Meson Structure Studies at EIC

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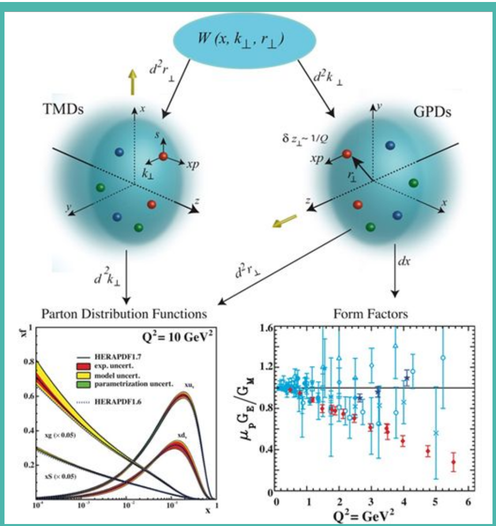
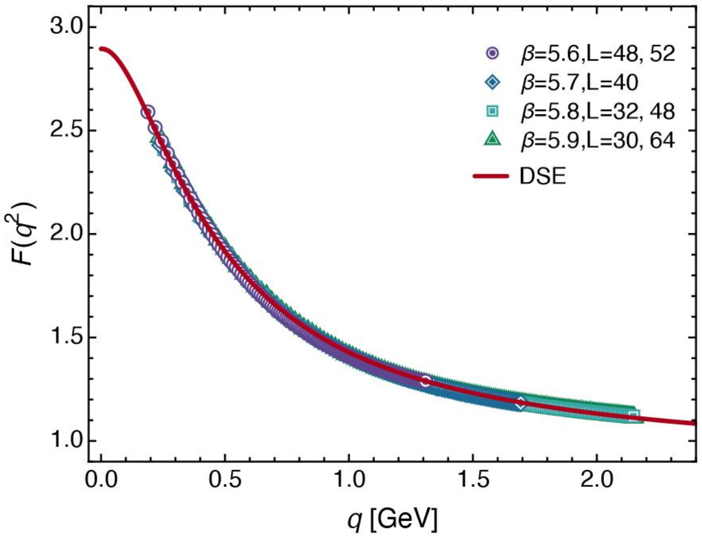
Overview

1. Introduction
2. π^+ Structure Functions at EIC
3. π^+ Form Factors at EIC
4. K^+ Structure at EIC

Introduction



Overview of Pion and Kaon Structure

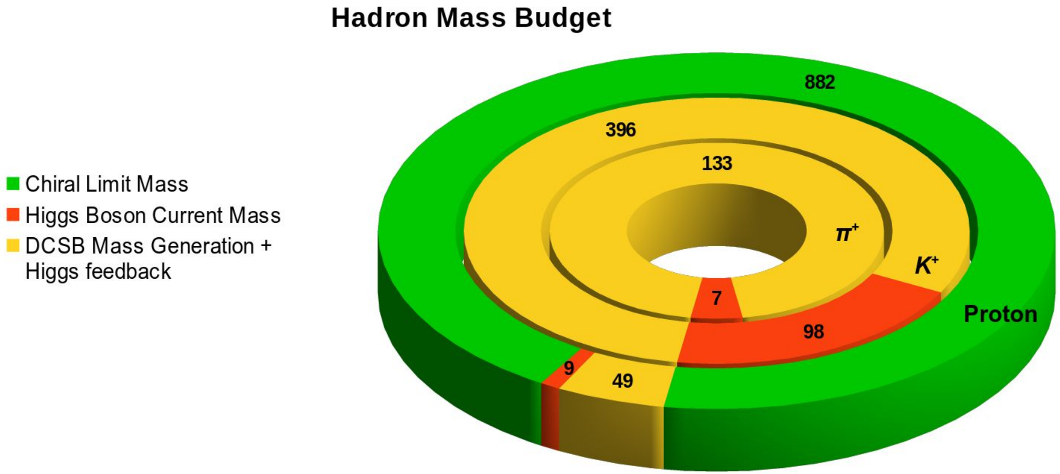


2203.00942 [hep-ph] Few Body Syst. 63 (2022) 2, 42

- The pion is both the lightest bound quark system with a valence $\bar{q}q$ structure
- The kaon is the next simplest system containing strangeness
- Both are Nambu-Goldstone bosons
- There are exact statements from QCD in terms of current quark masses due to PCAC [Phys. Rep. 87 (1982) 77; Phys. Rev. C 56 (1997) 3369; Phys. Lett. B420 (1998) 267]
    - From this, it follows the mass of bound states increase as $\sqrt{m}$ with the mass of the constituents
    - In both DSE and lQCD, the mass function of quarks is the same.

Pion and Kaon Discrepancy

- The mass budgets for the lightest mesons, π and K, differ significantly from those of heavy nucleons and even from each other!
- By comparing distributions of light versus strange quarks within mesons…
  - We can measure signals of EHM

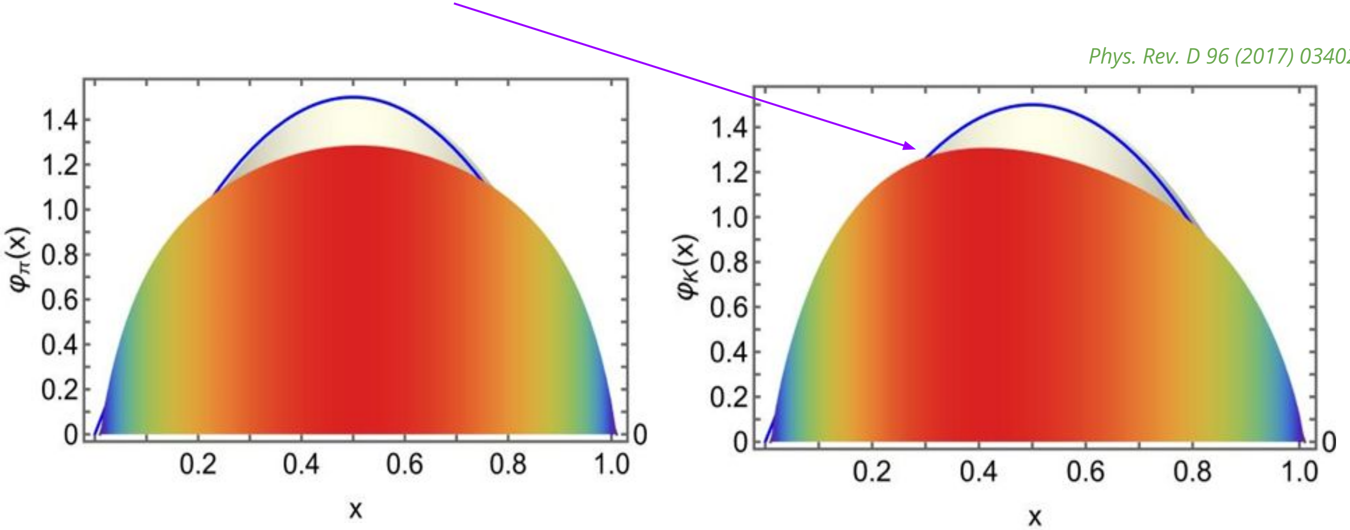


Journal of Physics G (2021) arXiv:2102.11788

Kaon Strangeness

- Data suggests that heavier flavor quark mass is primarily generated through the Higgs mechanism
- The kaon sits in a unique position because its quark composition is both light and heavy ($u\bar{s}$)
  - EHM generates broadening in both π & K
  - EHM + Higgs interference is responsible for skewing in kaon

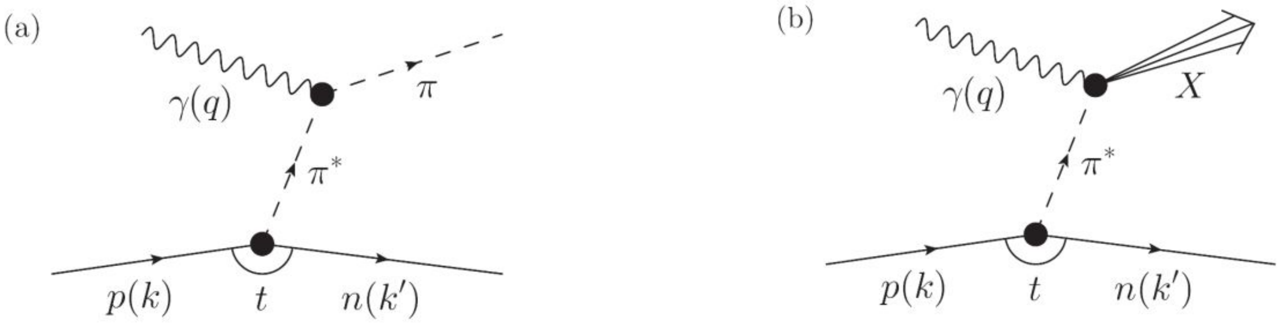
Phys. Rev. D 96 (2017) 034024/1-8



Broadening can be verified, e.g., in π and K elastic form factor measurements at large Q^2

Accessing the Pion and Kaon Structure

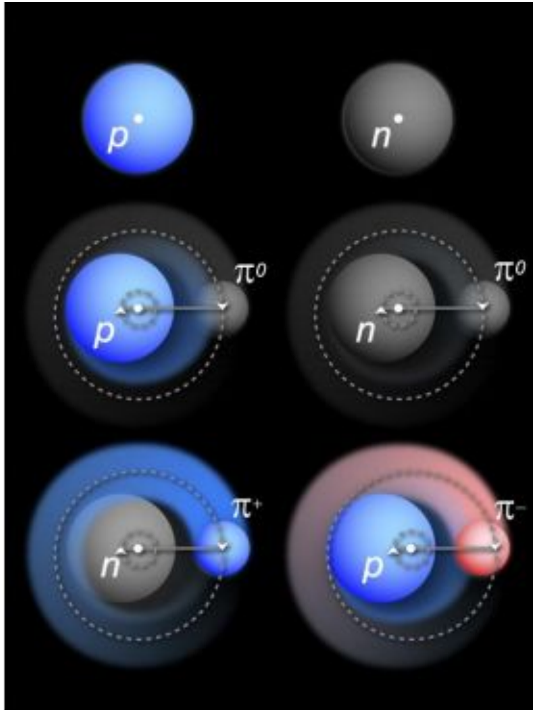
- At low -t values, the cross-section displays behavior characteristic of meson pole dominance
  - The Sullivan process can provide reliable access to a meson target in this region
- Experimental studies over the last decade have given confidence in the electroproduction method yielding the physical pion form factor



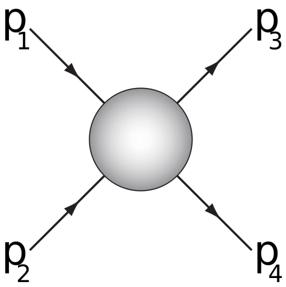
Pion cloud can access a) Elastic Form Factor b) PDF

Arlene C. Aguilar, et al., Eur. Phy. J. A (2019) DOI:10.1140/epja/i2019-12885-0

Sullivan Process

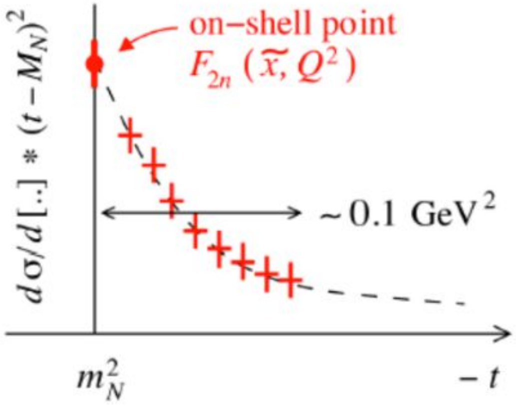


- Sullivan process is probing the meson cloud of the proton to study the structure of pions and kaons.
- At low t, the cross-section of the forward nucleon exhibits characteristics consistent with meson pole dominance.
- Meson pole dominance implies that the scattering behavior observed is primarily governed by the exchange of mesons
    - Leading to resonant enhancements in the scattering cross-sections



$$t = (p_1 - p_3)^2 = (p_4 - p_2)^2$$

Off-Shell Considerations

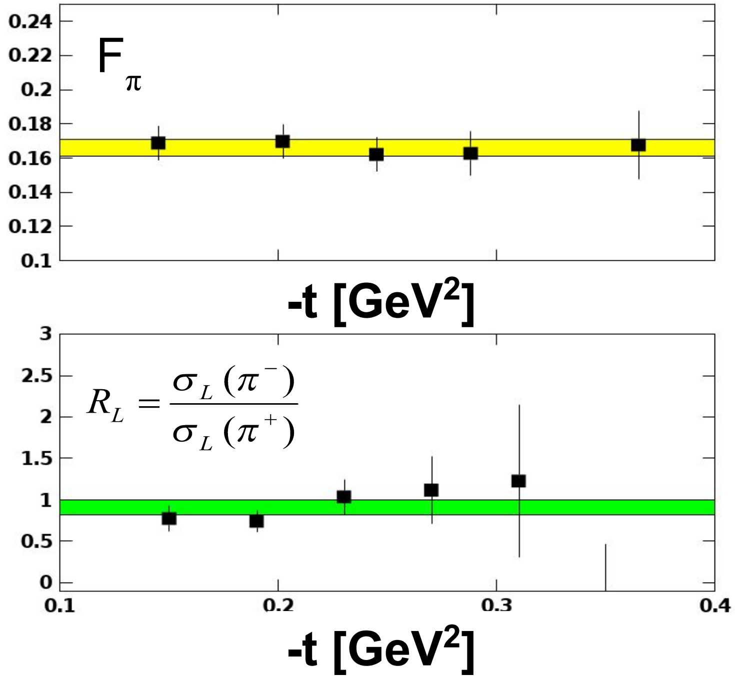


S-X Qin, C. Chen, C. Mezrag, C.D. Roberts, Phys. Rev. C 97 (2018) 015203

- A concern of using the Sullivan process is the off-shell considerations that arise from using a virtual (off-shell) particle as a target.
- Sullivan process can provide reliable access to a meson target as t becomes space-like
- If the pole associated with the ground-state meson remains the dominant feature of the process…
    - The structure of the related correlation evolves slowly and smoothly with virtuality
- A well-constrained experimental analysis should be reliable
    - For the pion when $-t \leq 0.6$ GeV^2
    - For the kaon when $-t \leq 0.9$ GeV^2

Experimental Validation

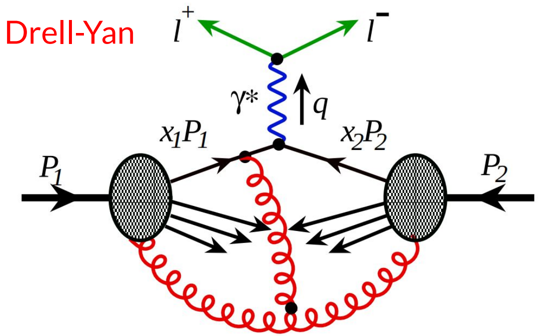
- Data is taken covering a range in t
- Compare this data with phenomenological and theoretical expectations
  - F_π values do not depend on -t which gives confidence in applicability of model to the kinematic regime of the data
- Verify that the pion pole diagram is the dominant contribution in the reaction mechanism
  - R_L (= $\sigma_L(\pi^-)/\sigma_L(\pi^+)$) approaches the pion charge ratio, consistent with pion pole dominance

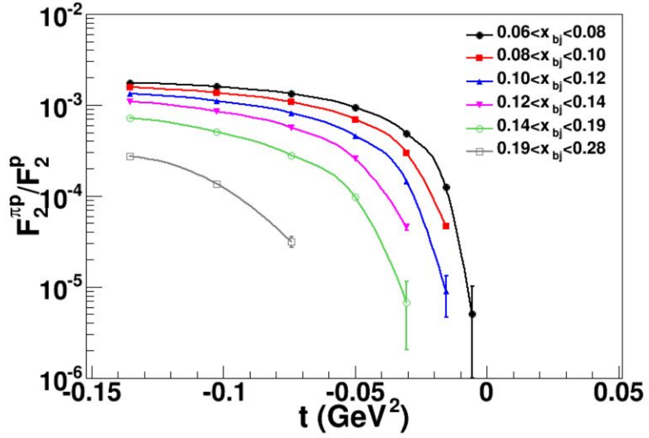


T. Horn, C.D. Roberts, J. Phys. G43 (2016) no.7, 073001
G. Huber et al, PRL112 (2014)182501
R. J. Perry et al., arXiV:1811.09356 (2019)

EIC Capabilities

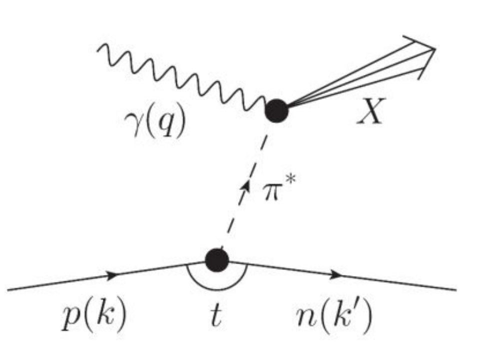
- L_{EIC} = 10^{34} e-nucleons/cm^2/s = 1000 x L_{HERA}
- Fraction of proton wave function related to pion Sullivan process is roughly 10^{-3} for a small –t bin (0.02)
  - Pion data at EIC should be comparable or better than the proton data at HERA, or the 3D nucleon structure data at COMPASS
- By mapping pion (kaon) structure for –t < 0.6 (0.9) GeV^2, we gain at least a decade as compared to HERA/COMPASS
- Consistency checks with complementary COMPASS++/AMBER Drell-Yan data can show process-independence of pion structure information





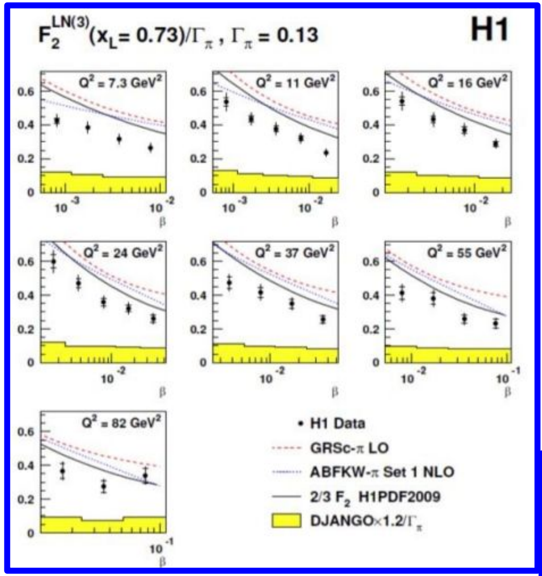
Jefferson Lab TDIS Collaboration, JLab Experiment C12-15-005
Journal of Physics G (2021) arXiv:2102.11788

π^+ Structure Functions at EIC

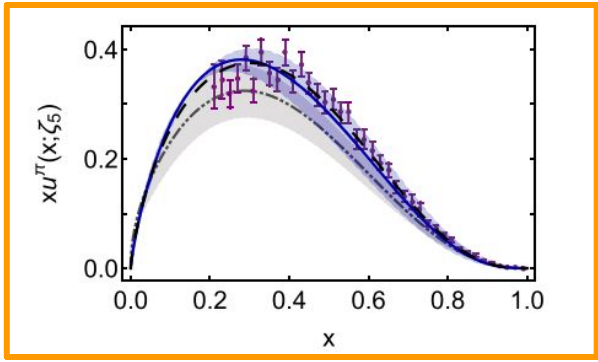


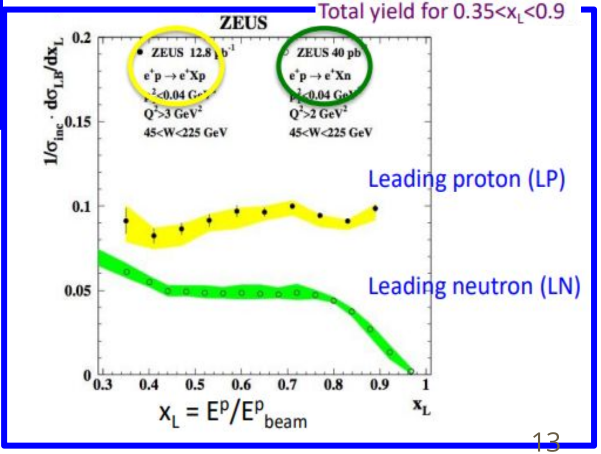
Existing Meson Structure Function Measurements

- Knowledge of the pion structure function is very limited...
  - At low x - HERA TDIS data through Sullivan process
  - At large x - Pionic Drell-Yan from nucleons in nuclei



DESY 08-176 JHEP06 (2009) 74
Eur. Phy. J. C (2020) DOI:10.1140/epjc/s10052-020-08578-4

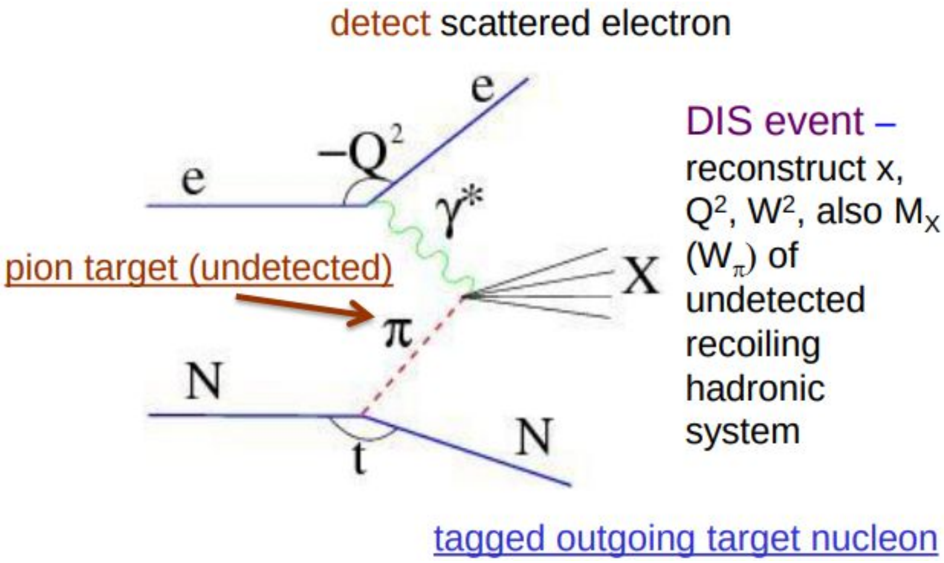


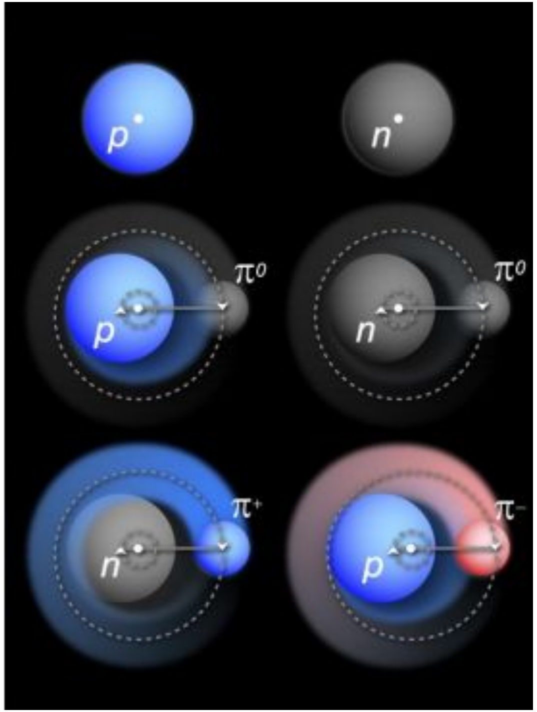


- One pion exchange is the dominant mechanism
  - Can extract pion structure function
  - In practice, use in-depth model and kinematic studies to include rescattering, absorption...

Tagged Deep Inelastic Scattering (TDIS)

- Using the Sullivan process – scattering from nucleon-meson fluctuations

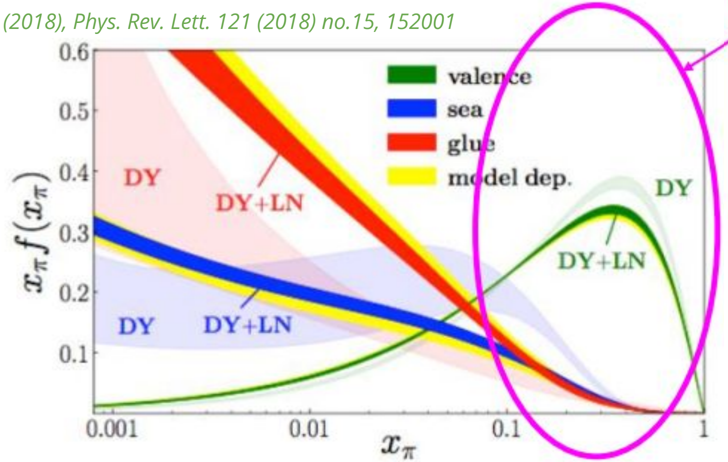




Global Fits: Pion and Kaon Structure Functions

- First MC global QCD analysis of pion PDFs
  - Using Fermilab DY and HERA Leading Neutron data
  - Significant reduction of uncertainties on sea quark and gluon distributions in the pion with inclusion of HERA leading neutron data
  - Implications for “TDIS” (Tagged DIS) experiments at JLab

Barry, Sato, Melnitchouk, Ji (2018), Phys. Rev. Lett. 121 (2018) no.15, 152001

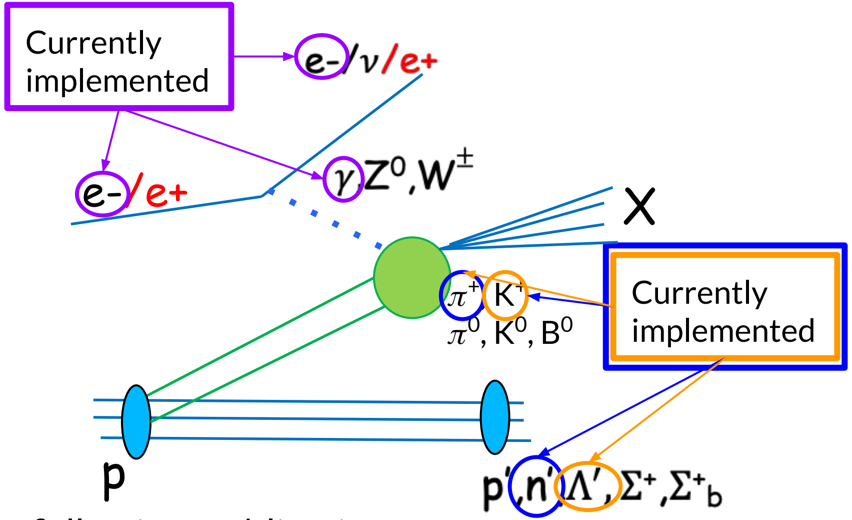


- JLab 12 GeV: Tagged Pion and Kaon TDIS
- Also prospects for kaon DY at COMPASS and pion and kaon LN at EIC

DY = πN Drell-Yan

LN = Leading Neutron

π^+ Structure Functions (F^{π}_2)

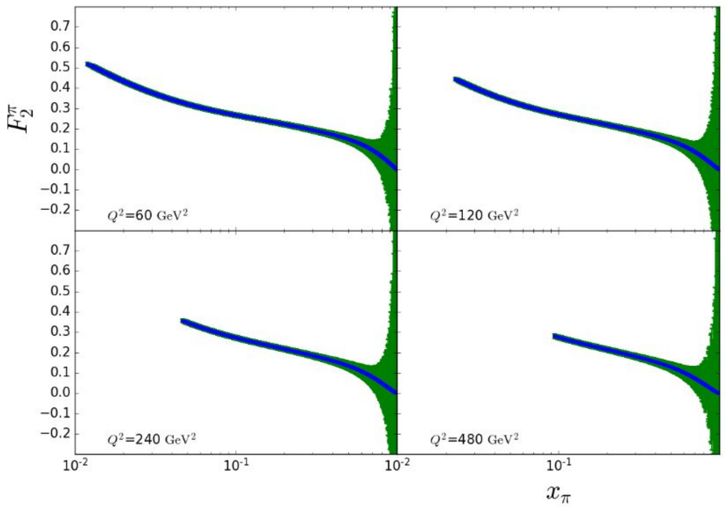


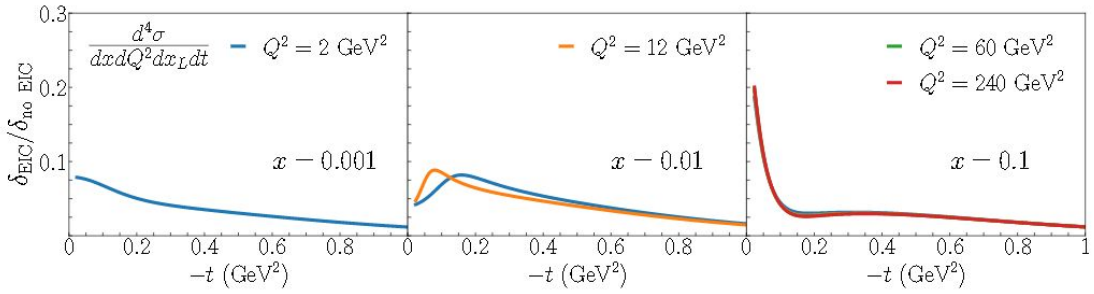
- For projections, a Fast Monte Carlo that includes the Sullivan process is used
  - PDFs, form factor, fragmentation function projections
- Progress made with generator documented in the following publications...
  - Feasibility of structure function data [2019 EPJA article (DOI:10.1140/epja/i2019-12885-0)]
  - Pion structure function projections [2021 JPhysG (arXiv:2102.11788)]
  - Detector proposals using ePIC configuration [2023 NIM (DOI:10.1016/j.nima.2023.168238)]
- π structure function: Measure DIS cross section with tagged neutron at small -t
- Beam energies: 5 on 41, 5 on 100, 10 on 100, 10 on 135, 18 on 275

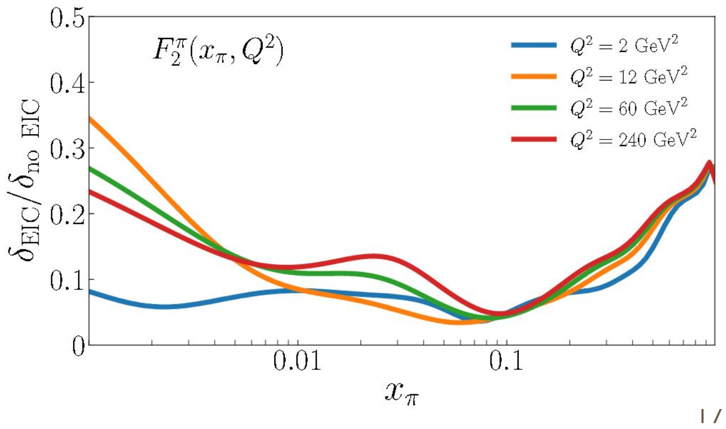
F^{π}_2 Projections

- Reasonable uncertainties in the mid-to-large x region but increasing rapidly as x→1
    - Even with these restrictions, the coverage in mid to high x is unprecedented
- Access to a significant range of Q^2 and x, for appropriately small −t
    - Allows for much-improved insights in the gluonic content of the pion

NLO through pion PDFs



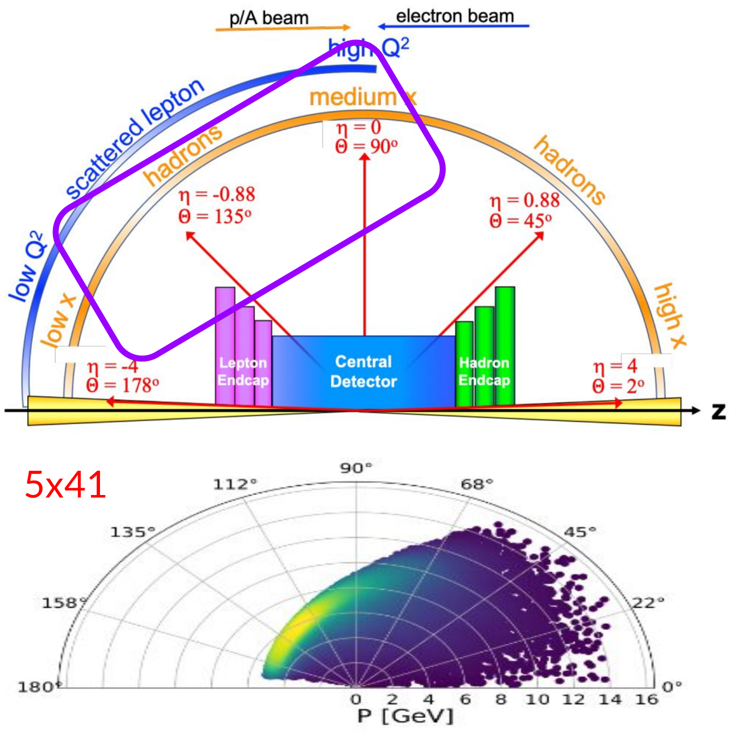


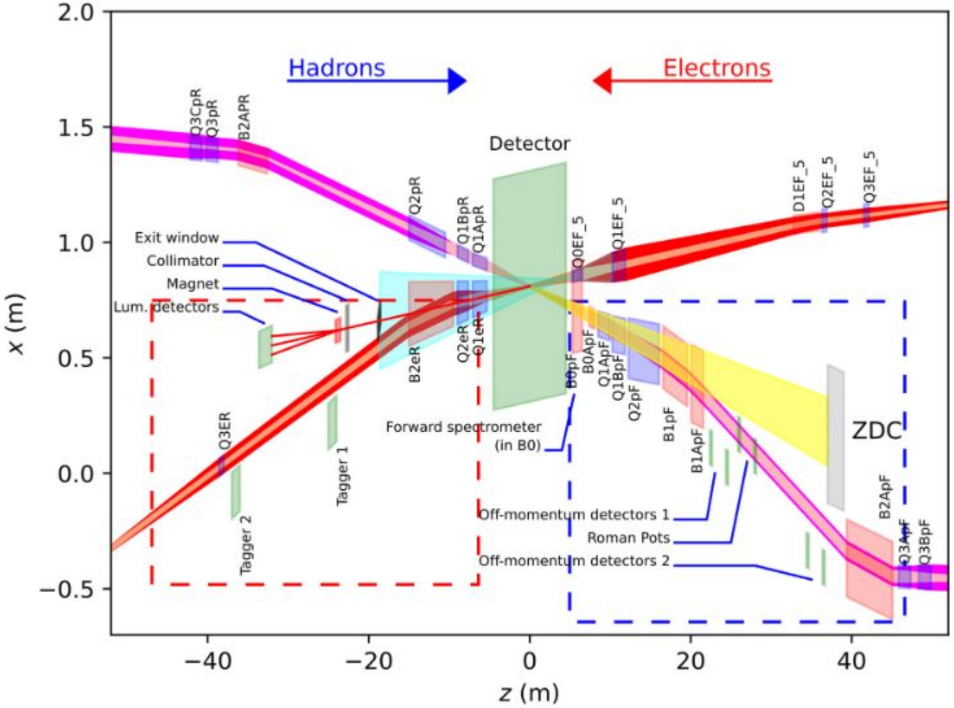


J Arrington, et al., J. Phys. G (2021) arXiv:2102.11788

Meson SF – Scattered Electron

- Scattered electrons can be detected in the central detector

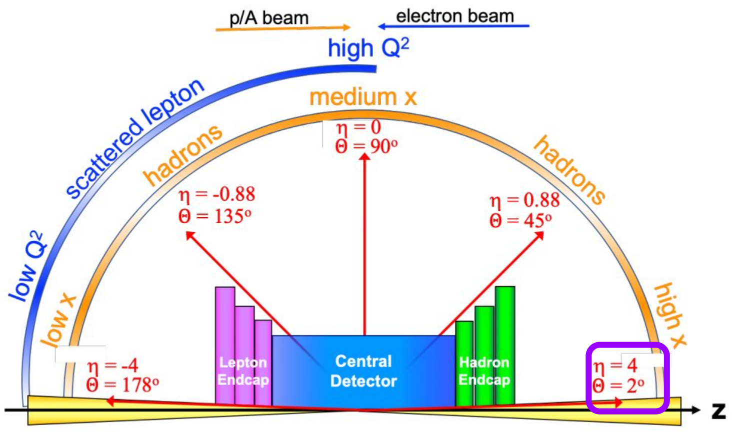




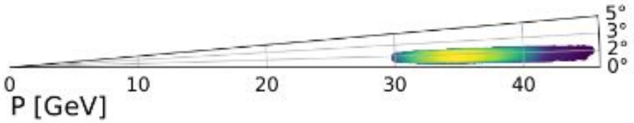
DOI:10.1016/j.nima.2023.168238

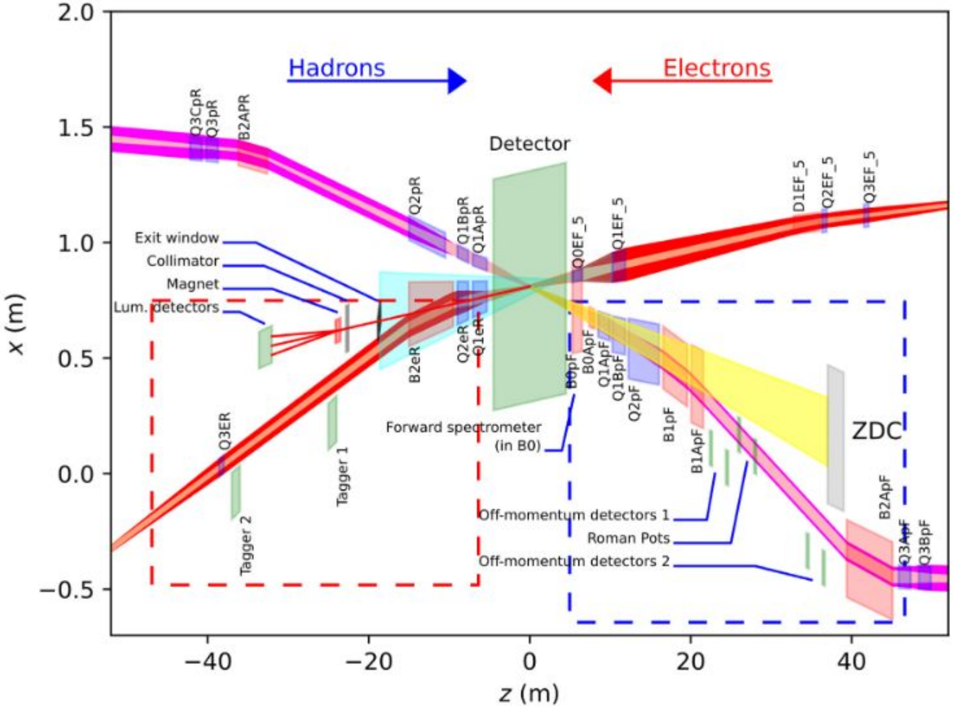
Meson SF – Forward Baryon

- Baryon (neutron, lambda) at very small forward angles and nearly the beam momentum



5x41

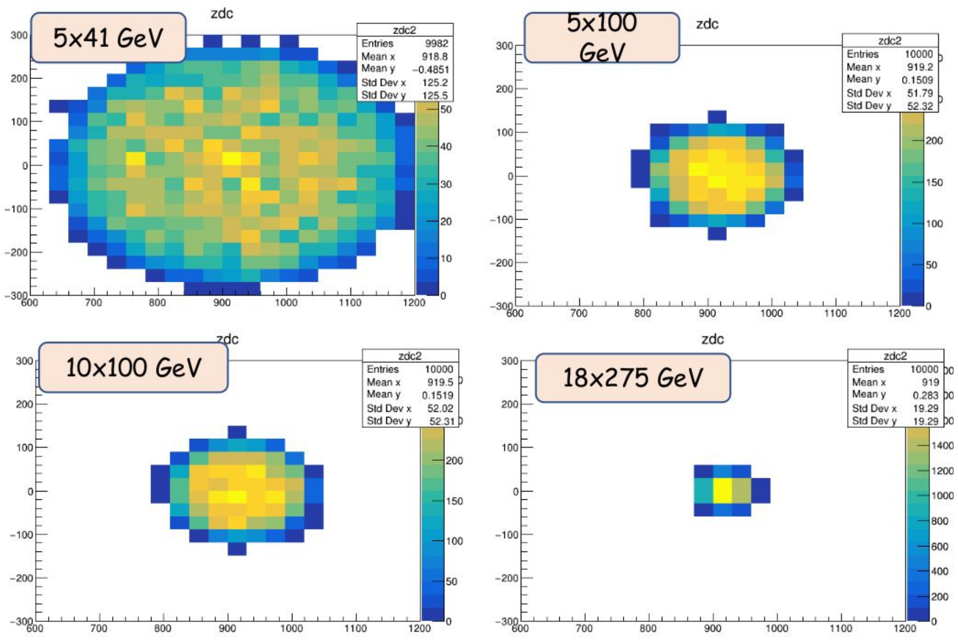


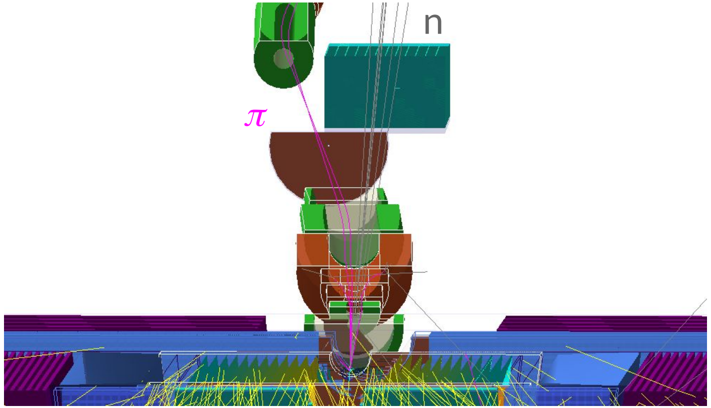


DOI:10.1016/j.nima.2023.168238

F^{π}_{2} Neutron Final State (1)

- For neutron final state use ZDC
  - detection fractions ~100% for 60x60 cm ZDC size
  - Need good ZDC angular resolution for required t resolution

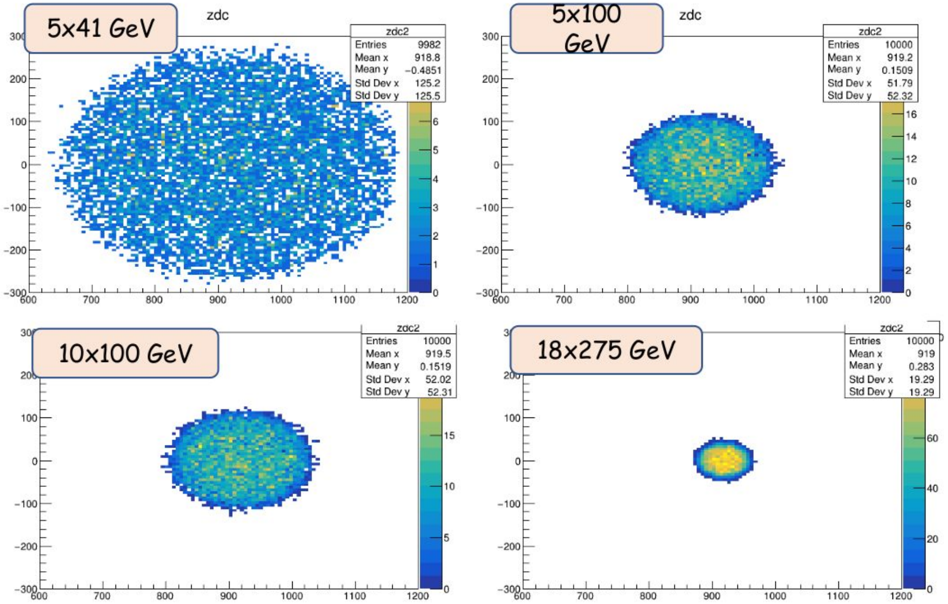


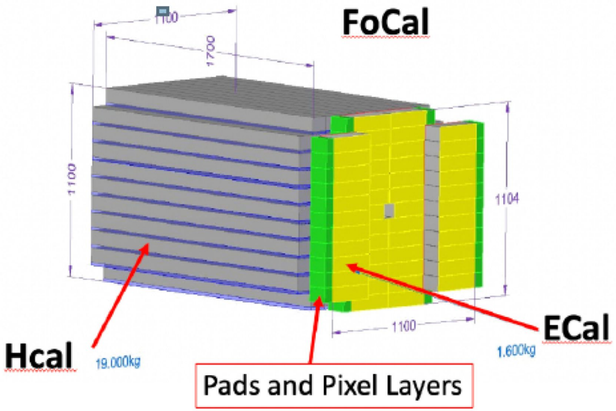


- ZDC: [60x60 cm, 20 bins → 3 cm towers]
- The 60x60 cm ZDC allows for high detection efficiency for wide range of energies (K-Λ detection benefits from 5 on 41, 5 on 100)
  - Higher energies (10 on 100, 18 on 275) show too coarse of a distribution at this resolution

F^{π}_{2} Neutron Final State (2)

- For neutron final state use ZDC
  - detection fractions ~100% for 60x60 cm ZDC size
  - Need good ZDC angular resolution for required t resolution

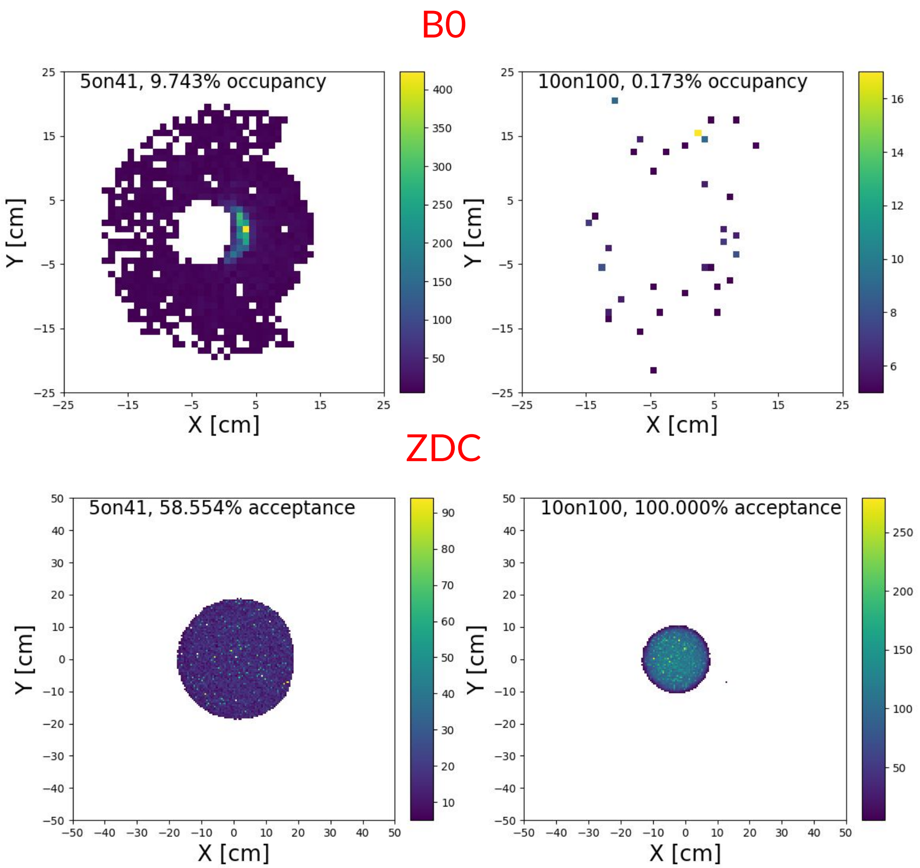




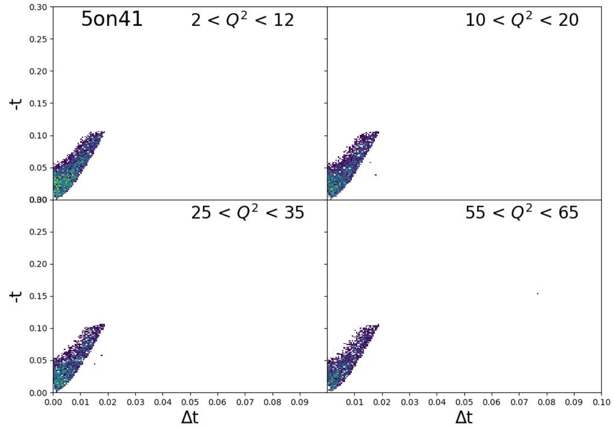
- ZDC: [60x60 cm, 100 bins → 0.6 cm towers]
- If we want energies over 100 GeV, we will need resolution of ~1 cm or better

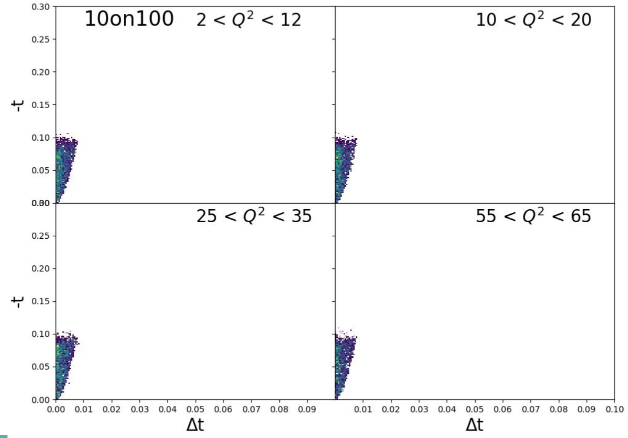
F^{π}_{2} Neutron Final State (3)

- Neutron final state uses Zero Degree Calorimeter (ZDC)
- Constraining neutron energy around 50%/√E will assure an achievable resolution in x
- The ZDC must reconstruct the energy and position well enough to constrain both scattering kinematics and 4-momentum of pion
- Acceptance ~100% for energies >5on41 with the 60x60 cm ZDC size
- B0 occupancy shows significant amount of leading neutrons hitting the detector for 5on41 corresponding to a significant drop in ZDC acceptance



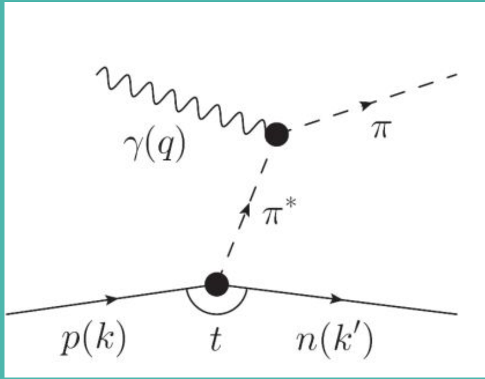
F^{π}_{2} -t reconstruction



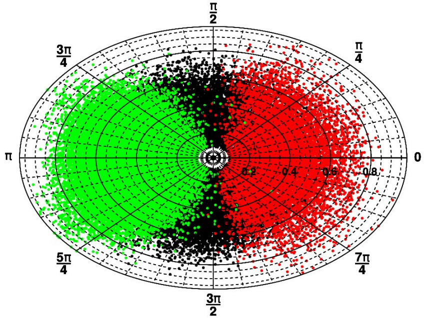


- A good ZDC angular resolution is required for a sufficient -t resolution
- The deviation of t from its detected value, $\Delta t = t - t_{Truth}$, is much greater for 5on41
- This provides a consistent picture between ZDC acceptance and -t resolution for the energy ranges
- Access to a significant range of Q^2 and x, for appropriately small −t, will allow for much improved insights in the gluonic content of the pion

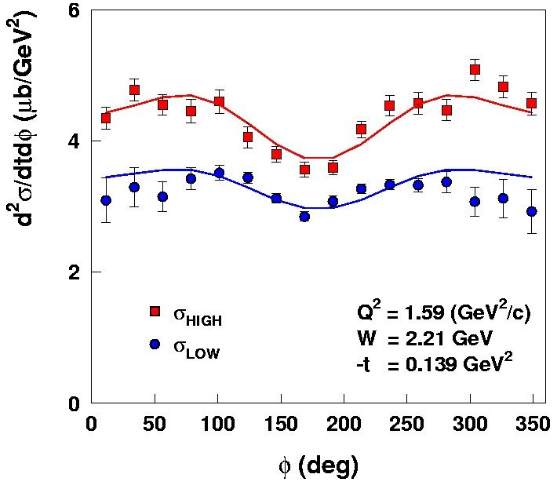
π^+ Form Factors at EIC



Experimental considerations for FF extraction



- σ_L is isolated using the Rosenbluth separation technique
- Measure the cross section at two beam energies and fixed W, Q^2, -t

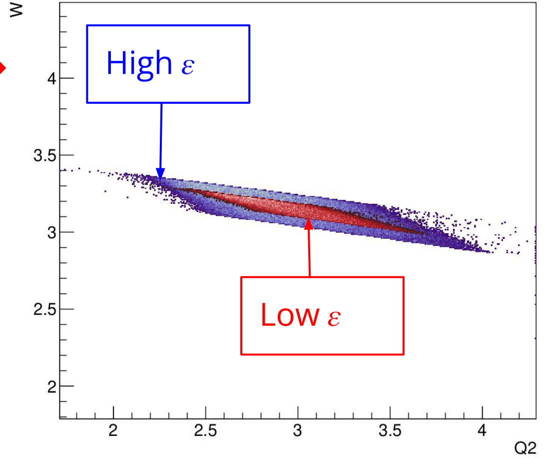


*T. Horn et al., PhysRevC **97**(2006)192001*

1. Phase space matching to constrain the kinematic region for the two differing beam energies
2. Extract cross section in -t and ϕ bins

$$\left(\frac{d\sigma^2_{exp}}{dtd\phi}\right)\Bigg|_{Q^2=\bar{Q^2},t=\bar{t}} = \frac{Y_{exp}}{Y_{SIMC}}\left(\frac{d\sigma^2_{model}}{dtd\phi}\right)\Bigg|_{Q^2=\bar{Q^2},t=\bar{t}}$$

3. This allows for the simultaneous extraction of L, T, LT, and TT

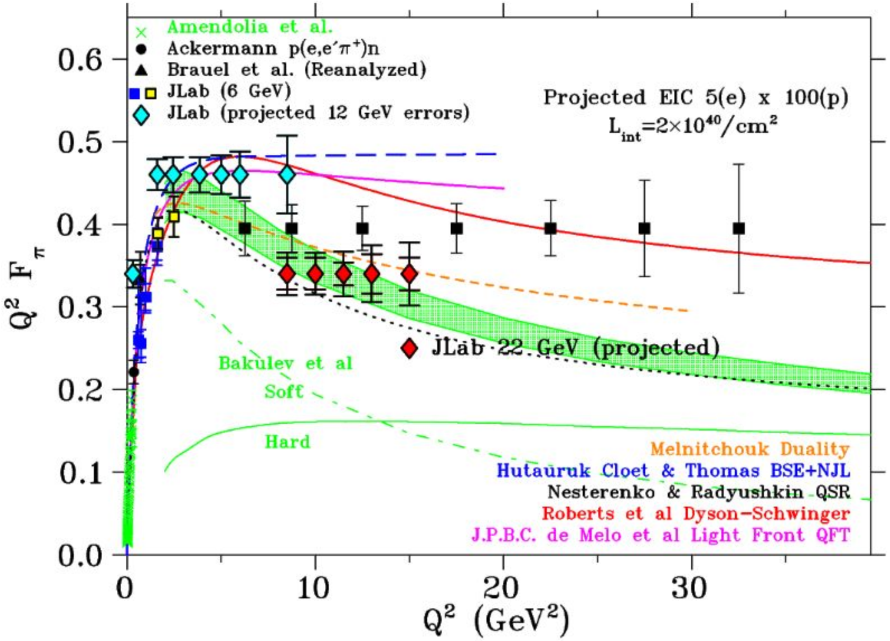


$$2\pi\frac{d^2\sigma}{dtd\phi} = \varepsilon\frac{d\sigma_L}{dt} + \frac{d\sigma_T}{dt} + \sqrt{2\varepsilon(\varepsilon+1)}\,\frac{d\sigma_{LT}}{dt}\cos\phi + \varepsilon\frac{d\sigma_{TT}}{dt}\cos 2\phi$$

Existing Charged Meson Form Factor Measurements

- π^+ and K^+ form factors are of special interest in hadron structure studies
- Clearest case for studying transition from non-perturbative to perturbative regions
- π^+ form factor has data covering a wide rang of Q^2 (up to 8.5 GeV^2)
  - Fπ1/Fπ2: 2006, 2008
  - PionLT: E12-09-011 which covers KaonLT data plus Summer 2019
  - PionLT: E12-19-006 ran Fall 2021, Winter 2022, Summer 2022 and Fall 2022

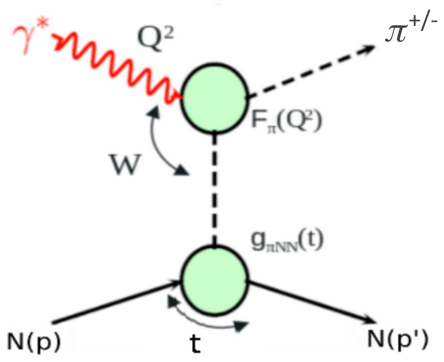
J Arrington, et al., J. Phys. G (2021) arXiv:2102.11788



- Meanwhile, the K^+ form factor data is very limited
  - Before the JLab 12 GeV upgrade, there was a lack of facilities with capabilities required

π^+ Form Factor: An alternate technique

- An alternate technique is available to access σ_L via a model validated with exclusive π^-/π^+ ratios from deuterium.
- After evaluating $d\sigma_L/dt$ across the $-t$ range from $-t_{min}$ to approximately $-t = 0.6$ GeV^2 (i.e., pion pole region)
  - $F_\pi(Q^2)$ is derived by comparing observed dL/dt values with the most accurate electroproduction model available
- This model considers off-shell pion and recoil nucleon effects
- The acquired F_π values theoretically rely on the employed model
  - However, it's expected that this reliance diminishes as $-t$ decreases
  - Conducting measurements across various $-t$ values is crucial for validating the model.

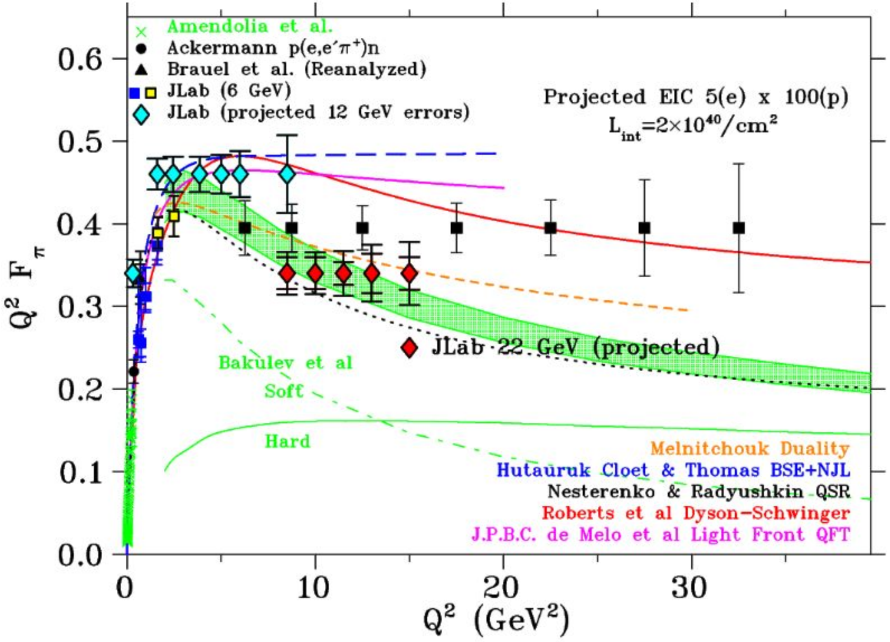


$$R = \frac{\sigma[n(e, e'\pi^- p)]}{\sigma[p(e, e'\pi^+ n)]} = \frac{|A_V - A_S|^2}{|A_V + A_S|^2}$$

π^+ Form Factors (F_π)

- Measurements of the p(e, e'π^+n) reaction at the EIC can potentially extend the Q^2 reach of F_π measurements even further
- Exclusive reactions are of interest
  - p(e,e'π^+n) exclusive reaction particular with p(e,e'π^+n)X SIDIS events as the background
  - A clean sample of p(e,e'π^+n) events needs to be isolated by detecting the neutron
- A challenging measurement however
  - Need good identification of p(e, e'π^+n) triple coincidences
  - Conventional L-T separations are not feasible due to the inability to reach low enough ε values, which are essential for accurate separation.
  - Need to use a model to isolate $d\sigma_L/dt$ from $d\sigma_{uns}/dt$

J Arrington, et al., J. Phys. G (2021) arXiv:2102.11788

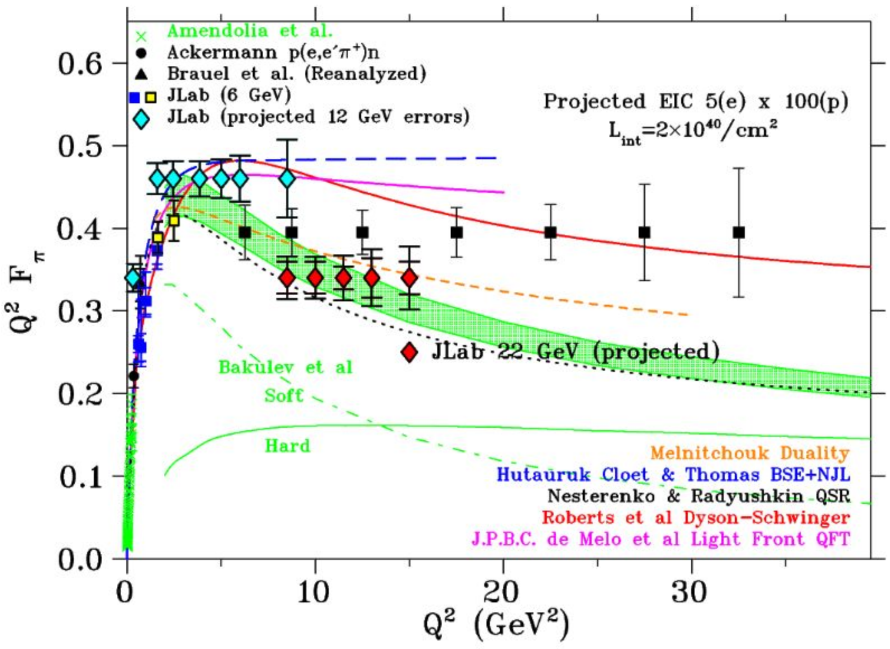


- Major updates have been made to the Deep Exclusive Meson Production event generator (DEMPgen) to enhance the reliability of feasibility studies
- Updated DEMPgen is used to generate new files for both pion and kaon reactions, which will then undergo the latest ePIC simulations

F_π Projections

- ePIC appears to be capable of measuring F_π to Q^2 ~ 32.5 GeV^2
- Error bars represent real projected error bars
  - 2.5% point-to-point
  - 12% scale
  - $\delta R = R$, $R = \sigma_L/\sigma_T$
  - R = 0.013 − 014 at lowest −t from VR model
- Uncertainties dominated by R at low Q^2
- Statistical uncertainties dominate at high Q^2
- Results look promising, need to test π^- too
- More details in...
  - 2024 DEMPgen (arXiv: 2403.060 [hep-ph])
  - 2023 A. Bylinkin et al. (NIM A 1052 (2023) 168238 1-40)

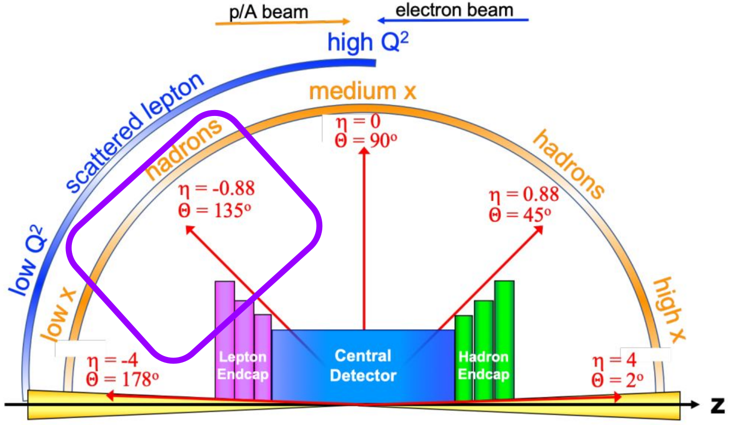
J Arrington, et al., J. Phys. G (2021) arXiv:2102.11788



Analysis by Stephen Kay and Garth Huber

π^+ Form Factor – Scattered Electron

- The exclusive electron are stuck to a tight band



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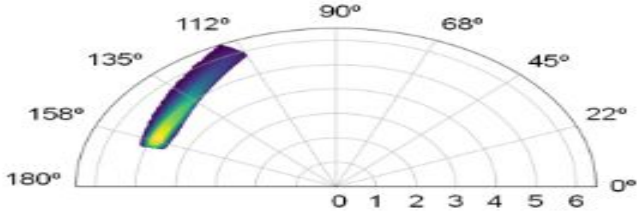
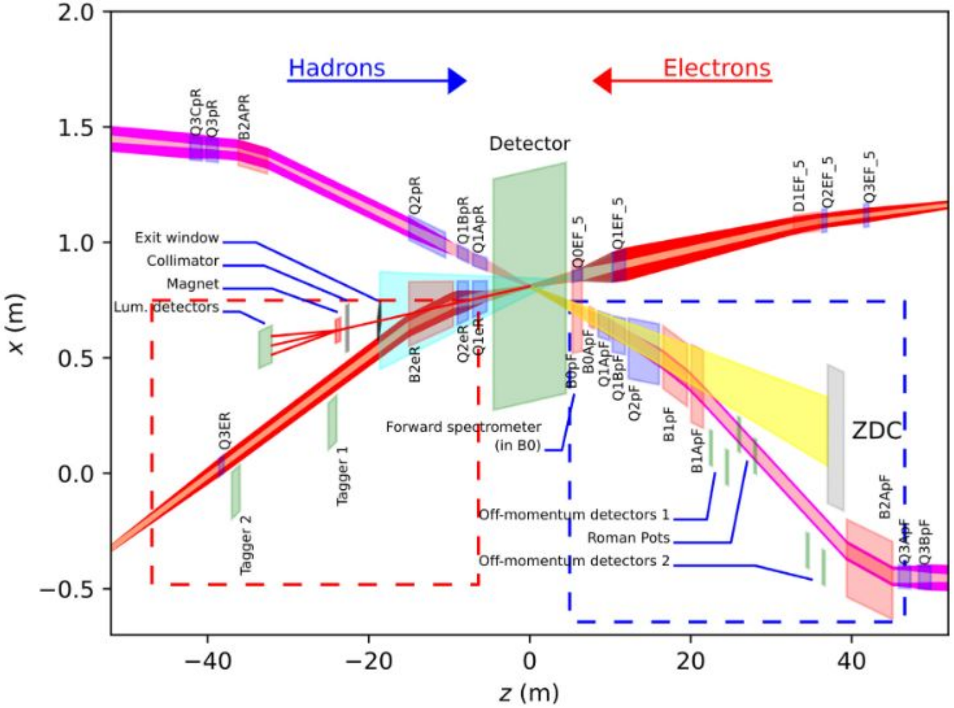
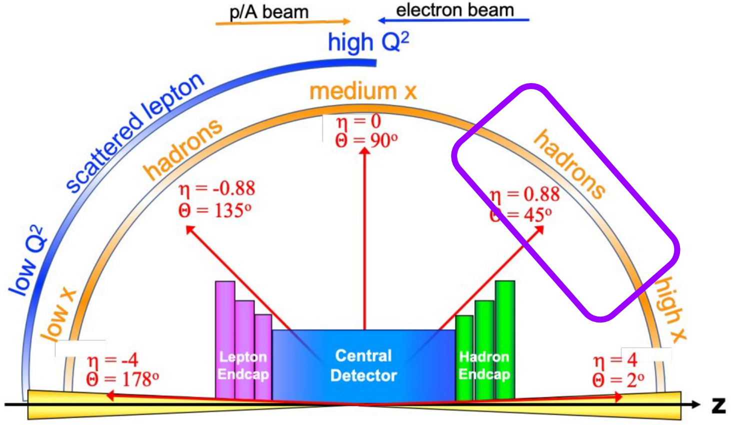




DOI:10.1016/j.nima.2023.168238

π^+ Form Factor – Scattered π^+

- Baryon (neutron, lambda) at very small forward angles and nearly the beam momentum



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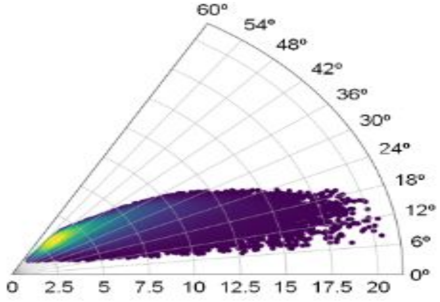
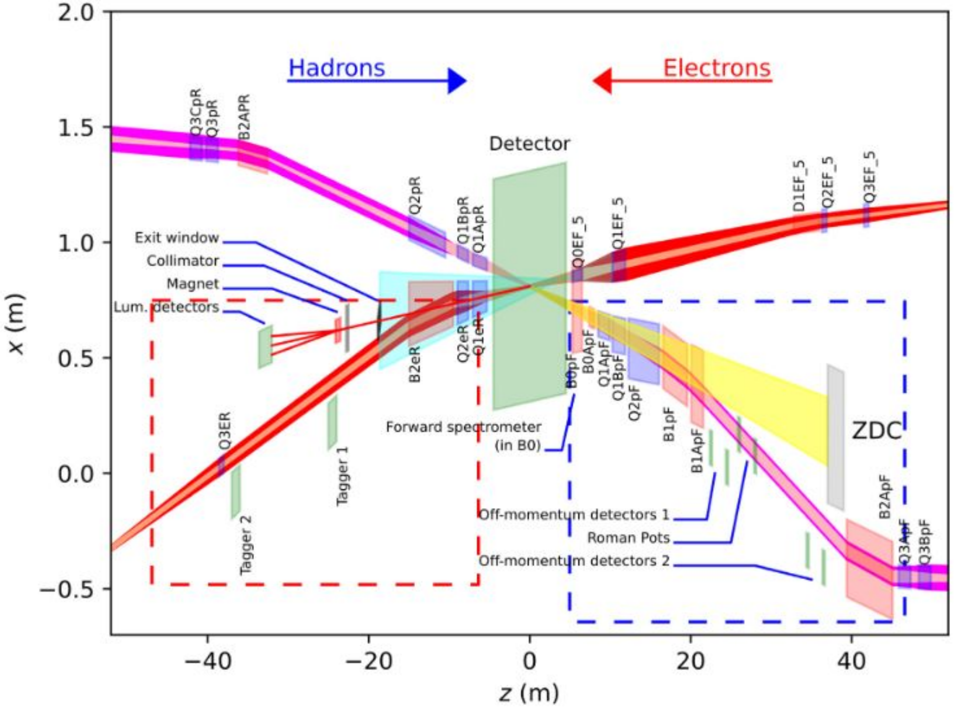
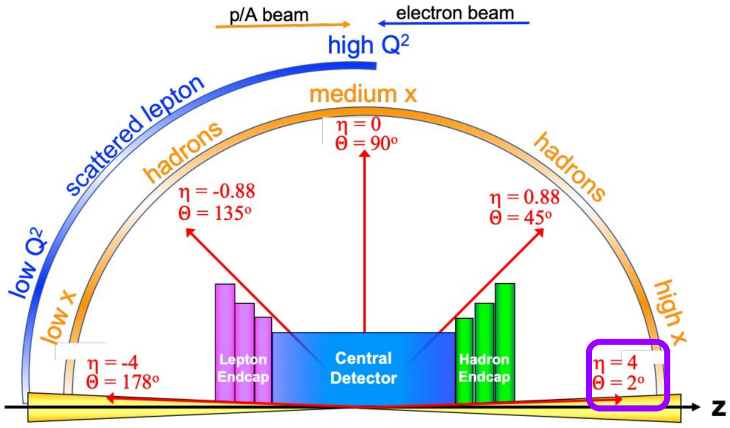




DOI:10.1016/j.nima.2023.168238

π^+ Form Factor – Forward Baryon

- Neutron carries ~80% of the momentum within 0.2° of outgoing proton



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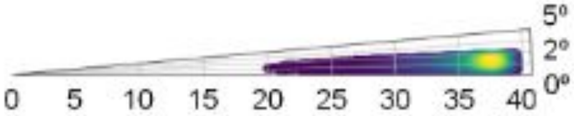
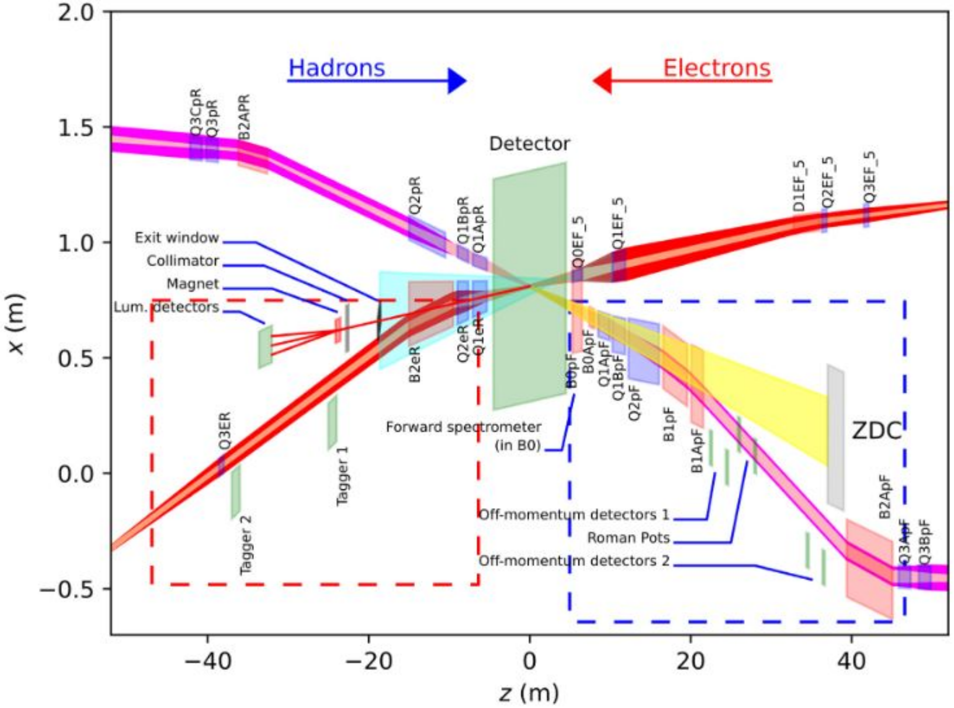




DOI:10.1016/j.nima.2023.168238

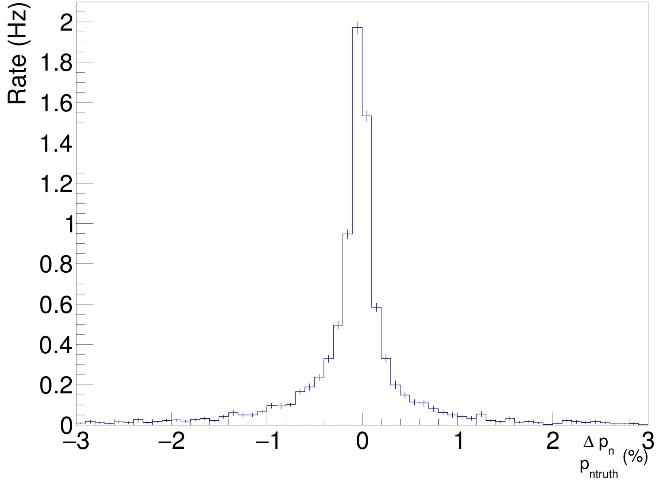
F_{π} Neutron Reconstruction

- High energy ZDC hit requirement used as a veto
  - ZDC neutron ERes is relatively poor though
- However, position resolution is excellent, ~ 1.5 mm
- Combine ZDC position info with missing momentum track to reconstruct the neutron track

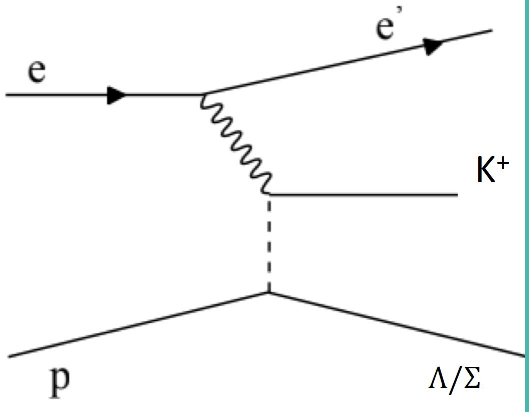
$$\frac{35\%}{\sqrt{E}} \oplus 2\%$$

$$p_{miss} = |\vec{p}_e + \vec{p}_p - \vec{p}_{e'} - \vec{p}_{\pi^+}|$$

- Use ZDC angles, θ_{ZDC} and φ_{ZDC} rather than the missing momentum angles, θ_{pMiss} and φ_{pMiss}
- Adjust E_{Miss} to reproduce m_n
- After adjustments, reconstructed neutron track matches “truth” momentum closely



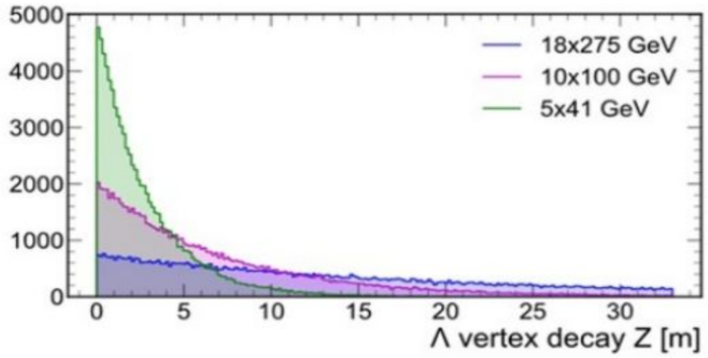
K^+ Structure at EIC



Plans for F_K projections

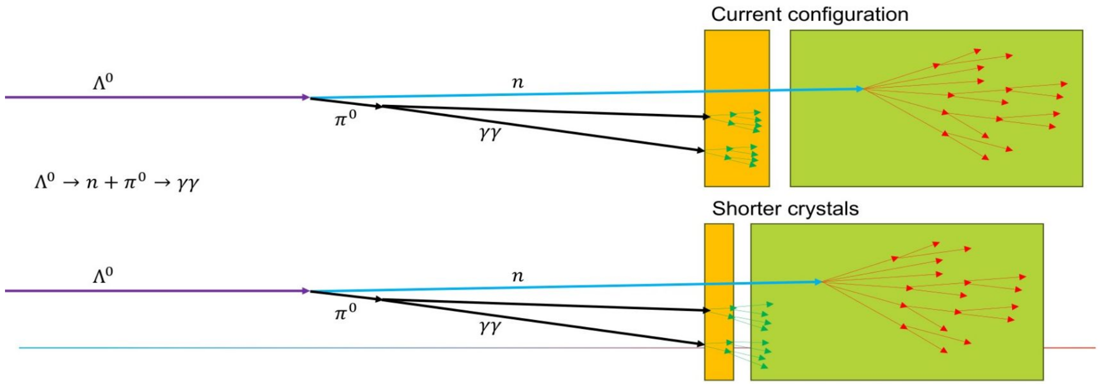
J Arrington, et al., J. Phys. G (2021) arXiv:2102.11788

- Track photons and neutrons from Λ in the ZDC – EMCAL and ZDC – HCAL
  - Will help to investigate ZDC – EMCAL thickness.
  - Impact on the Λ reconstruction from photons and neutrons.
- Reconstruction is considerably challenging, uncertain about the achievable extent at present



$$e + p \rightarrow e' + K^+ + \Lambda$$

$$\Lambda \rightarrow n + \pi^0, \pi^0 \rightarrow \gamma\gamma$$

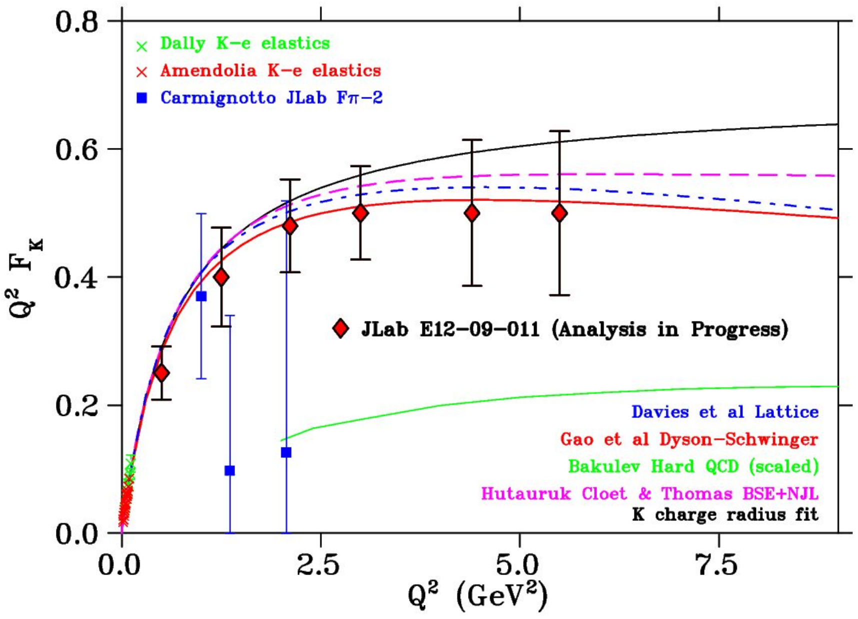


- Will perform tests on Λ reconstruction, focusing on efficiency, acceptance and resolution
- Aim to determine the $F_K(Q^2)$ projections in the long term
- Analysis by Stephen Kay, Garth Huber and Love Preet

F_K from KaonLT at Jefferson Lab

- JLab 12 GeV KaonLT (E12-09-011) experiment will provide much needed data in a wide range of Q^2, W, t
- Data taken…
  - Fall and Winter 2018
  - Spring 2019
- **Results coming soon!**

E (GeV)	Q^2 (GeV^2)	W (GeV)	x	$\varepsilon_{high}/\varepsilon_{low}$	$\Delta\varepsilon$
10.6/8.2	5.5	3.02	0.40	0.53/0.18	0.35
10.6/8.2	4.4	2.74	0.40	0.72/0.48	0.24
10.6/6.2	3.0	2.32	0.40	0.88/0.57	0.31
10.6/8.2	3.0	3.14	0.25	0.67/0.39	0.28
10.6/6.2	2.115	2.95	0.21	0.79/0.25	0.54
4.9/3.8	0.5	2.40	0.09	0.70/0.45	0.25



Plans for F^K_2 projections

- Goal is to extend to tagged kaon structure function
- Very limited data on F^K_2
  - Exploratory data on kaon SF are planned to come from TDIS JLab experiment (C12-15-006A) in the next few years.
- Kaon projected structure function data will be of similar quality as the projected pion structure function data for the small-t geometric forward particle detection acceptances at EIC - studies in progress
- Currently investigating splitting functions as way to gain insights

$$F_2^T = \kappa f F_2 \rightarrow f_{KY}^{(rbw)}(y) = \frac{C_{KY}^2 \bar{M}^2}{(4\pi f_\phi)^2}\left[f_Y^{(on)}(y) + f_K^{(\delta)}(y)\right] \rightarrow f_Y^{(on)}(y) = y \int dk_\perp^2 \frac{k_\perp^2 + (M_Y + \Delta)^2}{(1-y)^2 D_{KY}^2} F^{(on)}$$

J. R. McKenney, et al., 10.1103/Phys-RevD.93.054011
X. G. Wang, et al., 10.1103/PhysRevD.94.094035

Summary

- Produced initial physics deliverables, physics objects, and kinematic plots/coverage
    - Physics deliverables: π/K structure function plots, π form factor plot
    - Physics objects:
        - scattered electron
        - Measure π and tagged neutron (π form factor)
        - Measure “X” and tagged neutron (π structure function)
        - Measure K and tagged Λ (K form factor)
        - Measure “X” and tagged Λ (K structure function)
- Next steps are to…
    - Simulate KΛ and KΣ events
    - Extend π to K structure function and form factor
        - Splitting functions
        - Track photons and neutrons from Λ in the ZDC – EMCAL and ZDC – HCAL
    - Continue far-forward analysis and extend to the 2nd IR (ie IP8)

Meson structure working group members

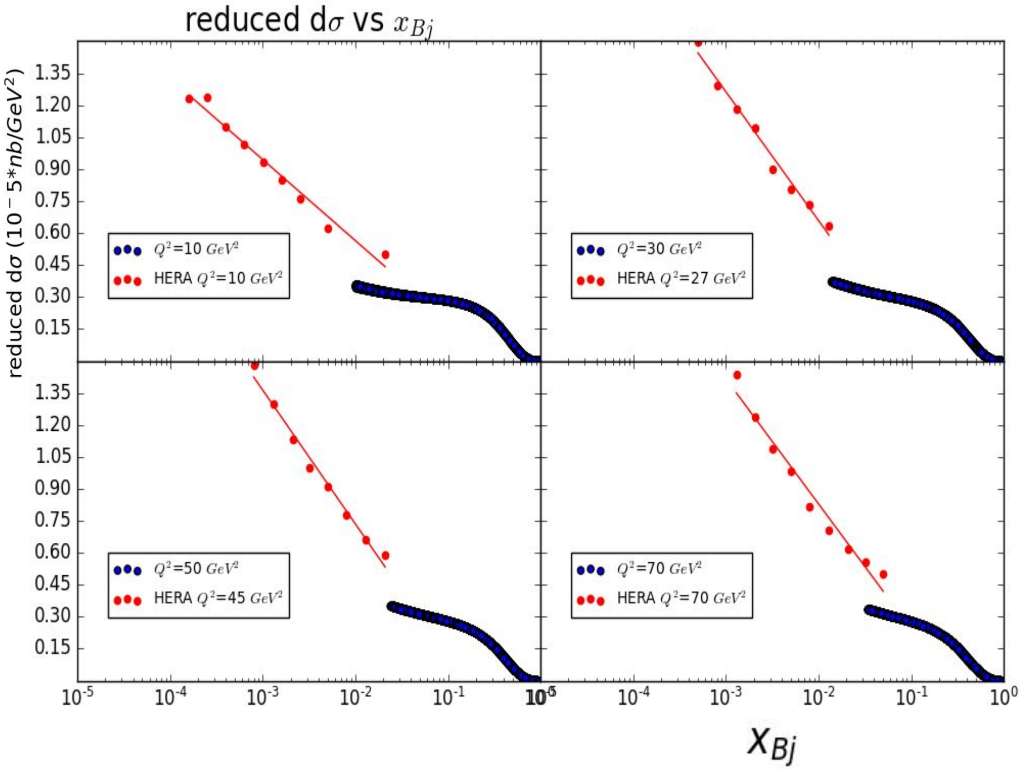
Daniele Binosi , Huey-Wen Lin, Timothy Hobbs, Arun Tadepalli, Rachel Montgomery, Paul Reimer, David Richards, Rik Yoshida, Craig Roberts, Garth Huber, Thia Keppel, John Arrington, Lei Chang, Stephen Kay, Ian L. Pegg, Love Preet, Jorge Segovia, Carlos Ayerbe Gayoso, Bill Li, Yulia Furletova, Dmitry Romanov, Markus Diefenthaler, Richard L. Trotta, Tanja Horn, Rolf Ent, Tobias Frederico, Ali Usman

Thank You for Your Time!

Extra

Validation: Reduced cross-section compared with HERA

- HERA data from *ZEUS collab, Eur. Phys. J. C 21 (2001) DOI:10.1007/s100520100749*
- Proton beam = 100 GeV/c
- Electron beam = 5 GeV/c
- x_{Bj}=(0.01-1.0)
- Q^2=(10-100)



$$\tilde{\sigma}^{e^+p} = \left[\frac{2\pi\alpha^2}{xQ^4}Y_+\right]^{-1} \frac{d^2\sigma^{e^+p}_{\rm Born}}{dx\, dQ^2}$$

Geometric particle detection fractions

- For the pion structure function, the final state neutron moves with an energy near that of the initial proton beam
  - The Zero Degree Calorimeter (ZDC) must reconstruct the energy and position well enough to constrain both scattering kinematics and 4-momentum of pion
  - Constraining neutron energy around 35%/√E will assure an achievable resolution in x
- For the kaon structure function, the decay products of the Λ must be tracked through the very forward spectrometer
  - Distinguishing decay products is crucial

Process	Forward Particle	Geometric Detection Efficiency (at small -*t*)
$^{1}H(e, e' \pi^{+})\, n$	n	>20%
$^{1}H(e, e' K^{+})\, \Lambda$	Λ	50%
$^{1}H(e, e' K^{+})\, \Sigma$	Σ	17%

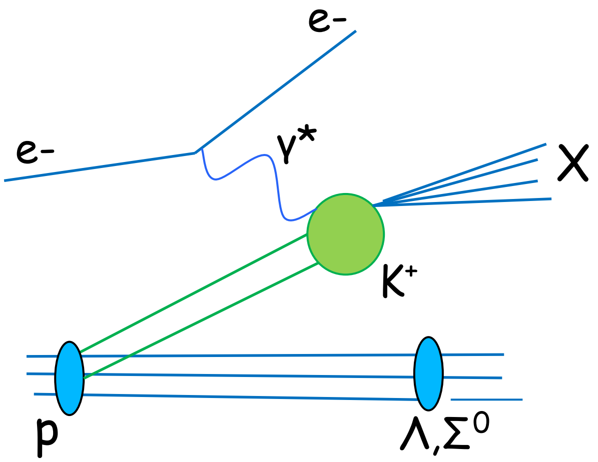
Arlene C. Aguilar, et al., Eur. Phy. J. A (2019) DOI:10.1140/epja/i2019-12885-0

K^+ Structure Functions (F^K_2)

- Λ has two primary decay modes…

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

- Optimizing the detection efficiency of these decay products is critical for kaon studies
- The decay length of Λ is dependent on the initial proton beam energy
    - Proper choice of this beam energy is a must since decay lengths can reach past the forward spectrometer at higher energies



Lambda Final State

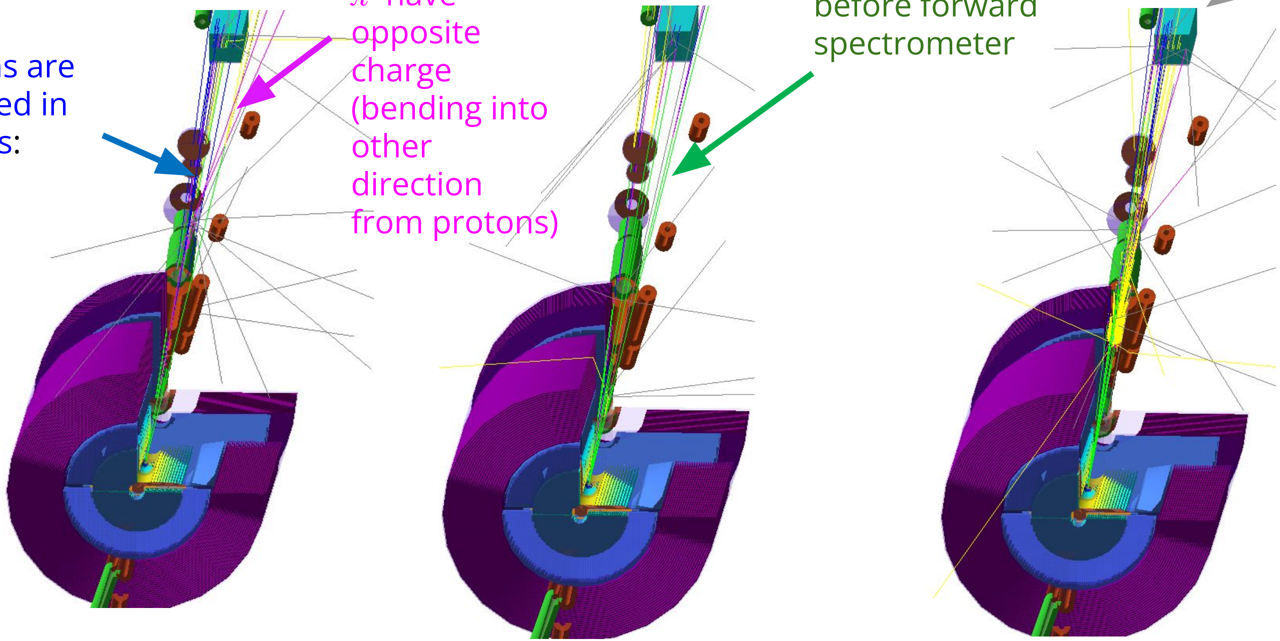
$$\Lambda \rightarrow p + \pi^-$$
$$\Lambda \rightarrow n + \pi^0$$

Protons are detected in the RPs:

π^- have opposite charge (bending into other direction from protons)

30% of Λ at high energy does not decay before forward spectrometer

Neutrons and a fraction of π^0 goes into ZDC



18 x 275

Decay Length

- There are some advantages for lower proton energy for K-Λ detection
- Possible advantage of the second IR