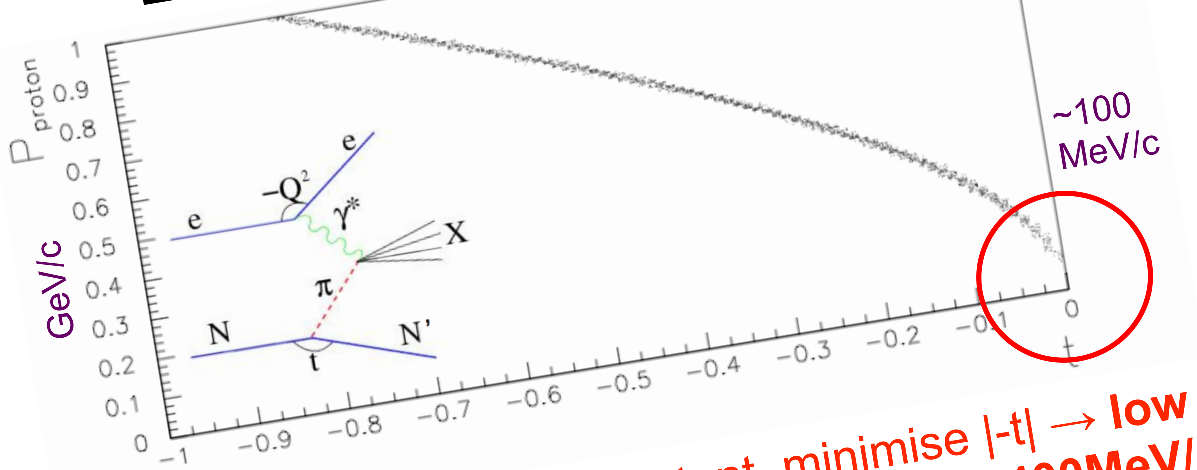
1st direct kaon SF extraction

Extrapolation to pion (kaon) pole

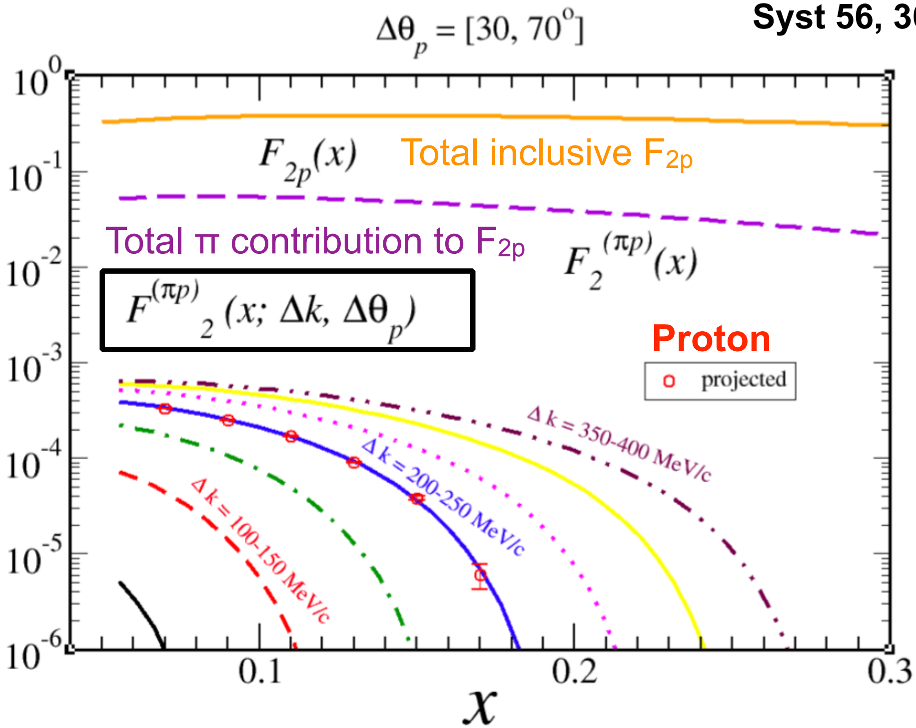


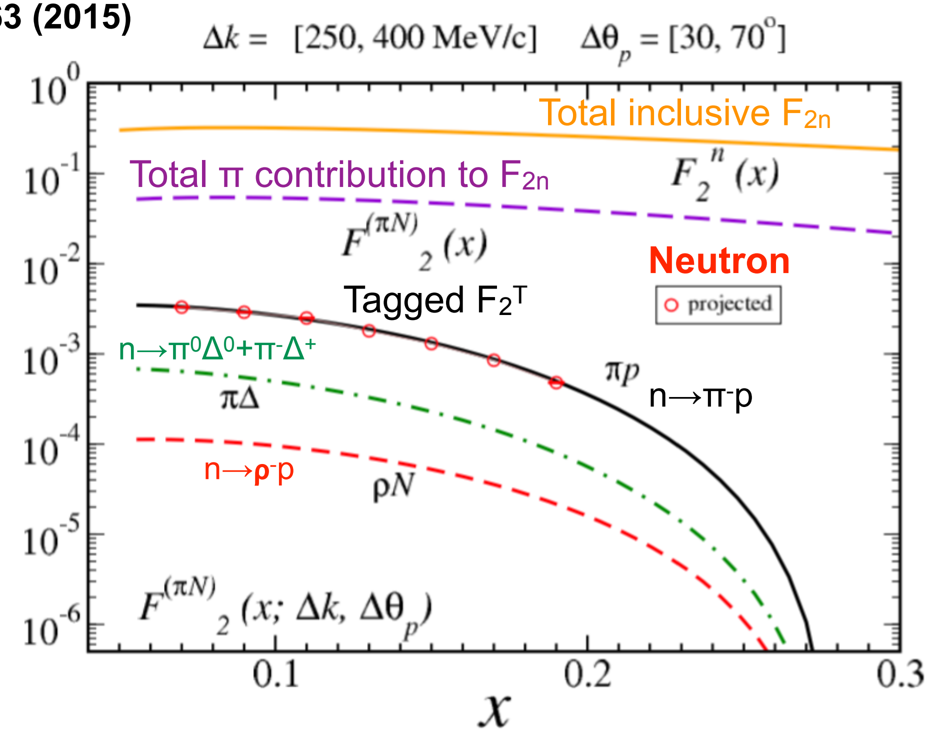
To maximise “true” pion content, minimise |-t| → **low momentum final state protons/pions (60 - 400MeV/c)**
(-t = 4-mom transfer squared at nucleon vertex)

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

SF Extraction and Need for High Luminosity

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





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

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

SF extraction depends on pion flux model
Assuming pion exchange dominant

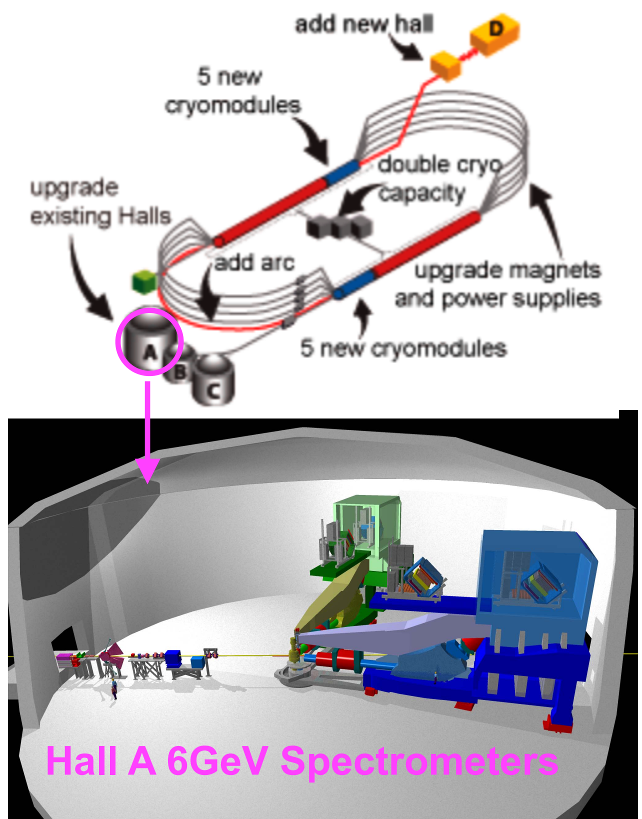
$$\boxed{F_2^T(x,Q^2,z,t) = \frac{R^T}{\Delta z\Delta t}F_2^p(x,Q^2)}$$

Projections for kaon use same method

Where Will TDIS be Performed?

<u>Jefferson Lab, VA, USA:</u>

- Shutdown 2012, electron beam 6GeV → 12GeV (now in 12GeV era)
- Upgrade existing equipment, new detectors, new hall
- Fixed target experiments
- Upgraded facility provides access to pioneering DIS techniques



<u>Hall A 6GeV Era:</u>

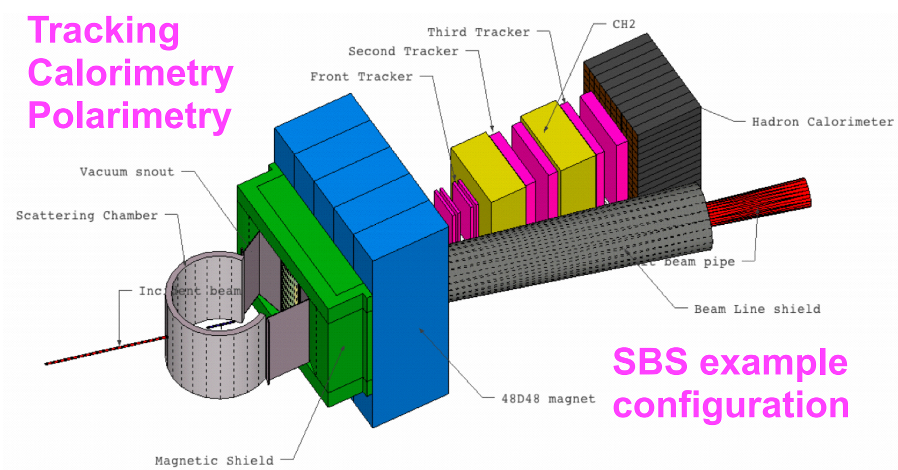
- High-resolution spectrometer pair
- Solid angle ~6msr
- σ_p/p: ~1×10^{-4}

<u>For 12GeV era:</u>

» Installation of new open geometry spectrometers…

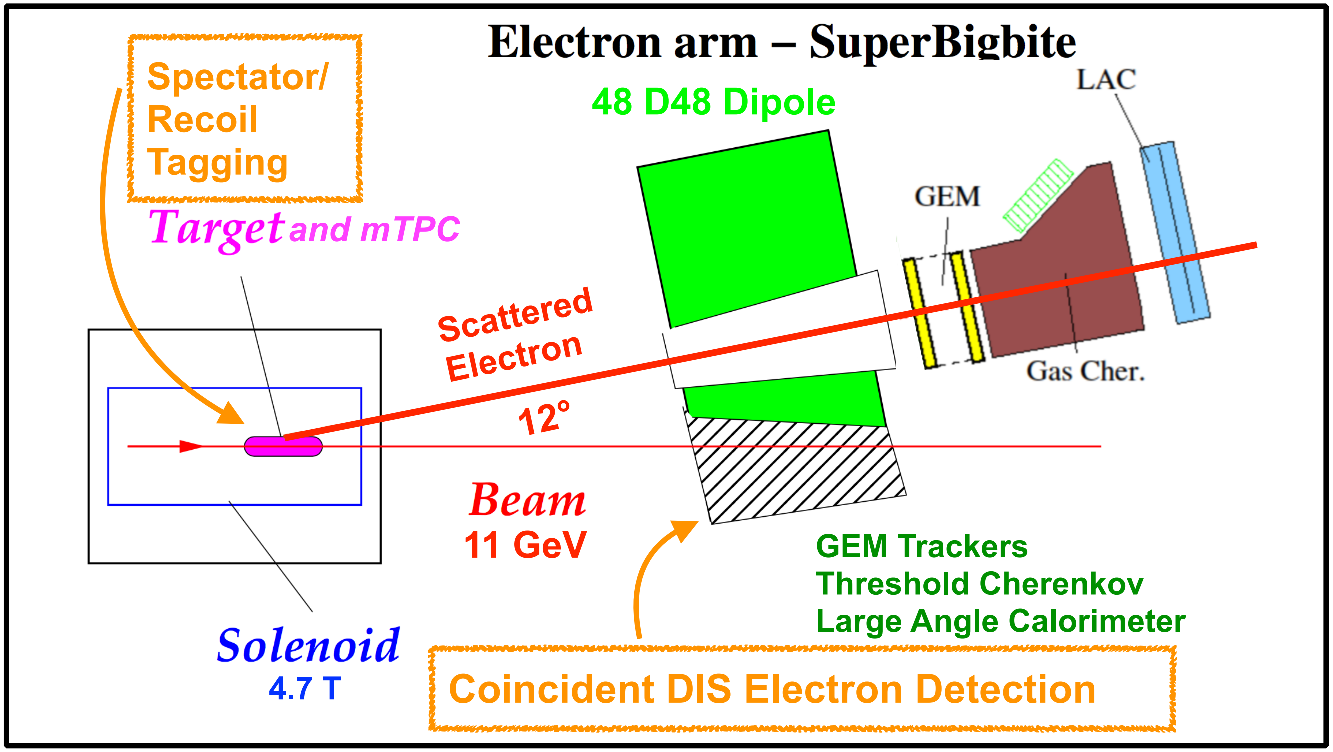
Novel Super BigBite Spectrometer

- Higher luminosities (~8×10^{38}Hz/cm^2)
- Increased acceptance (~70msr)
- **Measure rapidly decreasing cross sections at higher Q^2 (>10GeV^2)**
- Open-geometry magnet
- Highly modular; segmented
- Polarised targets
- Suite of nucleon structure experiments with SBS as hadron arm
- Nucleon em form factors at large Q^2



- $\Delta\Omega$: 76msr @ 15°, 5msr @ 3.5°
- Δp: 2-10GeV/c
- σ_p/p: ~$1\times10^{-3}p$[GeV/c]
- Angular resolution 0.5mrad

TDIS Experimental Setup



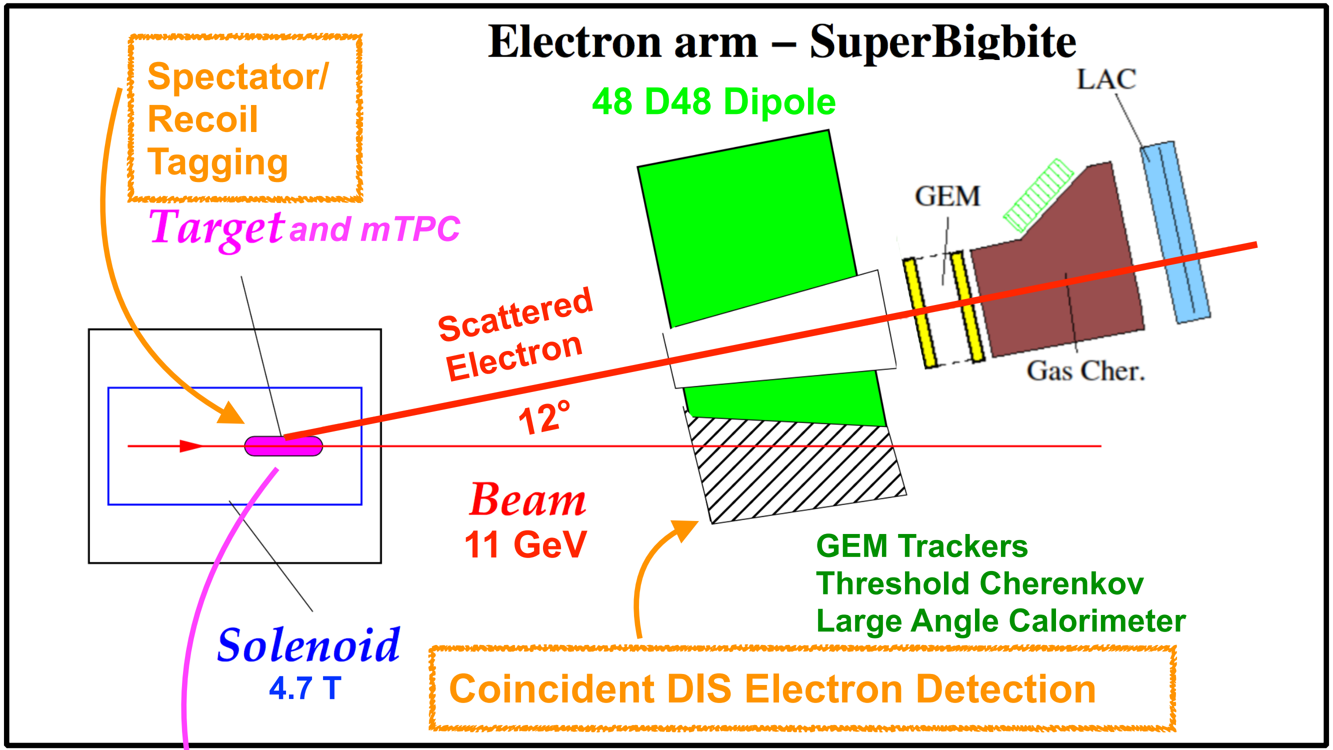
Very challenging measurement = lots of exciting activities/R&D on-going

- High density straw target; H/D; 40cm length; 1cm diameter

- Multiple Time Projection Chamber (mTPC) for recoil/spectator tagging
- Solenoid (4.7T, from UVa) for momentum analysis of recoils/spectators ($p_\perp = 0.3B\rho$)
- SBS configured for coincident e- detection

- 11 GeV e^- beam, 50μA, high luminosity $3\text{x}10^{36}\text{cm}^2/\text{s}^{-1}$
- High rates (hundreds of MHz of overlapping background in mTPC region)…

TDIS Experimental Setup



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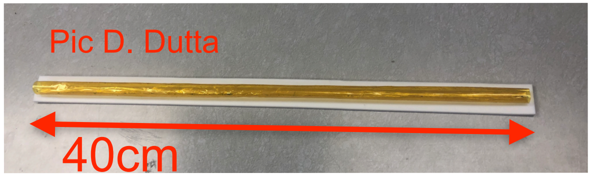
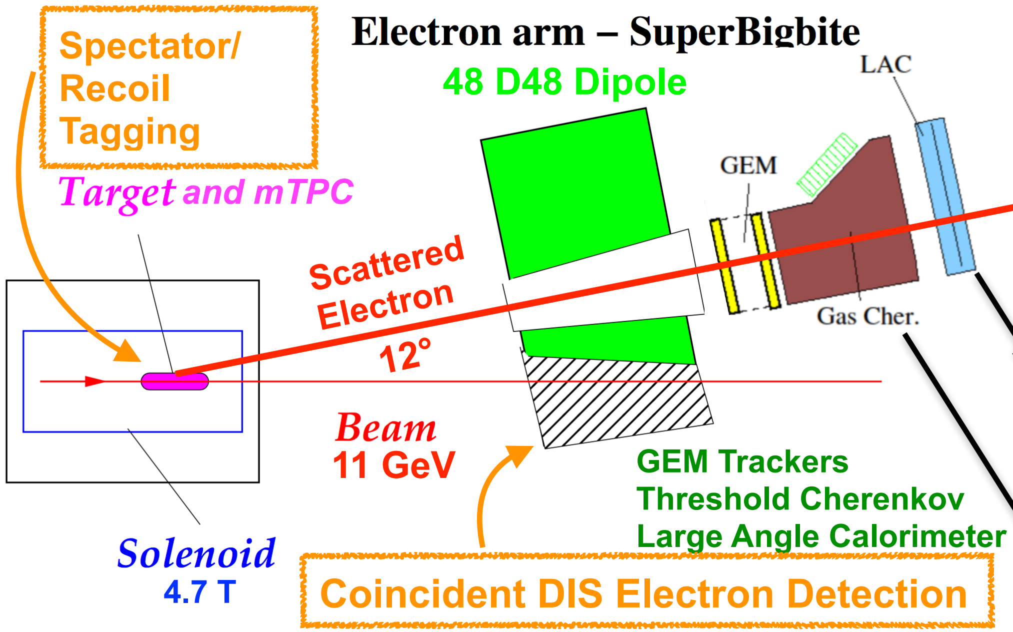
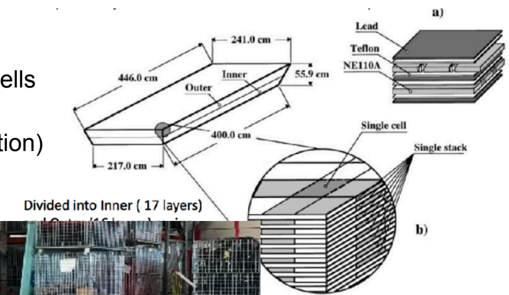


- Re-design of target for mTPC (D. Dutta et al MSU)
- Cold target → room temperature
- Several atm
- Prototyping, assembly procedure development and testing (MSU/JLab)

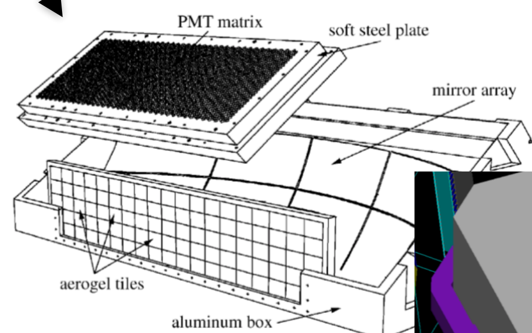
TDIS Experimental Setup



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

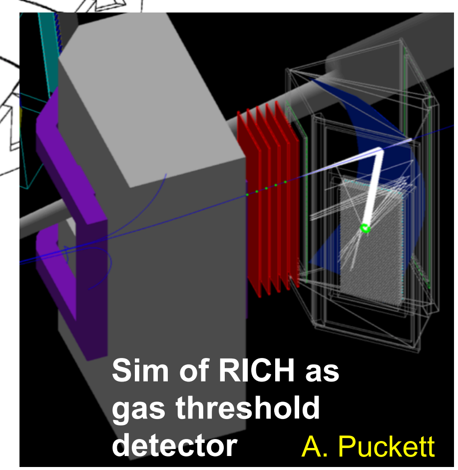


(NIMA 537 (2005) 562)
(NIMA 447 (2000) 424)



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

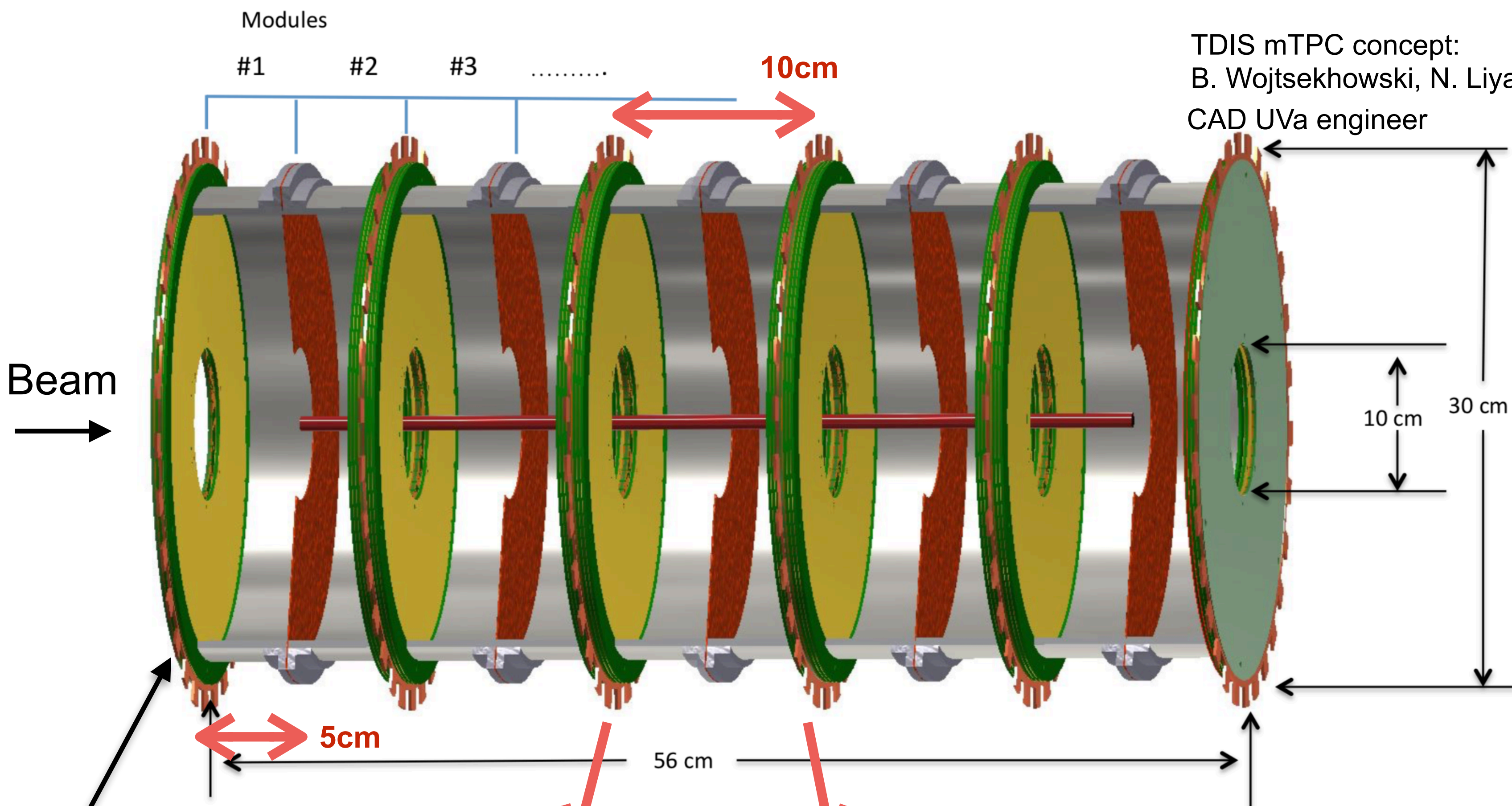
π/K/p PID separation over momentum range suited to SBS



- SBS reconfigured from hadron to e' detector
  - 5 GEM planes for tracking (from SBS GEp, 70μm resolution) (INFN, UVa)
  - For PID/pion rejection and e' trigger:
    - HERMES RICH as threshold Cherenkov & refurbished CLAS LAC
    - Refurbishments underway: RICH - UConn (A. Pucket, E. Fuchey); LAC - (D. Dutta MSU, S. Malace JLab)

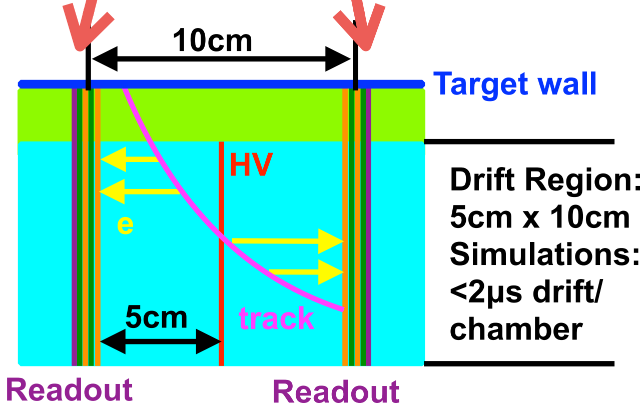
Innovative High Rate mTPC

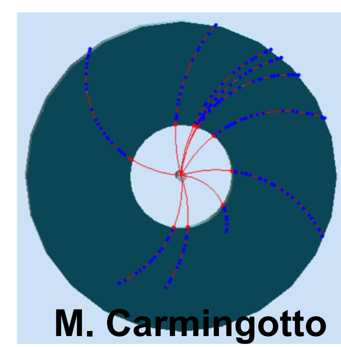
TDIS mTPC concept:
B. Wojtsekhowski, N. Liyanage
CAD UVa engineer



Readout: double layer GEM foils
(N. Liyanage, K. Gnanvo, UVa)

mTPC: multiple time projection chamber for tagging recoil/spectator protons and pions - vertex and momentum analysis, PID by dE/dx



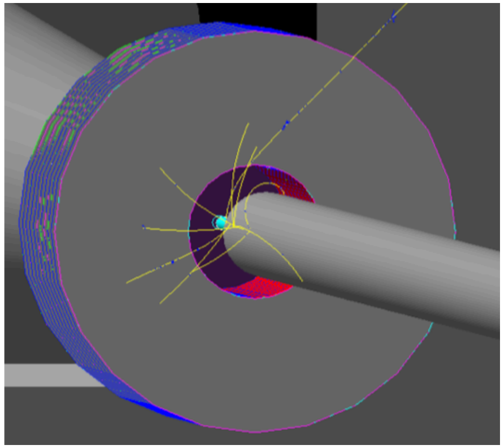


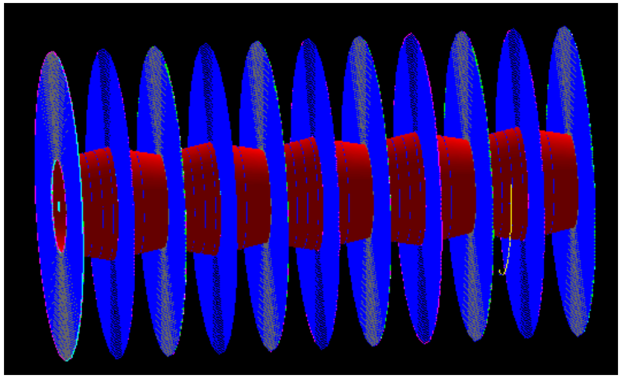
Track reconstruction gives p_T and vertex

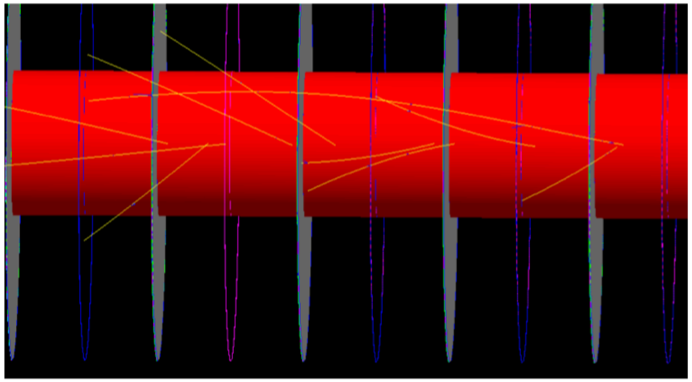
End view one readout plane

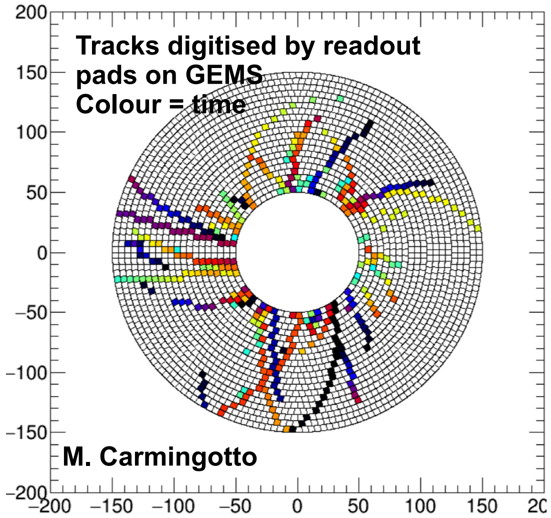
Innovative High Rate mTPC

- mTPC will be highest rate TPC of its size - cutting edge!
- Geometry fully simulated in Geant4 JLAB SBS g4sbs framework
- Background rates biggest challenge (final estimates underway)
    - Accidentals: H2 - elastic protons; D2 - photodisintigration/ QE scattering/delta production and decay into pp
- Several simulation/reconstruction studies on-going (S. Wood, A. Tadepalli, C. Ayerbe Gayoso, E. Fuchey, R. Montgomery)
    - Tracking and reconstruction/final rate estimates/inclusion of background and up to date event generators in g4sbs…
- Plans for construction/testing prototype chamber (N. Liyanage, K. Gnanvo et al. UVa)

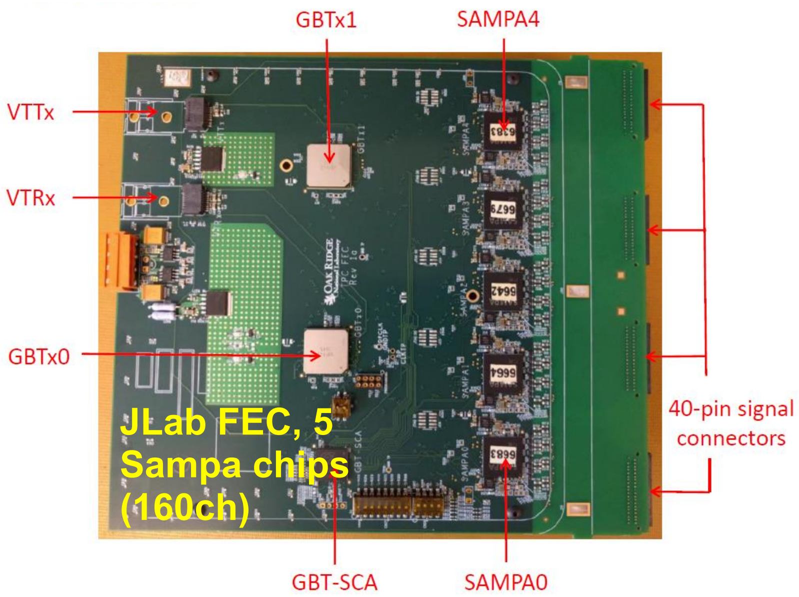








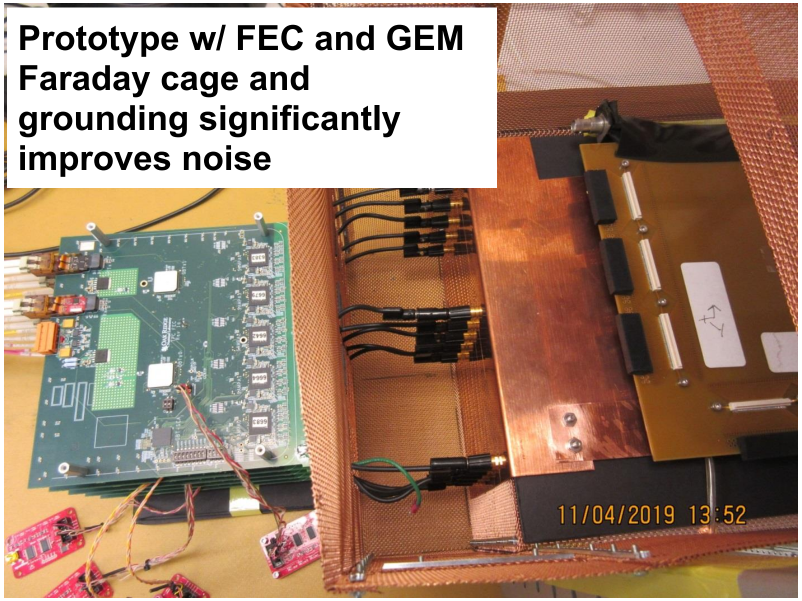
Streaming Readout

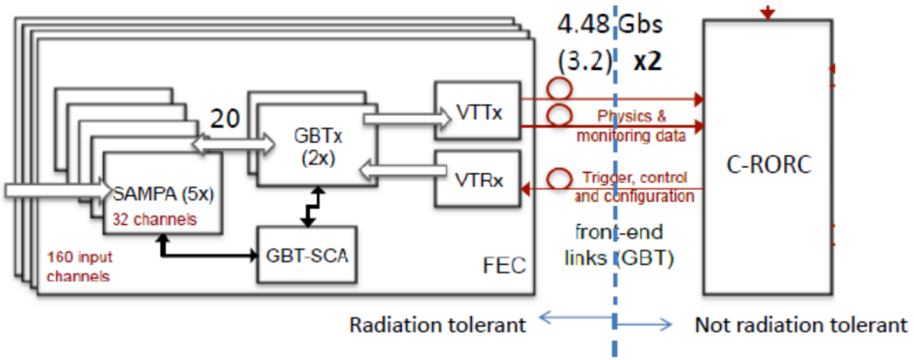


- Design/prototyping/testing @JLab (E. Jastrzembski, E. Pooser, G. Heyes)

- SAMPA chip (Univ. Sao Paolo) and streaming readout developed for ALICE TPC upgrade (~1TB/s post zero-supp)
- SAMPA - charge-sensitive pre-amp, ADC, DSP (zero-suppresion e.g.)

- Triggerless mode successfully tested summer 2019 (5 chips, ~160 chans)!





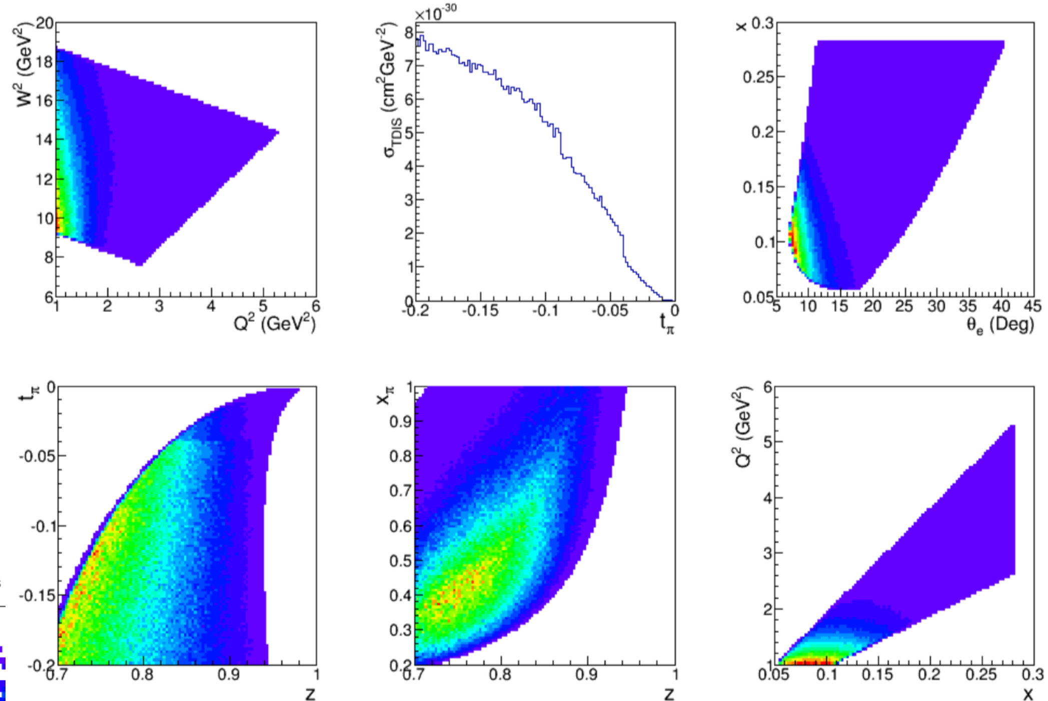
FEC – Front End Card (160 ch / FEC)   (5 FEC = 800 ch)
C-RORC – Common Read Out Receiver Card (PCIe)
GBTx – Giga Bit Transceivers
GBT-SCA – GBTx Slow Controls Adapter
VTTx, VTRx – Fiber optic transceivers

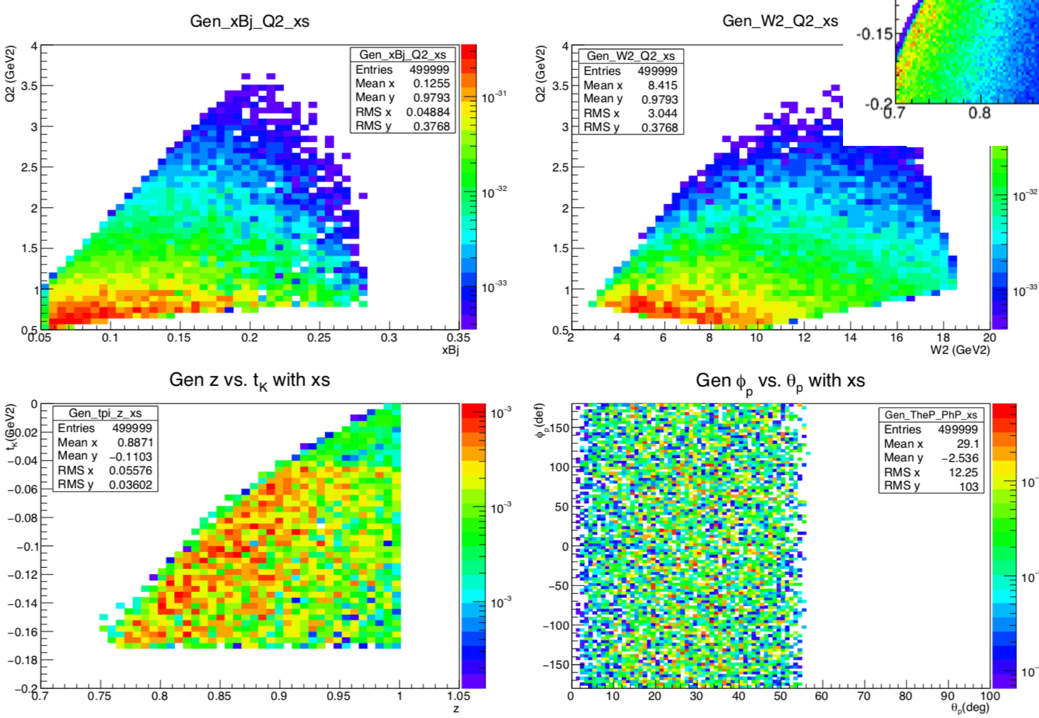
Pic credits: E. Jastrzembski

TDIS Kinematic Reach in Hall A

- Right, pion TDIS (H target)
- Below: kaon TDIS

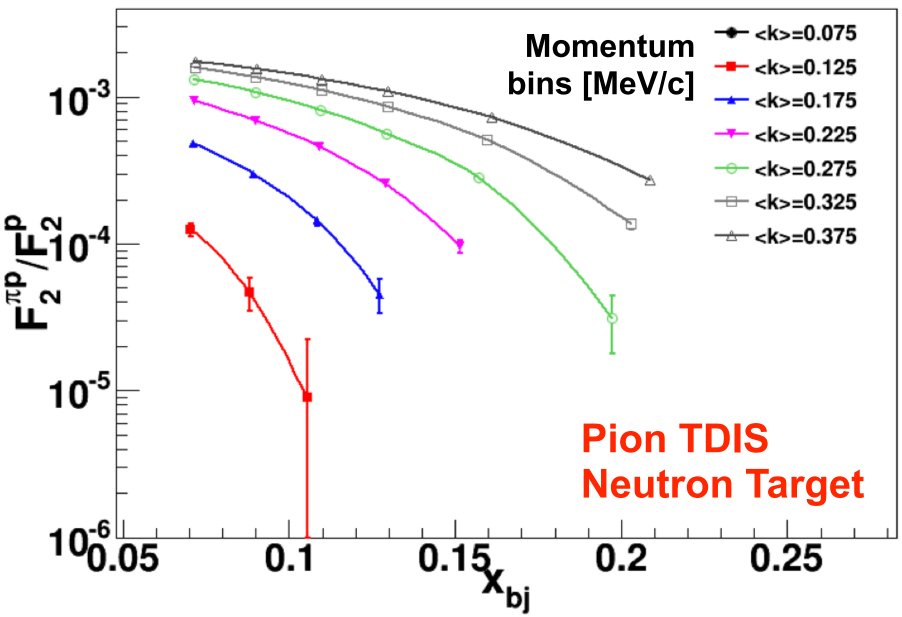
- Kaon case includes chiral effective theory for strange quark asymmetry (X. G. Wang et al., Phys. Rev. D 94, 094035(2016)), splitting functions, Feynman diagram contributions to s(bar) PDF in nucleon

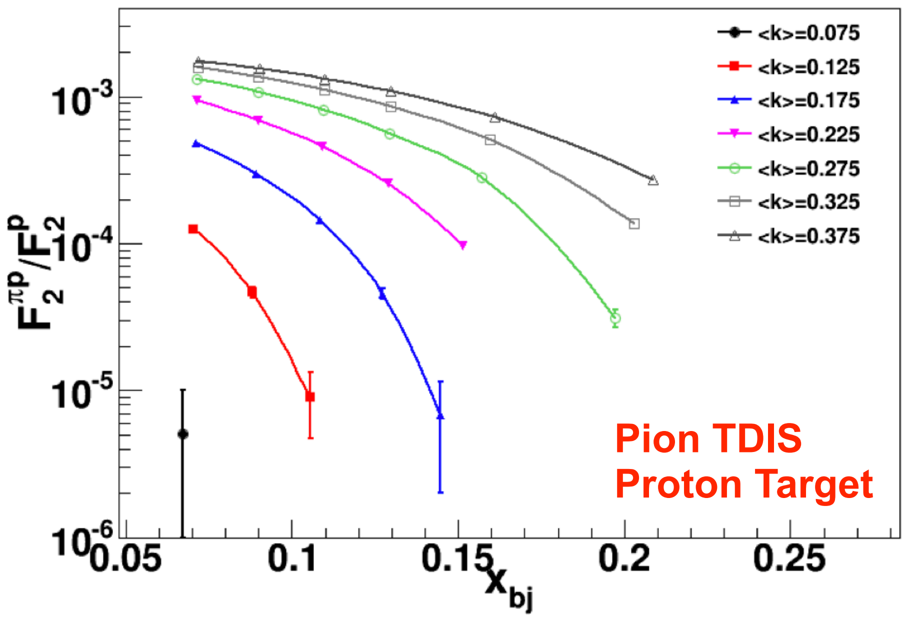


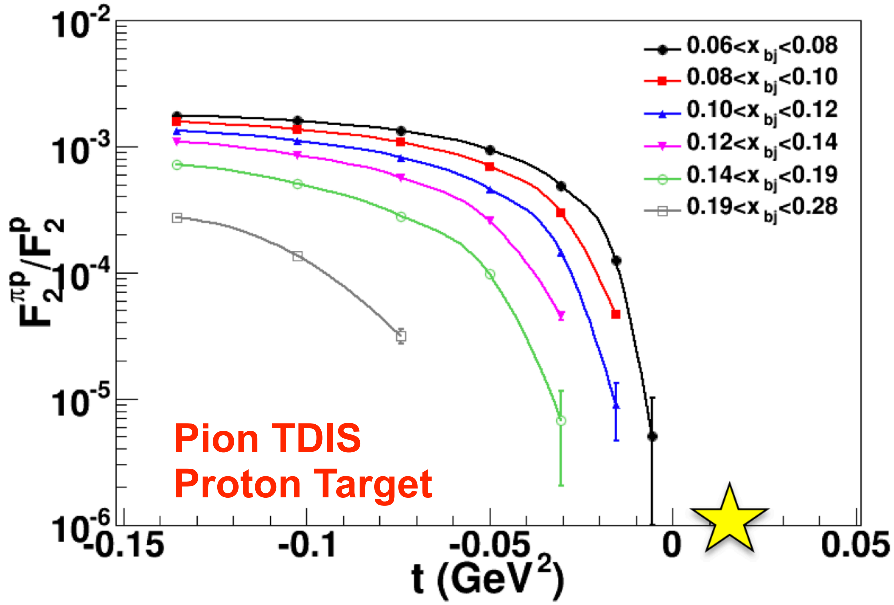


- All data obtained simultaneously (only H/D target changes)

- Bjorken-x range up to ~0.1
- Q^2 fixed by 11GeV e^- beam
- High W^2, M_X^2 DIS regime
- Similar reach for pion/kaon TDIS





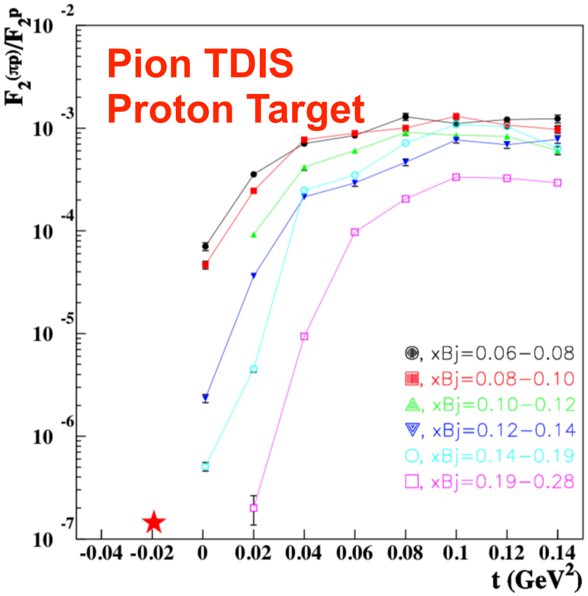


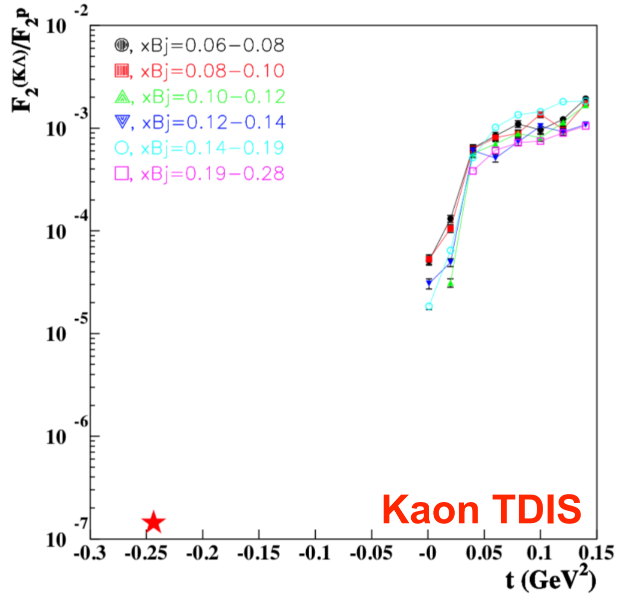
- Top: x_{bj} dependence of ratio semi-inclusive SF to inclusive nucleon SF (points) in bins of momentum integration ranges for recoiling hadrons

- Bottom example of potential reach in t towards pion pole

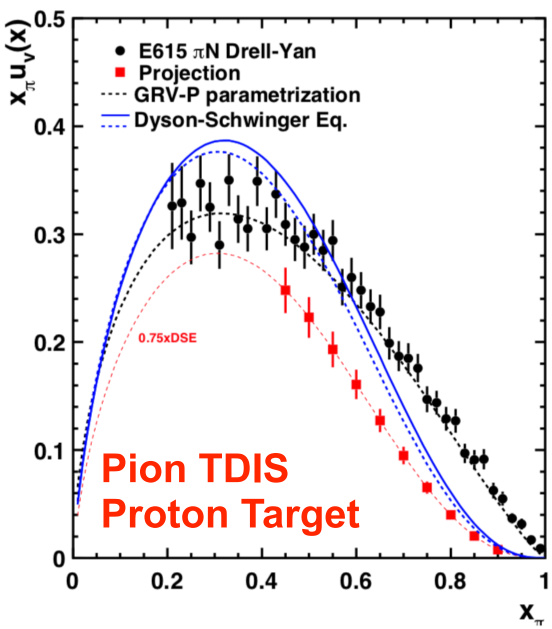
- Low momentum reach of mTPC crucial to map out shape

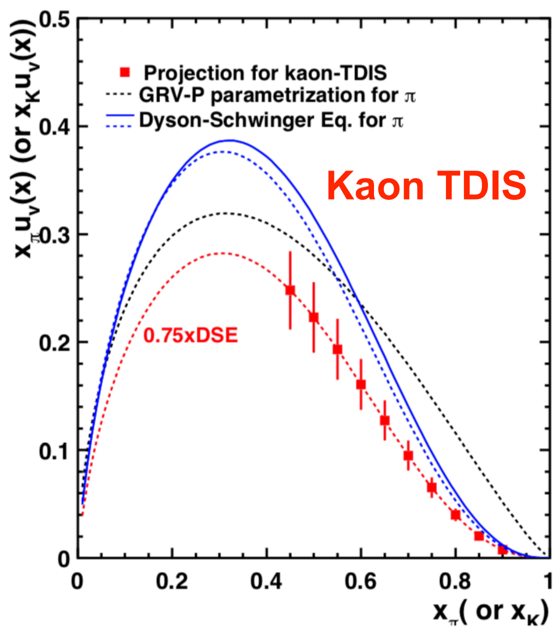
Example Projected Results





- Kinematical mapping of SF for both pion and kaon TDIS
- First ever direct kaon SF extraction





- Projected valence quark distributions compared with Drell Yan results

Summary

- TDIS: direct probe of nucleon's mesonic content to understand nucleon and light meson structure on deeper level
    - tag hard scattering from nucleon's meson cloud
    - both (model-dependent) pion and kaon SF in valence regime
    - pion TDIS - access to charged **and** neutral meson cloud, interesting large x tensions, vital input for global PDFs
    - Kaon TDIS - shed light on differences in gluon content pi/K
    - **Add to sparse world data sets, numerous data sets key**

- Pioneering experimental DIS techniques and instrumentation, developments on-going and collaboration growing

- Gateway to spectator tagging with forward TDIS-type experiments at future Electron Ion Collider (nucleon and nuclei), and input to future EIC studies

- This workshop prime opportunity to collect and strengthen complementarities of different experimental/theoretical efforts and our physics case

- Thanks to TDIS colleagues for input/material (work of many people shown/collective effort)

Phenomenological Pion Cloud Model

- Theoretical work used to study expected rates, required beam time, projected results etc based on a phenomenological pion cloud model
  - T.J. Hobbs, Phenomenological implications o the Nucleon's Meson Cloud, Few-Body Syst 56, 363 (2015)
  - H. Holtmann et al., Nucl. Phys. A 596, 631 (1996)
  - W. Melnitchouk, A.W. Thomas, Z. Phys. A 353, 311 (1995)

- Contribution to inclusive F_2 structure function of nucleon from scattering off virtual pion emitted by nucleon:

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

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

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

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

$k_\perp$ = transverse momentum of pion

- Semi-inclusive tagged structure function is un-integrated product:

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

Pion "flux" Pion SF

  - Seek to measure low-momentum region (pseudo scalar production dominates)
  - Interested in $z \lesssim 0.2$; $x<z \rightarrow$ defines maximum x, Q^2 (beam energy 11GeV)