Probing Meson Structure Via Tagged Deep Inelastic Scattering (TDIS)

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

Hall A Collaboration Meeting
31/01/2020
Jefferson Lab

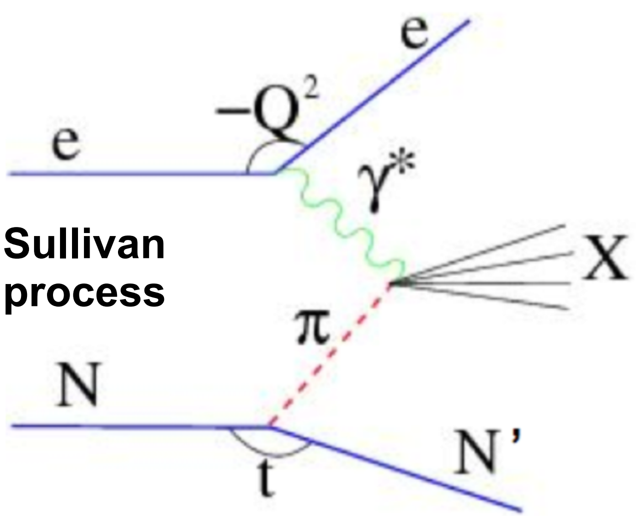
TDIS Overview

- Light mesons also building blocks of universe
- Key role in nucleon/nuclear structure
- Important to know meson structure
    - Test-beds for QCD (simpler $q\bar{q}$ system) - data sparse!

Tagged Deep Inelastic Scattering (TDIS)

- SIDIS (not to access current regime)
- Effective targets not readily found in nature
- **Tag nucleon's mesonic content**
- Novel probe of meson partonic structure
- Sullivan process in N(e,e'N')X
    - Scattering from meson cloud

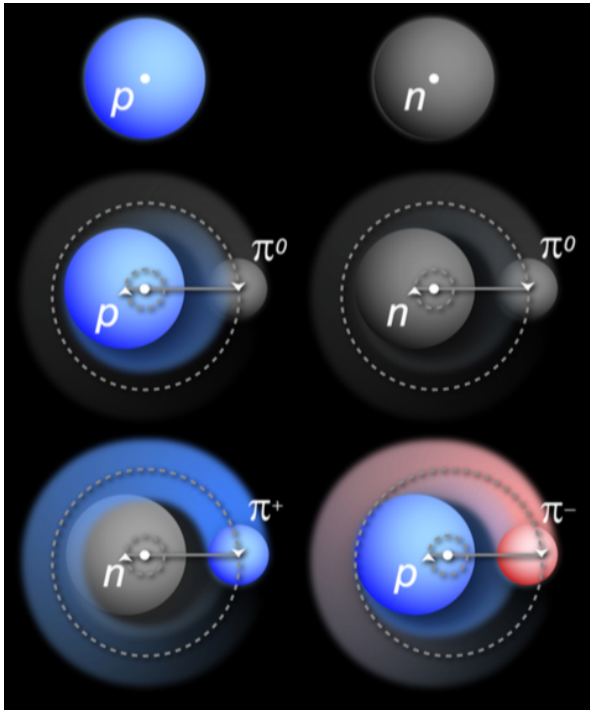
Sullivan process



- Mesonic contribution to nucleon's F_2 SF
- Pion and kaon F_2 SF
- Independent pion measurements in valence regime with proton and neutron targets - charged pion world first (PR12-15-006, accepted 2015)
- Kaon SF - world-first extraction (C12-15-006A, run-group accepted 2017)

TDIS Motivation - Light Meson Structure

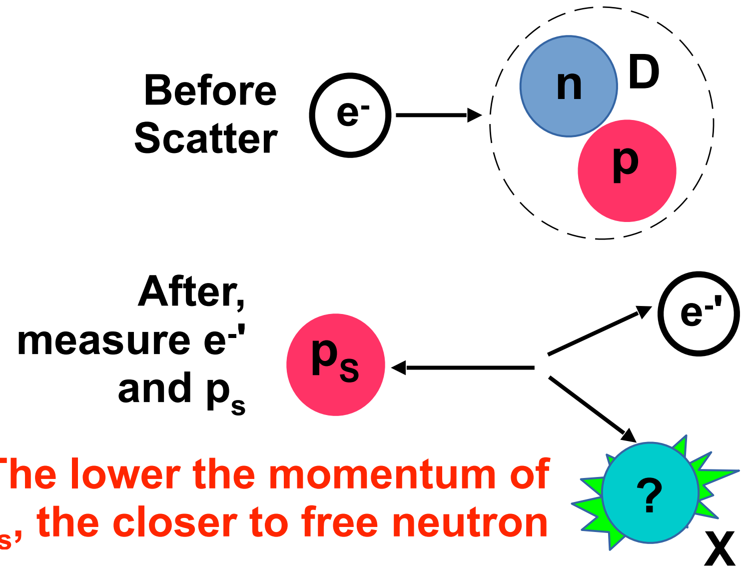
- Evidence for mesonic content of nucleon
  - Fermi, Marshal (1927) “nucleon exists ~20% time in virtual meson-nucleon state”; nucleon charge densities; pion form factor
- Nucleon’s pion content key in nucleon/nuclear structure
  - long range nucleon-nucleon interaction; simplest QCD state; dynamical chiral symmetry breaking; nucleon/nuclear PDFs, up/down sea-antiquark asymmetry…
- Kaon content also important:
  - access momentum fractions carried by sea/glue, less glue in kaon than pion, combine with valence quark info for PDF evolution
- Substantial theoretical work
- **Experimental data sparse (lack stable targets)**
  - Magnitude mesonic content unknown
  - How does mesonic content affect SF, PDF?



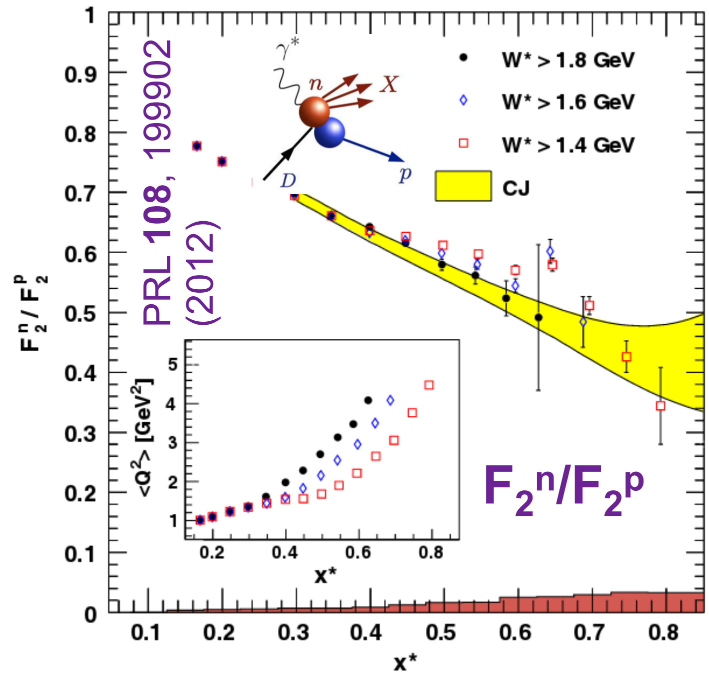
J. Arrington, arXiv:1208.4047

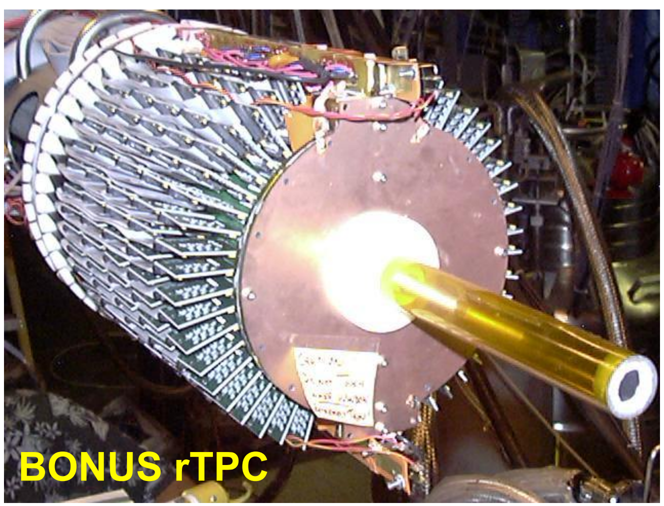
BONUS @CLAS - Spectator Tagging for Neutron Structure

Effective free neutron target in $eD \rightarrow e p_S X$



The lower the momentum of p_s, the closer to free neutron

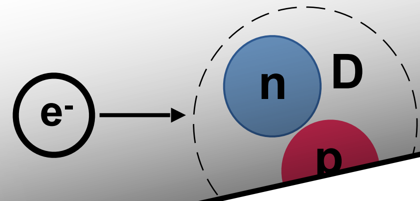


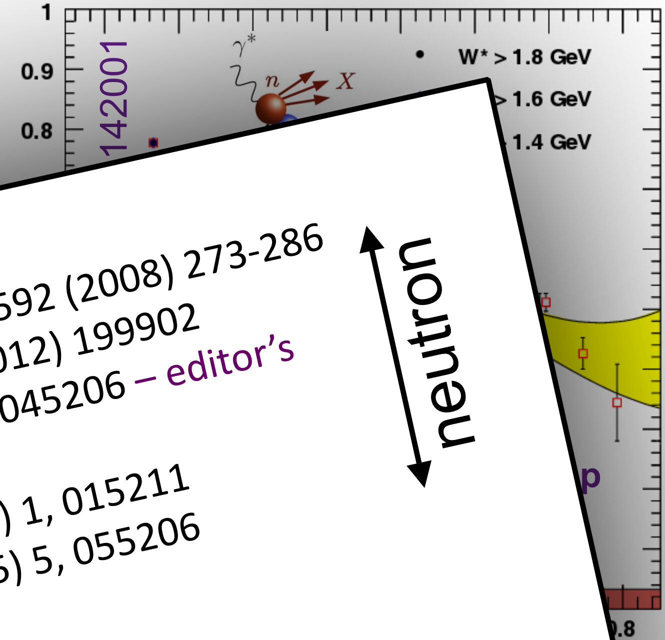


- rTPC - tag low momentum/backwards p_S
  - neutrons barely off shell
- >400 neutron data points
  - neutron valence structure (F_2^n)
  - global PDF fits; EMC effect in D; neutron duality
- BONUS12 E12-06-113 (installation 2020)
  - better precision, higher x, W^2

BONUS @CLAS - Spectator Tagging for Neutron Structure

Effective free neutron target in $eD \rightarrow ep_SX$



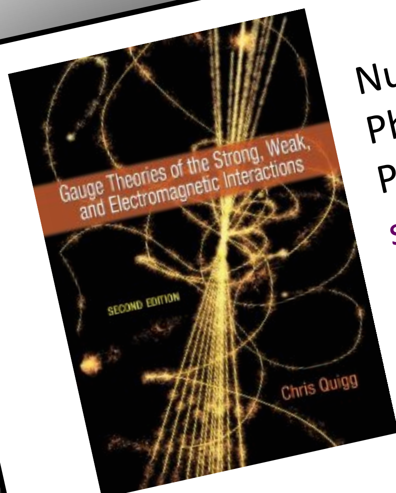


mea…

The lo…
p_s, the c…

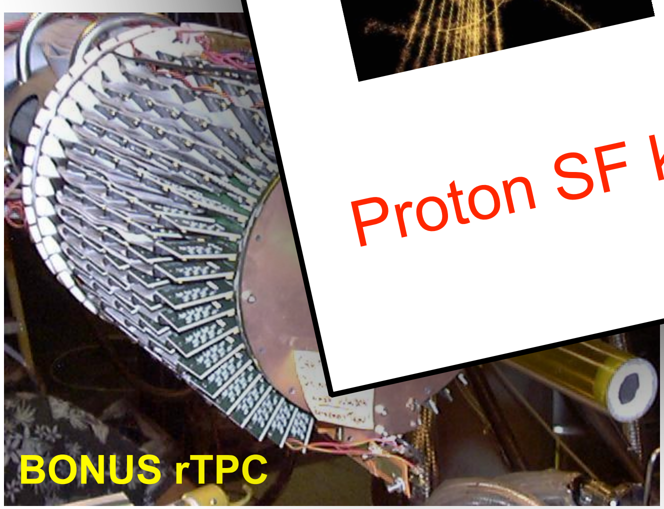
… p_S

Nucl. Instrum. Meth. A592 (2008) 273-286
Phys. Rev. Lett. 108 (2012) 199902
Phys. Rev. C89 (2014) 045206 – editor's suggestion
Phys. Rev. C92 (2015) 1, 015211
Phys. Rev. C91 (2015) 5, 055206



↕ neutron

Proton SF known very well…light mesons?



…nts

…n valence structure (F_2^n)

- global PDF fits; EMC effect in D; neutron duality

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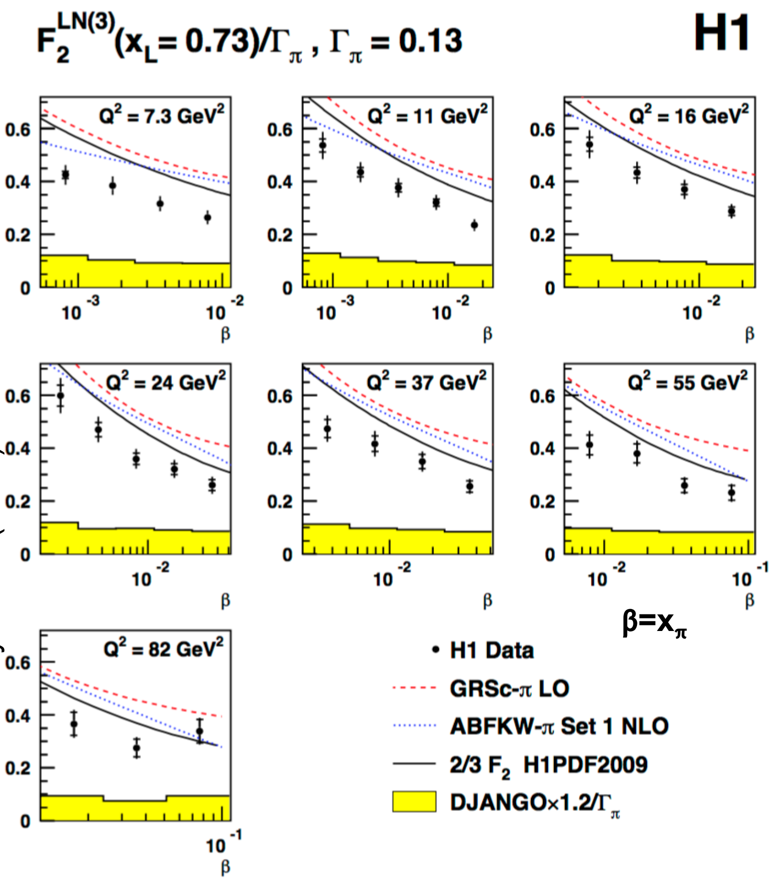
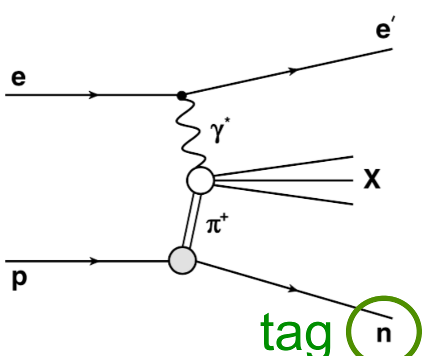


Eur. Phys. J. C (2010) 68: 381-399

Diffractive scattering, forward detectors



HERA Tagged DIS

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

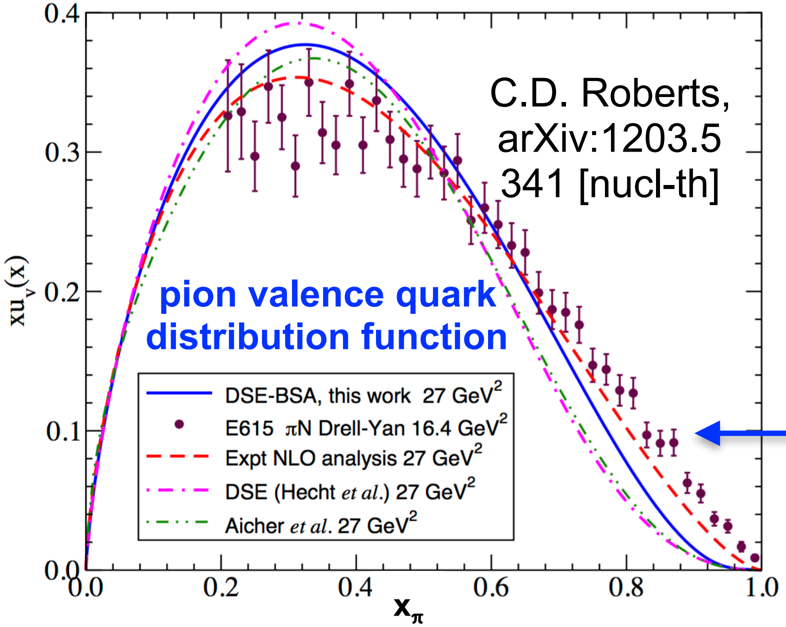
- Pion sea region
- Low Bjorken x, high Q^2
- $1.5e^{-4} < x < 3.0e^{-2}$, $6 < Q^2 < 100 GeV^2$

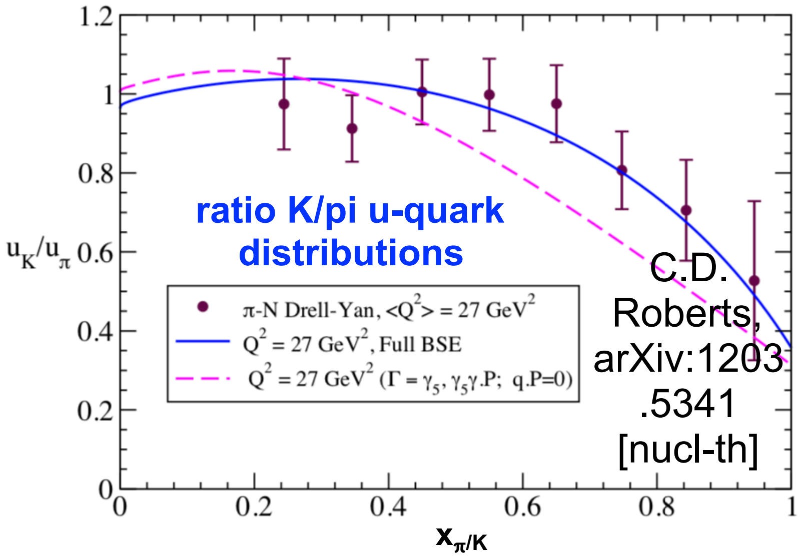
- DIS with forward going neutrons dominated by one pion exchange
- Charged pion SF extracted

TDIS

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

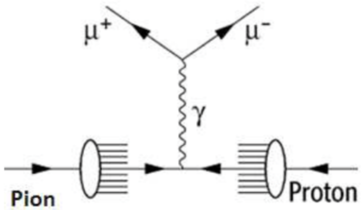
Previous Data for Pion/Kaon Structure





Valence region - Drell Yan

- e.g. CERN NA3
- FNAL E615 $\pi^- + N \rightarrow \mu^+ + \mu^- + X$ (shown)
- Data sparse
- Especially sparse for kaon
- Models tend to disagree at high x
- $\sim(1-x_\pi)$ as $x_\pi \rightarrow 1$ → structureless model, pQCD $(1-x_\pi)^2$

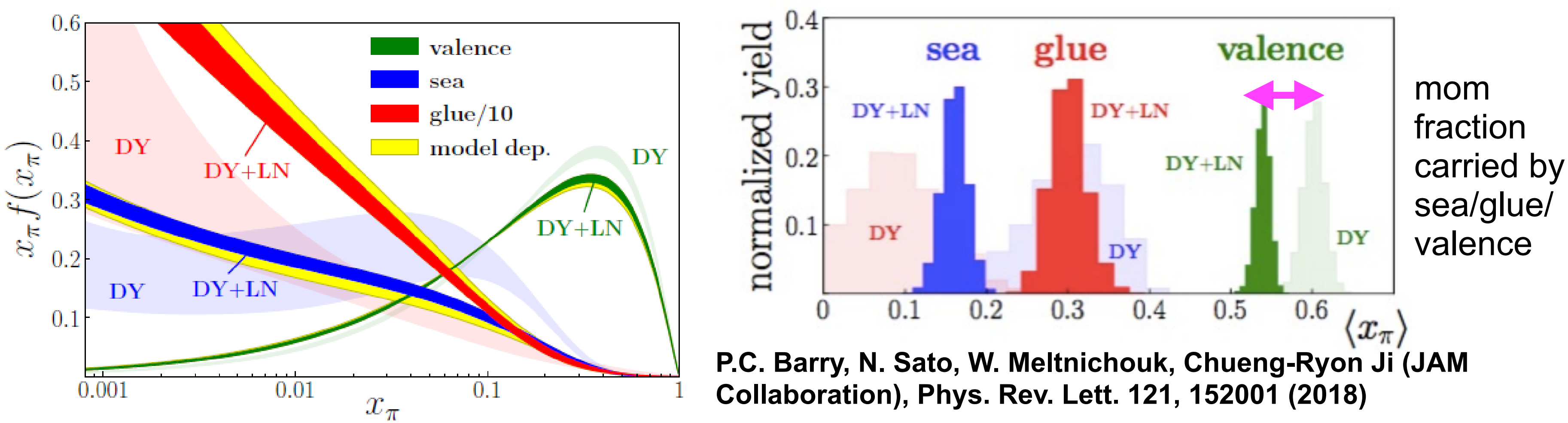


TDIS

- Independent cross-check at overlapping kinematics, more data
- Help resolve tensions for global PDF fits at high x (N. Sato et al. arXiv: 1804.01965 (2018))
- Extend to neutral pions

PDFs and Requirement for More Data

- Combined HERA/DY analysis for PDF fitting, w/ novel MC technique for uncertainties
- Non-overlapping uncertainties - tension at large x



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

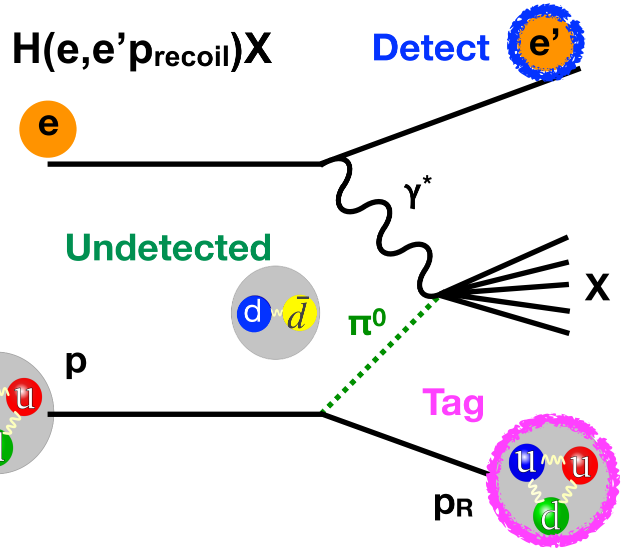
- Recent different basis light front quantisation (BFLQ) technique finds agreement in PDF evolution between DY and HERA
  - Jiangshan Lan, Chandan Mondal, Shaoyang Jia, Xingbo Zhao, James P. Vary, arXiv:1907.01509 (2019)

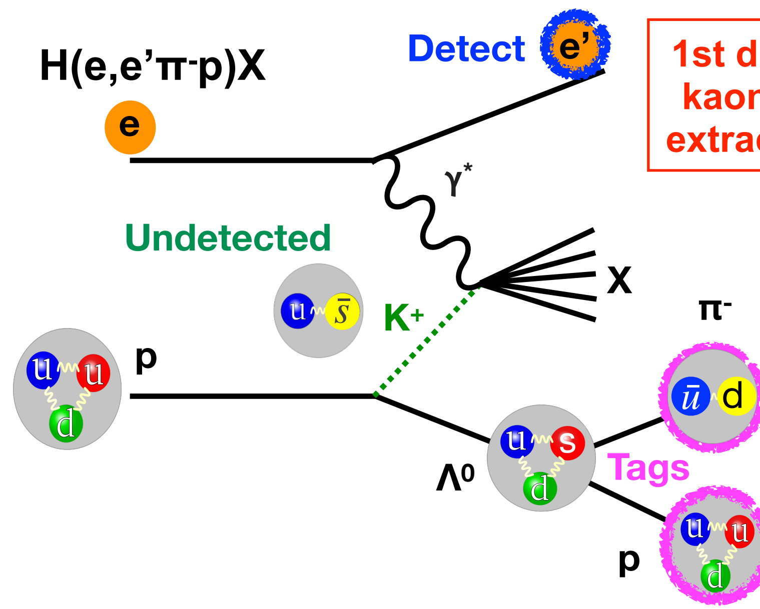
- More data needed to resolve tensions

Thanks C. Keppel

TDIS Measurements

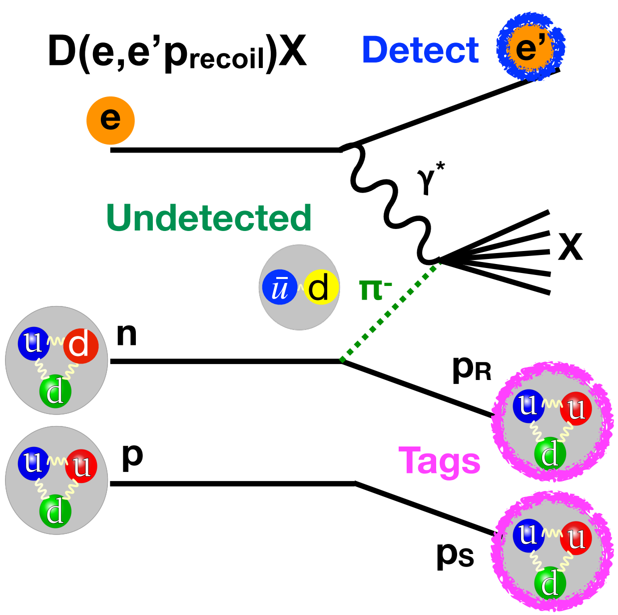
1st direct neutral pion SF extraction





1st direct kaon SF extraction

Help resolve QCD model tensions for charged pion



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

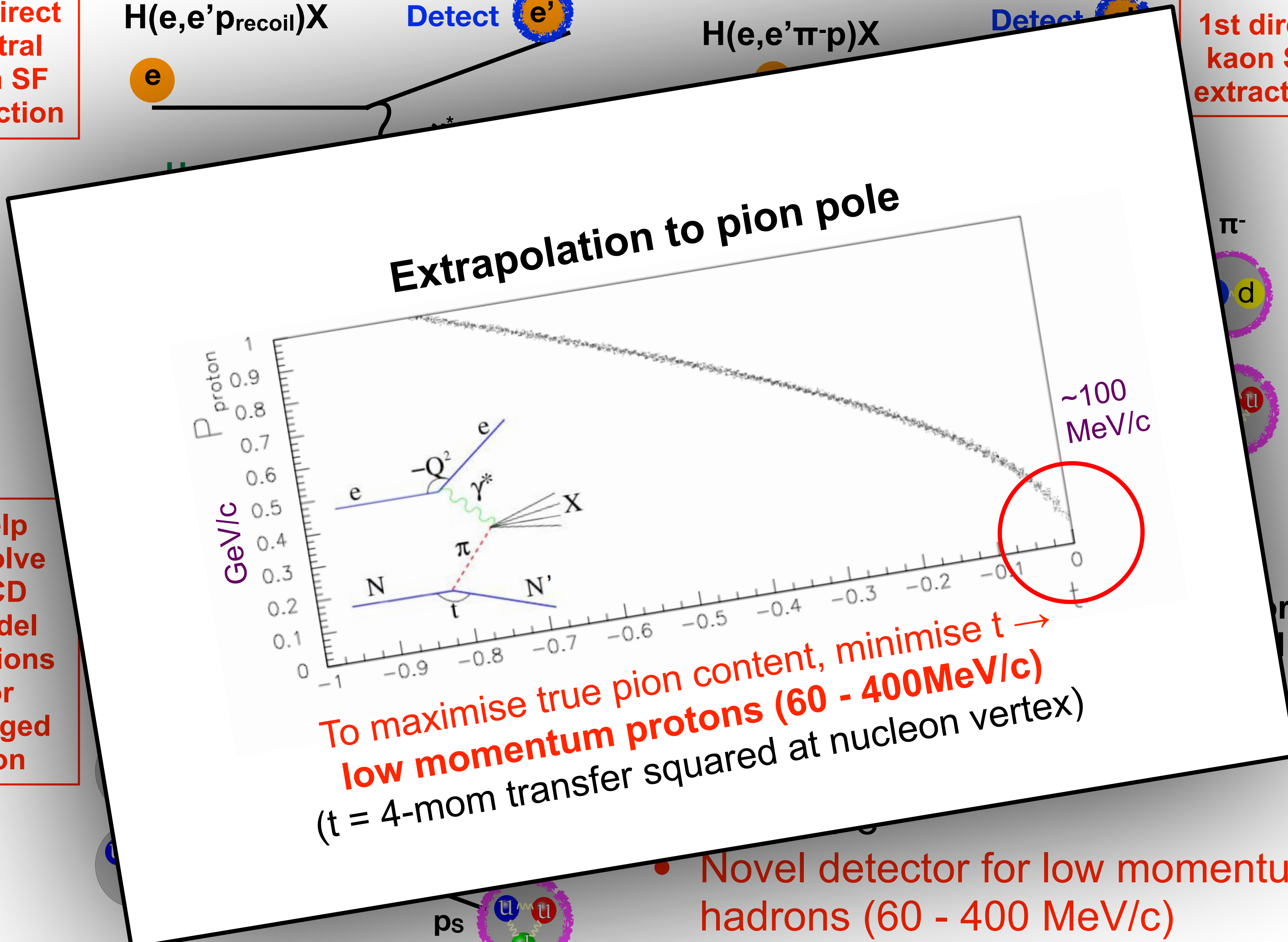
- **DIS regime**
- **Kinematics optimised for meson cloud**

1st direct neutral pion SF extraction

H(e,e'p_recoil)X

H(e,e'π-p)X

1st direct kaon SF extraction

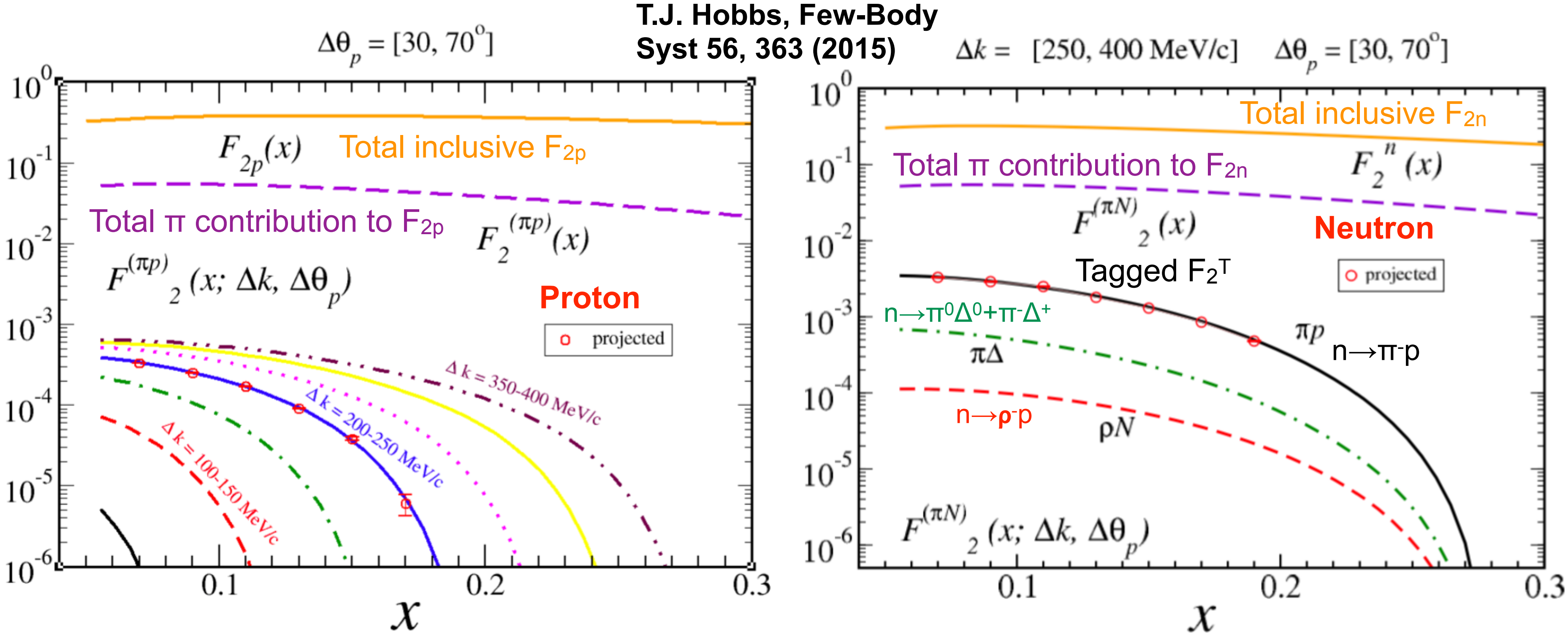


Help resolve QCD model tensions for charged pion

- Novel detector for low momentum hadrons (60 - 400 MeV/c)

SF Extraction and High Luminosity

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

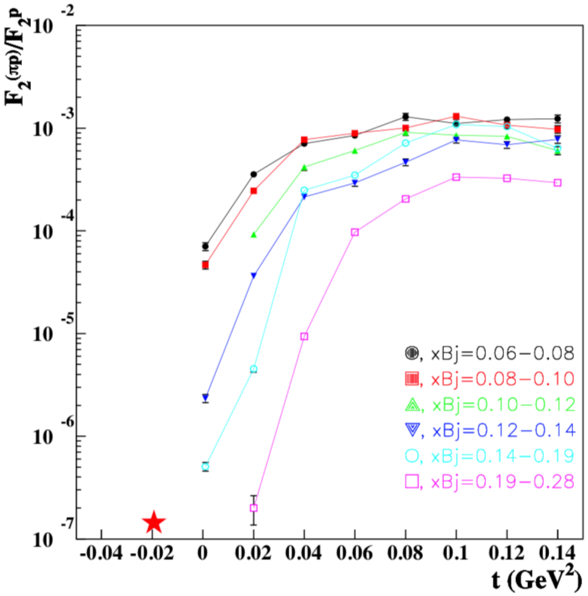


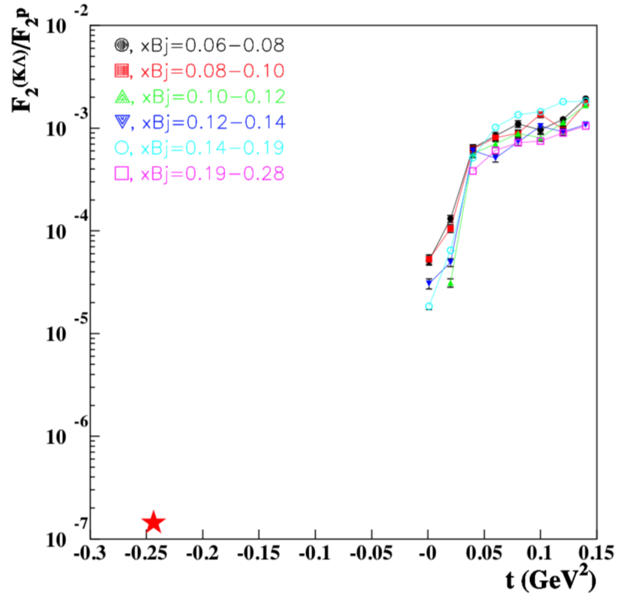
- Predictions based on phenomenological pion cloud model
- Tagged orders of magnitude smaller than DIS signal → high luminosity
- Ratio of tagged to total DIS cross-sections (reduce systematic uncertainties)

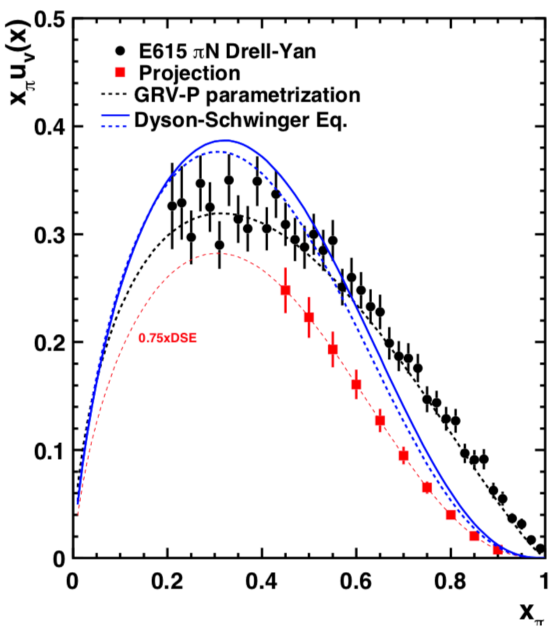
$$R^T = \frac{d^4\sigma(ep \to e'Xp')}{dxdQ^2dzdt} \Big/ \frac{d^2\sigma(ep \to e'X)}{dxdQ^2} \Delta z \Delta t \sim \frac{F_2^T(x,Q^2,z,t)}{F_2^p(x,Q^2)} \Delta z \Delta t$$

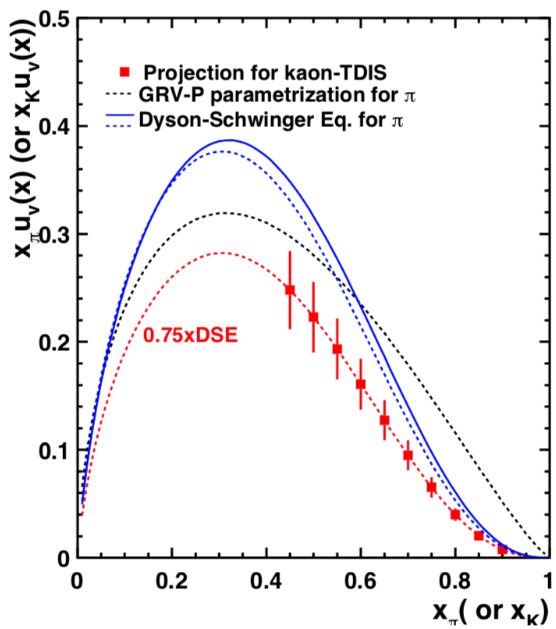
$$F_2^T(x,Q^2,z,t) = \frac{R^T}{\Delta z \Delta t} F_2^p(x,Q^2)$$

Projected Results









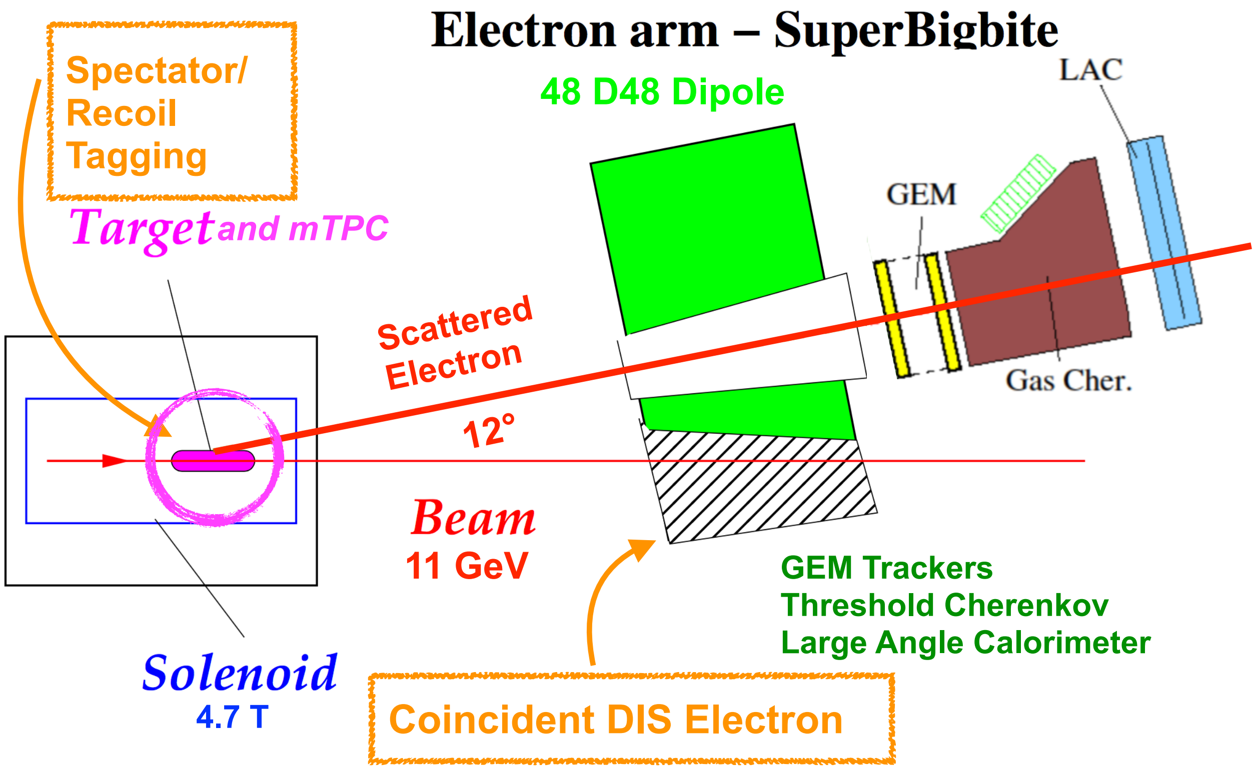
- Projected results
  - T.J. Hobbs, Few-Body Syst 56, 363 (2015)
  - H. Holtmann et al., Nucl. Phys. A 596, 631 (1996)
  - W. Melnitchouk, A.W. Thomas, Z. Phys. A 353, 311 (1995)

- Kinematical mapping of SF possible
- Low momentum reach for recoiling hadrons essential to obtain shape of curve

- Projected valence quark distributions

- Statistical, systematic uncertainties

TDIS Experimental Set Up



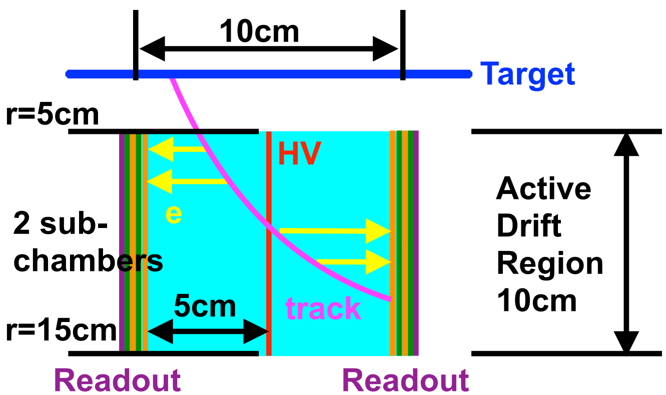
Very challenging measurement… Lots of exciting activities/R&D on-going!

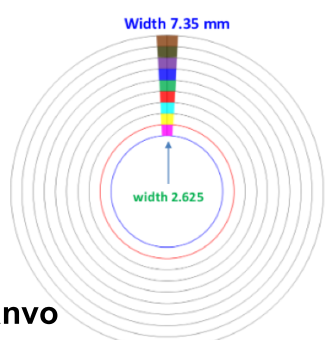
- Hall A - unique conditions for these rare processes
- High density H/D target; 40cm length; 1cm diameter
- **Novel multiple Time Projection Chamber (mTPC) for tagging**
- mTPC within solenoid
- SBS for e' (~50msr at 12°)
- 11 GeV e^- beam, 50μA, high luminosity $3x10^{36}cm^{-2}/s^{-1}$

➡ High rates (hundreds of MHz in overlapping kinematics)

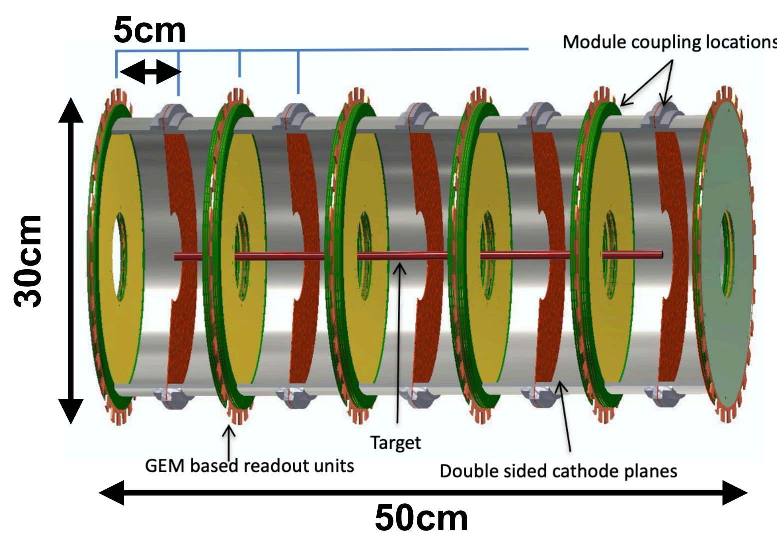
mTPC Design

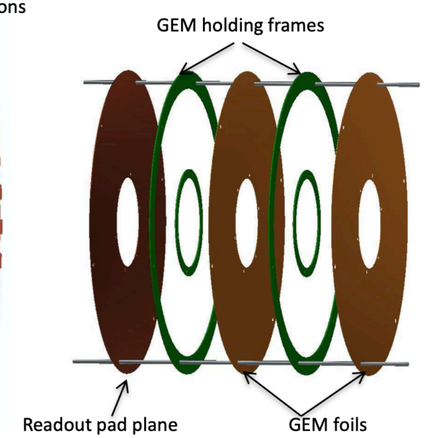
- UVa (N. Liyanage, K. Gnanvo et al)
- Plan to start prototype chamber 2020
- Solenoid for momentum analysis
- 10 x 5cm chambers filled with low density gas
- E-field parallel beam for ionisation drift
  - drift times ~couple of μs
- Double layer GEMs w/ segmented pad readout
  - pads smaller @ inner radii
- Highest rate TPC of its size - cutting edge!
  - ~10MHz background per chamber
  - ~<1MHz/readout channel



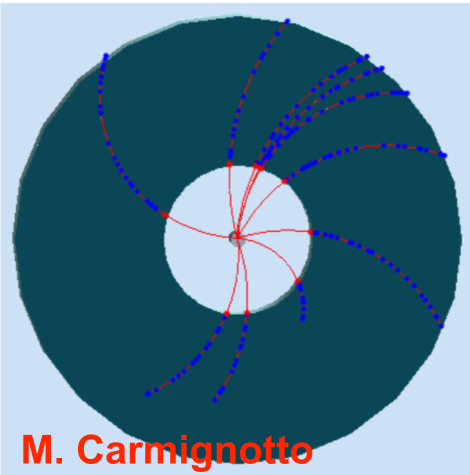


K. Gnanvo

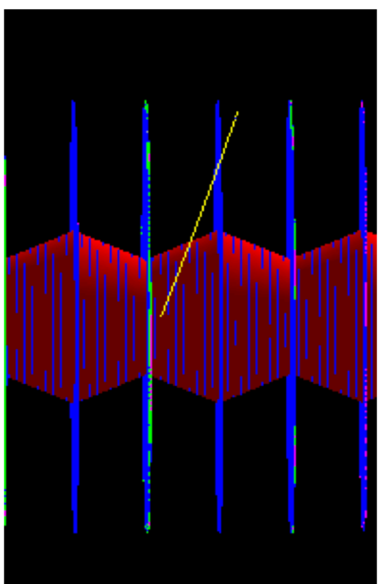


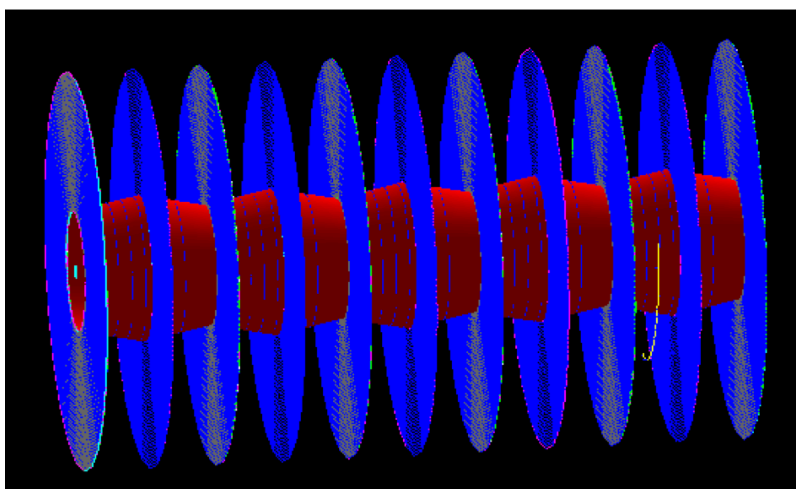


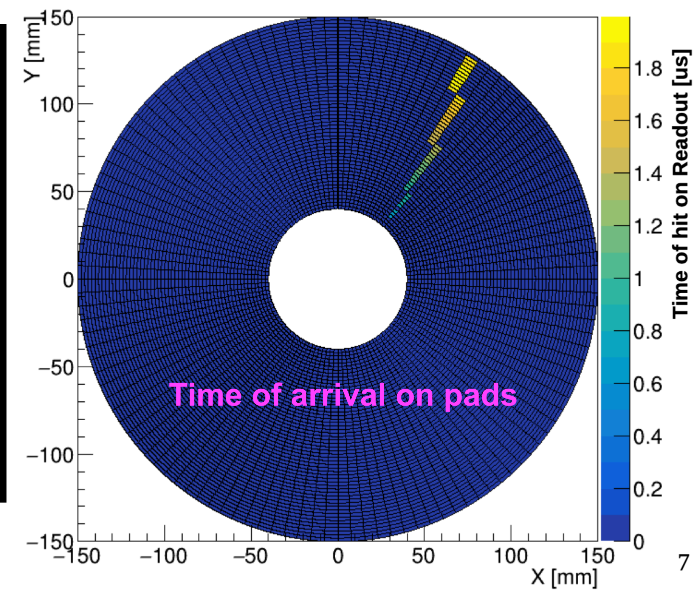
N. Liyanage



- mTPC modelled in g4sbs (R. Montgomery, E. Fuchey)
- Example current studies on-going:
  - conical design to improve z-vertex resolution for ambiguous tracks (concept B. Wojtsekhowski)
  - accidentals plus physics event generator (C. Ayerbe) and track reco (S. Wood, A. Tadepali)
  - accidentals: H2 - elastic protons; D2 photo-disintegration/QE scattering/delta production and decay into pp







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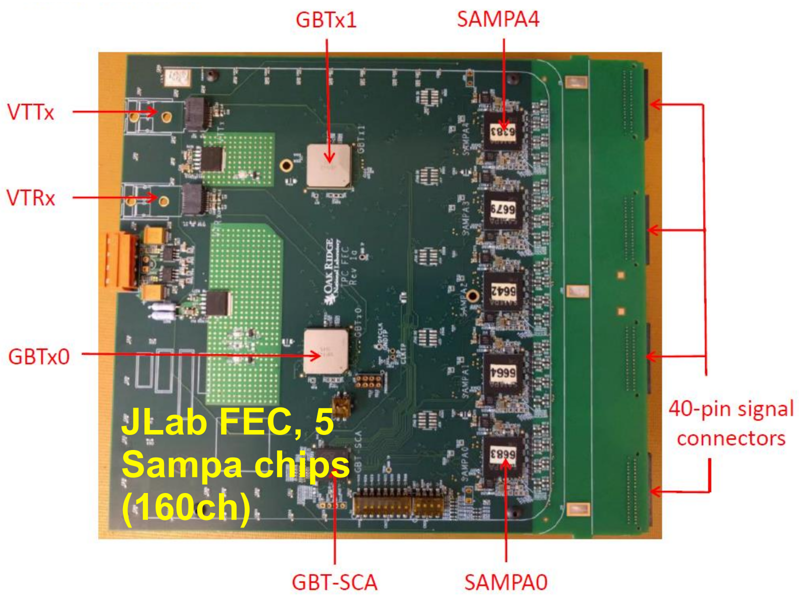
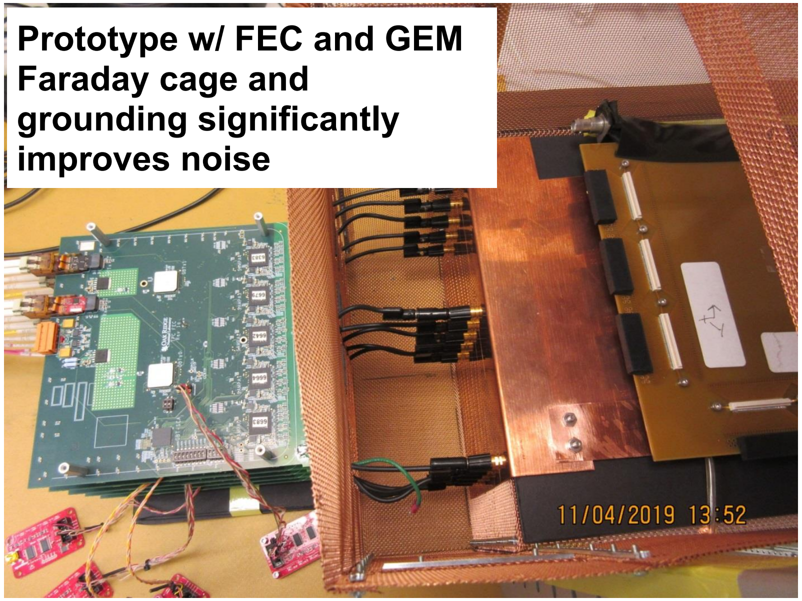
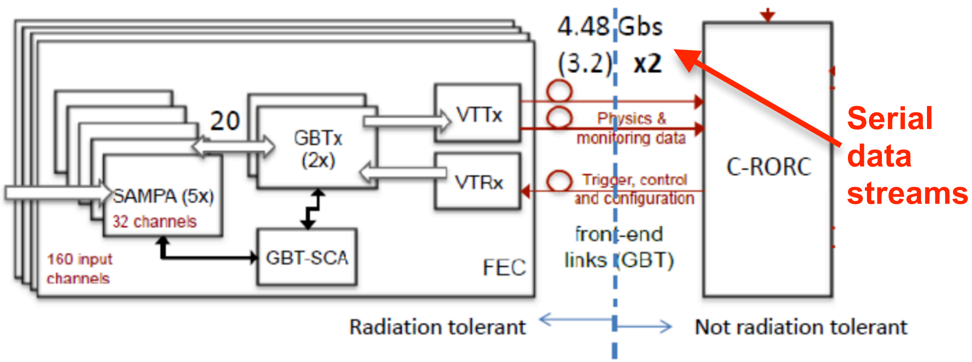
Streaming/High Rate GEM Data Acquisition Development



- Design/prototyping/testing @JLab (E. Jastrzembski, E. Pooser, G. Heyes)
- SAMPA chip (Univ. Sao Paolo) and streaming readout developed for ALICE TPC upgrade
- SAMPA - charge-sensitive pre-amp, ADC, DSP (zero-suppresion e.g.)

- Streaming/triggerless mode successfully tested summer 2019!



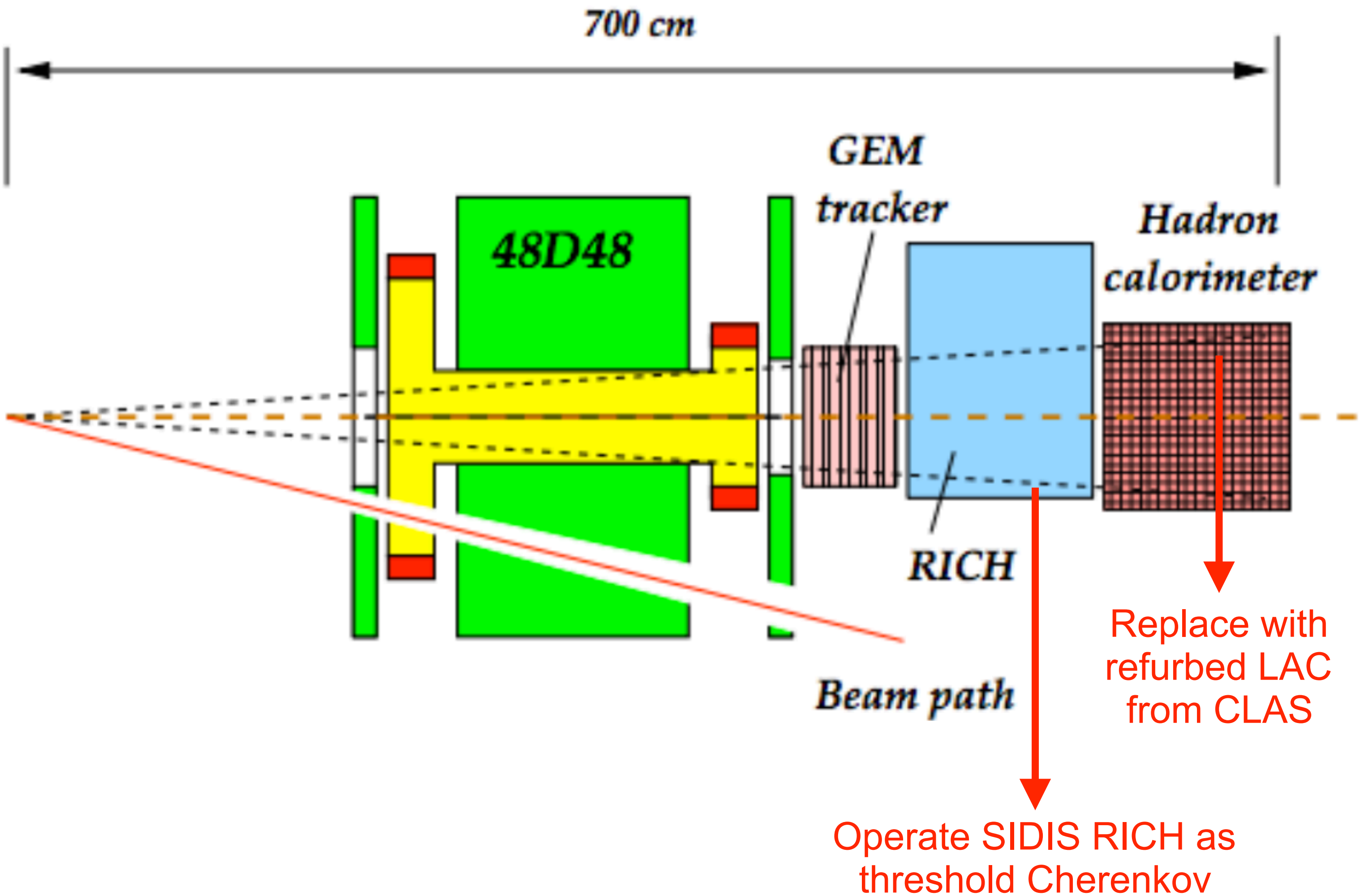


FEC – Front End Card (160 ch / FEC) (5 FEC = 800 ch)
C-RORC – Common Read Out Receiver Card (PCIe)
GBTx – Giga Bit Transceivers
GBT-SCA – GBTx Slow Controls Adapter
VTTx, VTRx – Fiber optic transceivers

Thanks E. Jastrzembski

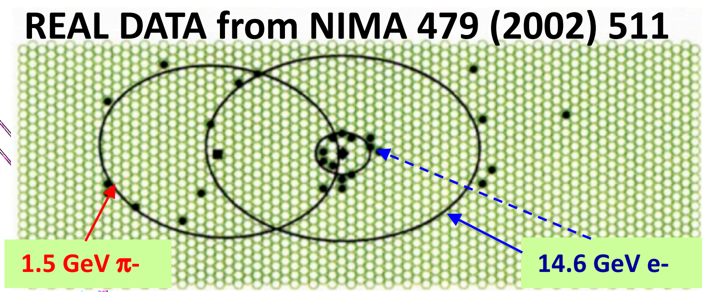
SBS as e' Detector

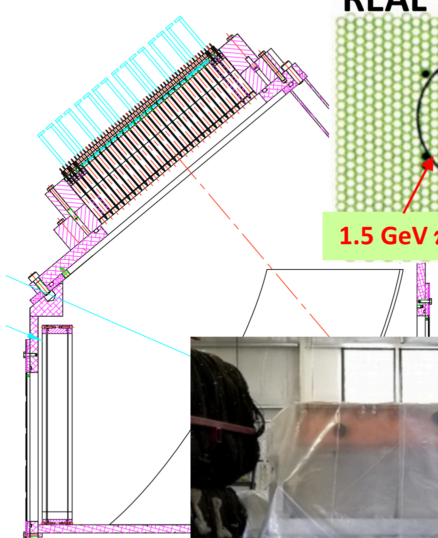
- SBS reconfigured from hadron to e' detector
  - 5 GEM planes (from SBS GEp, 70µm resolution)
  - For sufficient PID/pion rejection and e' trigger:
    - RICH as threshold Cherenkov and refurbished CLAS LAC

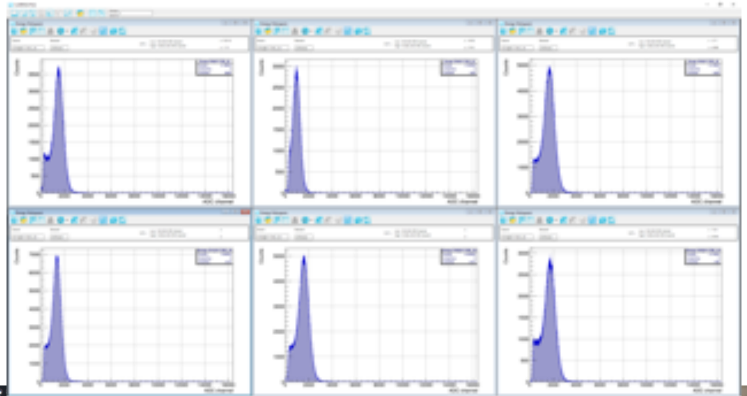


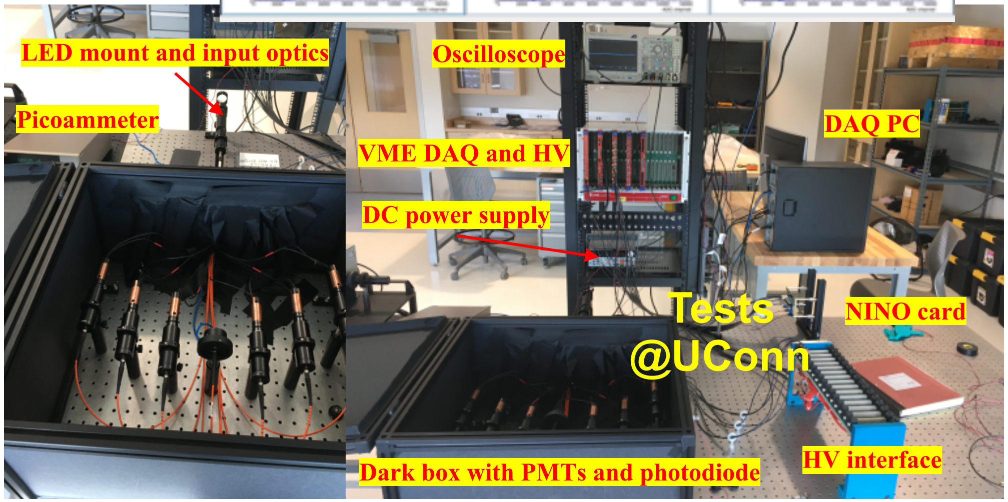
RICH Detector Preparations

- Half HERMES dual-radiator (gas/aerogel) RICH being refurbished by UConn for π/K/p PID in E12-09-018 (SIDIS)
- Stored ESB since Apr 2018; PMTs/spare aerogel @UConn for tests; will look for space to test at JLab until SIDIS install
- TDIS - fill w/ gas only (CO_2) and use as threshold Cherenkov







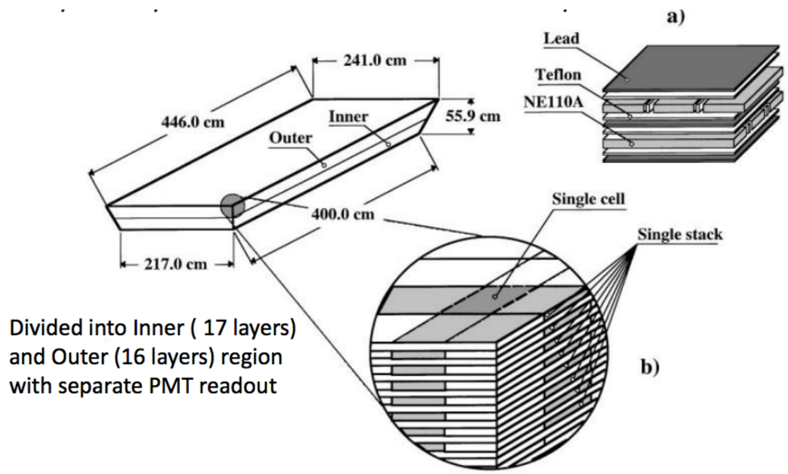


Thanks A. Puckett

LAC Preparations

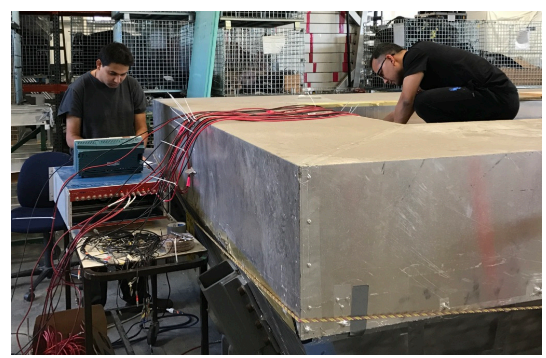
M. Anghinolfi et al., NIM A537, 562 (2005)

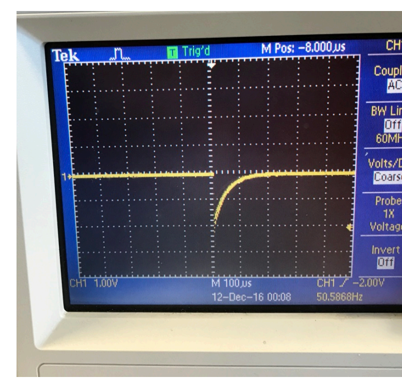
M. Anghinolfi et al., NIM A447, 424 (2000)



- CLAS (built by INFN)
- Lead/scintillator sandwich
- 4m x 2.2m active area
- position resolution 2.9cm
- time resolution 250ps
- π rejection factor ~10-20

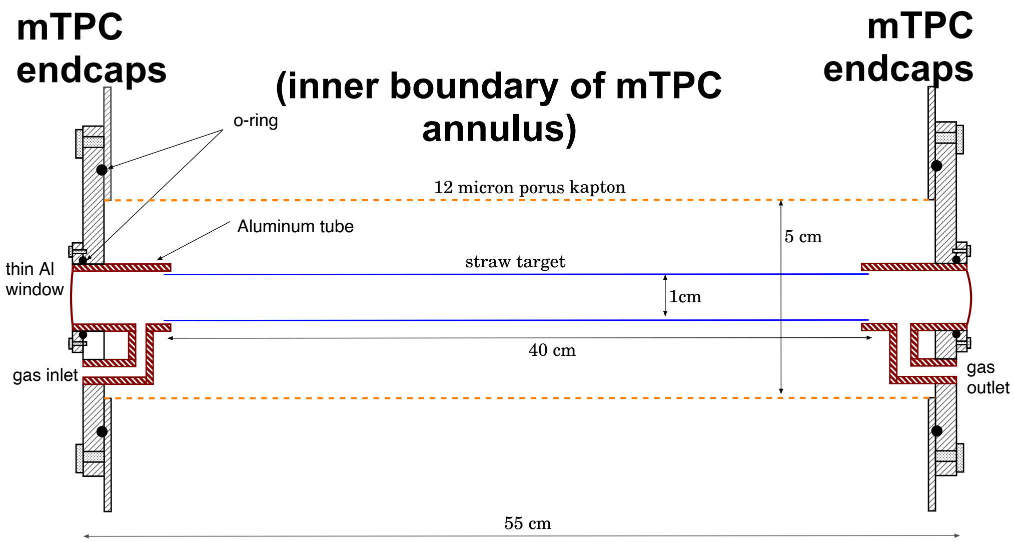
- Refurbishment underway by MSU and S. Malace
- Moved to ESB 2016
- PMTs tested 2017, broken ones replaced
- PMT characterisation eventual light-proofing/re-sealing underway
- Looking at FADC e-trigger w/ LAC





Thanks D. Dutta

Target Studies



- Re-design of target for mTPC (D. Dutta et al, MSU)
- Cold target → room temperature
- Prototyping, assembly and pressure testing @MSU

- First double layer straw (rolling technique, 24μm thick walls = 2x 12μm kapton)
- End-caps, pressure testing in progress
- Upcoming uniformity study@JLab

Thanks D. Dutta

Summary

- TDIS - direct probe of nucleon's mesonic content
  - Effective targets not readily found in nature

- Understand meson structure on deeper level
  - tag hard scattering from nucleon's meson cloud
  - both pion and kaon SF (expected high impact results)

- Very challenging measurement - **pioneering** experimental techniques
- e.g. mTPC/continuous readout for extremely high rates

- Pave way for spectator tagging and new TDIS era at EIC
  - Community working towards this (past and upcoming workshops)
  - e.g. Pion and Kaon Structure at an Electron Ion Collider arXiv:1907.08218v1 [nucl-ex]

Thanks for your attention, and to TDIS collab and TDIS colleagues for input/material (esp C. Keppel, E. Jasterzembski, D. Dutta, A. Puckett)

Phenomenological Pion Cloud Model and TDIS

- Projected rates/beam time/results used 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 nucleon F_2 from scattering off virtual pion:

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

(z = light cone momentum fraction of initial nucleon carried by pion)

- Unintegrated distribution function (light-cone momentum distribution of π 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 tagged SF is un-integrated product:

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

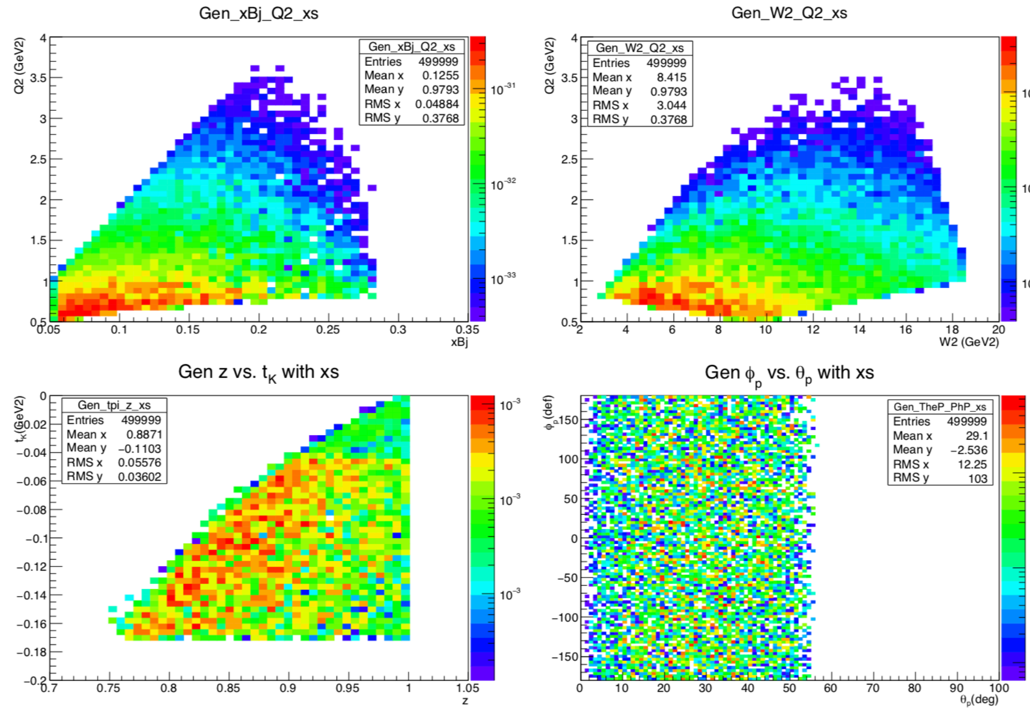
Pion "flux" Pion SF

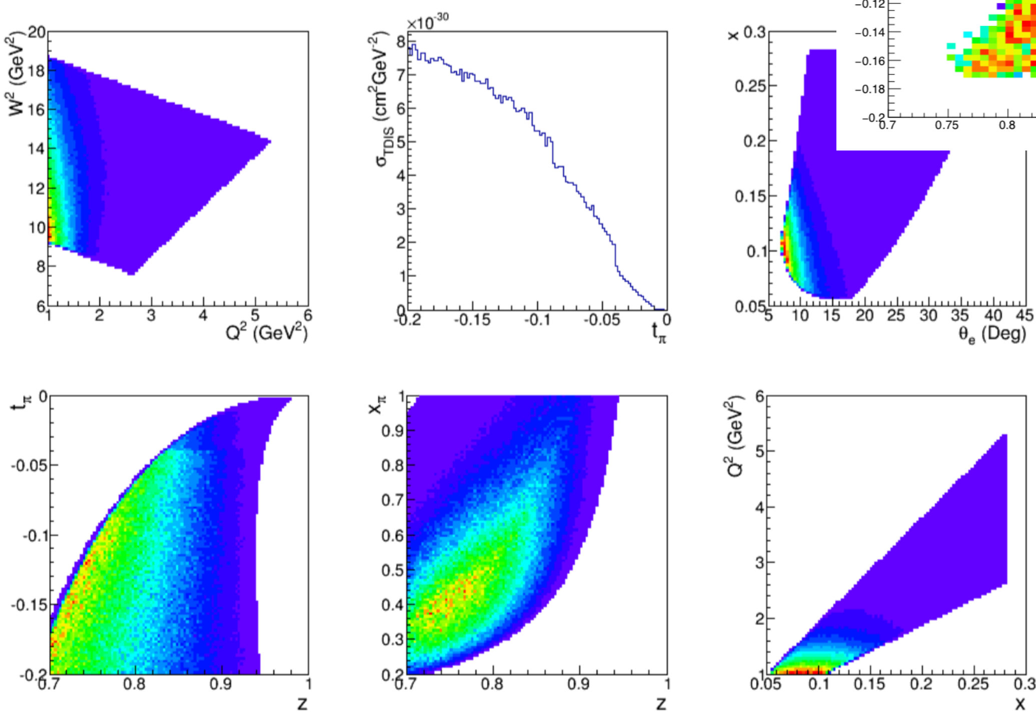
- Interested in $z \lesssim 0.2$; $x < z \rightarrow$ defines maximum x, Q^2 (beam 11GeV)

TDIS Kinematic Reach in Hall A

- Event generators written for both pion/kaon TDIS

- Right, kaon TDIS weighted by cross-section
- Left, pion TDIS weighted by cross-section (H target)





- x-range up to ~0.1
- After x-range optimised Q^2 reach fixed by 11GeV beam
- High W^2, M_x^2 - DIS regime

- **Similar reach for both pion/kaon TDIS and optimised for probing mesonic cloud**

Slide from C. Keppel

Extrapolation to the pole

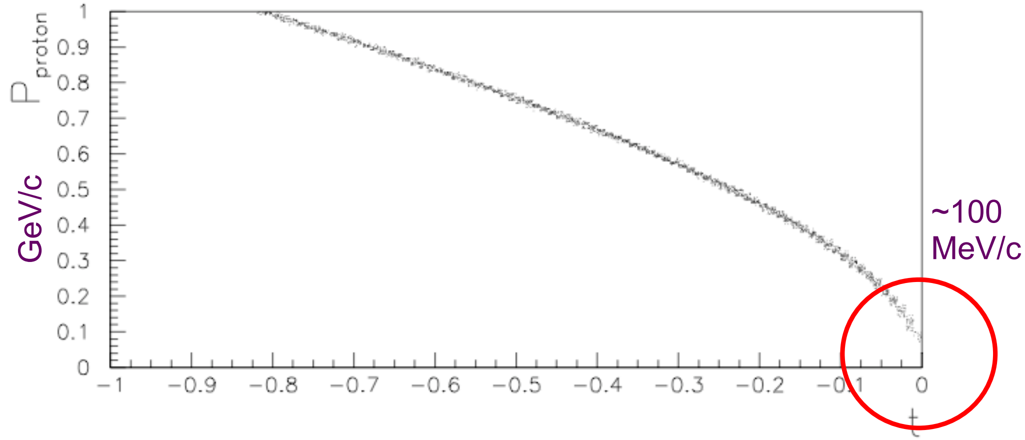
Need range of low momentum protons

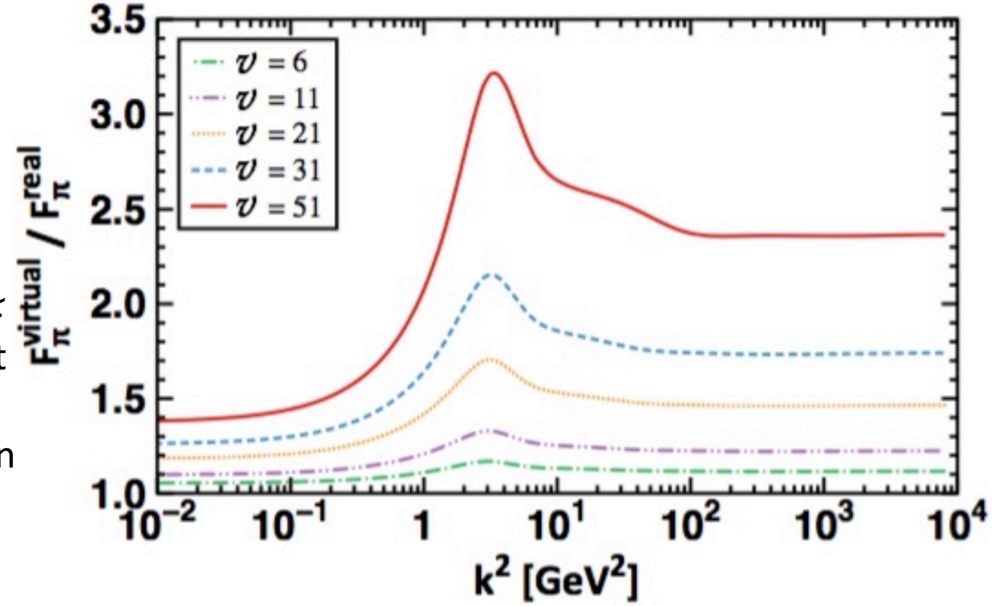
The ratio of off-shell to on-shell pion electromagnetic form factor

Si-Xue Qin, Chen Chen, Cedric Mezrag, Craig D. Roberts
Phys.Rev. C97 (2018) no.1

"…we demonstrated that for $v < v_S$ ~ 31, which corresponds to −t < ~0.6 GeV^2….the off-shell correlation serves as a valid pion target."

JLab TDIS kinematics best at lowest t values





Like BONUS, a challenging low p proton tag experiment – one low mass detector to rule them all