Meson Structure Functions at EIC

Early Career Workshop

June 7th, 2021

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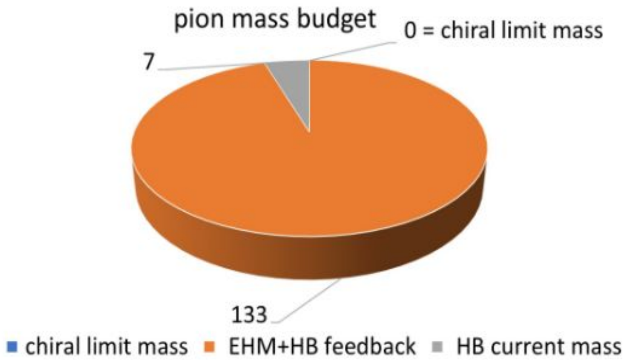
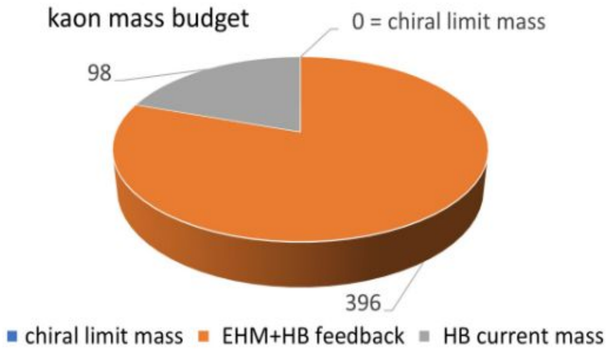
THE CATHOLIC UNIVERSITY OF AMERICA

See Craig's talk for more details!

Overview of Pion and Kaon Structure

- The pion is both the lightest bound quark system with a valence $\bar{q}q$ structure and a Nambu-Goldstone boson
- 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, regardless of what hadron the quarks reside in. It is the DCSB that makes the pion and kaon masses light.
- Pseudoscalar masses are generated dynamically

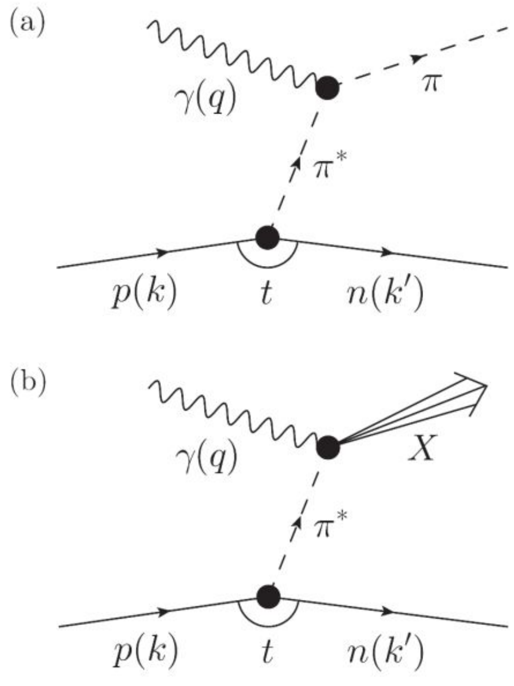




Journal of Physics G (2021) arXiv:2102.11788

Accessing the Pion and Kaon Structure

- At low -t values, the cross-section displays behavior characteristic of meson pole dominance
  - Using 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

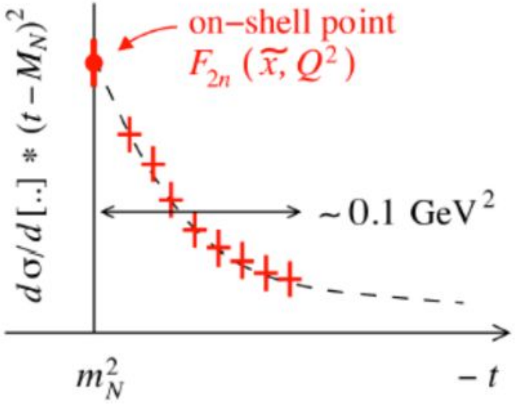


Pion cloud can access a) Elastic FF b) PDF

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

Off-Shell Considerations

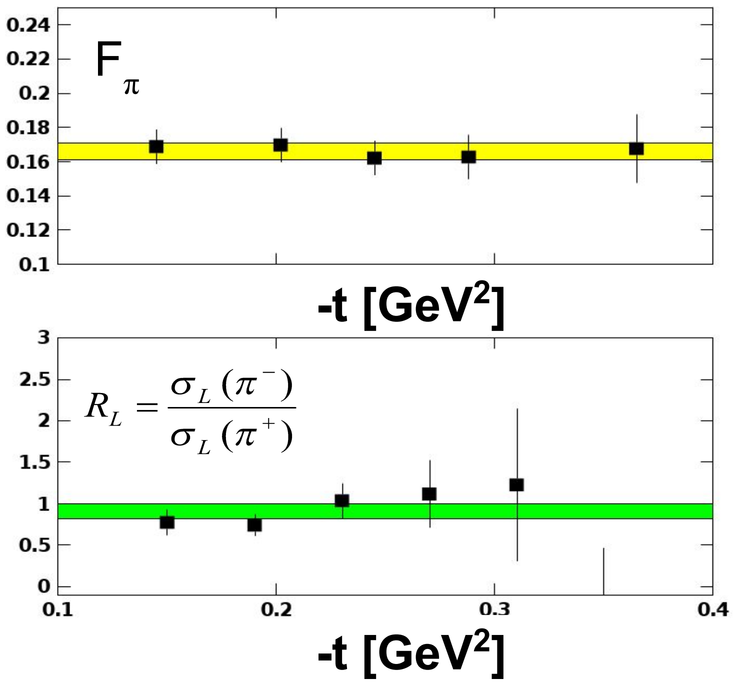
- The Sullivan process can provide reliable access to a meson target as t becomes space-like
- If the pole associated with the ground-state meson remains the dominant feature of the process
  - the structure of the related correlation evolves slowly and smoothly with virtuality
- Recent theoretical calculations found that changes in pion structure are modest so that a well-constrained experimental analysis should be reliable
  - For the pion when $-t \leq 0.6\ \text{GeV}^2$
  - For the kaon when $-t \leq 0.9\ \text{GeV}^2$



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

Experimental Validation

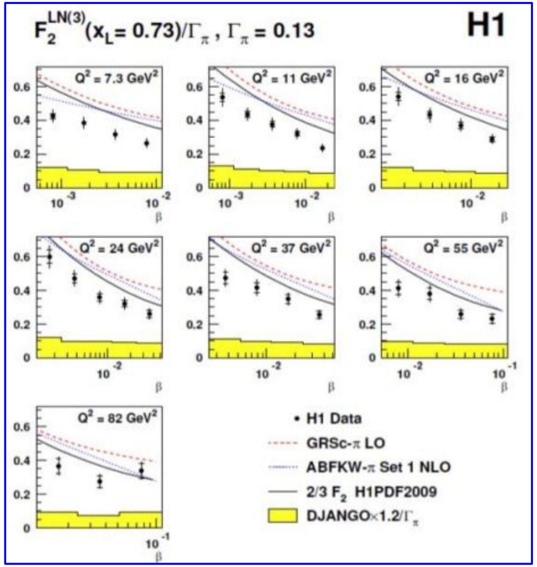
- To check these conditions are satisfied empirically...
  - data is taken covering a range in t
  - compare this data with phenomenological and theoretical expectations
    - F_π values do not depend on -t to give confidence in applicability of model to the kinematic regime of the data
  - Verify that 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

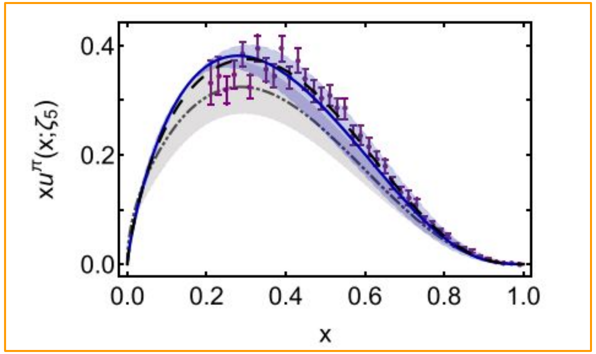


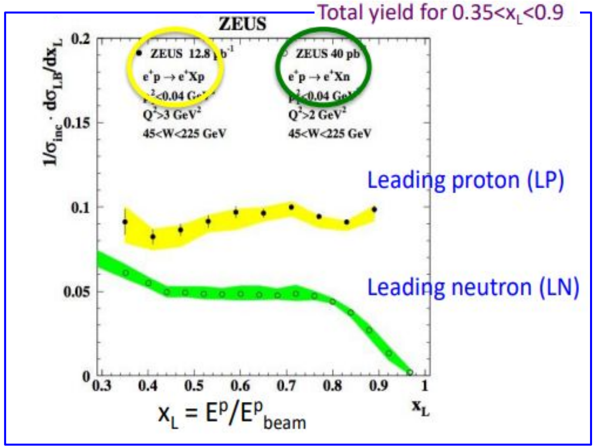
T. Horn, C.D. Roberts, J. Phys. G43 (2016) no.7, 073001
G. Huber et al, PRL112 (2014)182501
R. J. Perry et al., arXiV:1811.09356 (2019)

Existing 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
- 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…



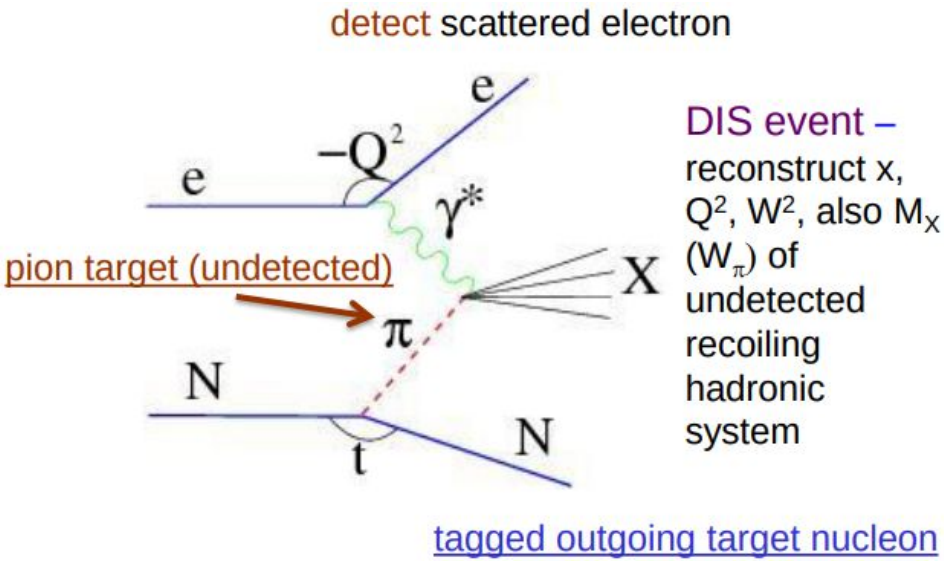


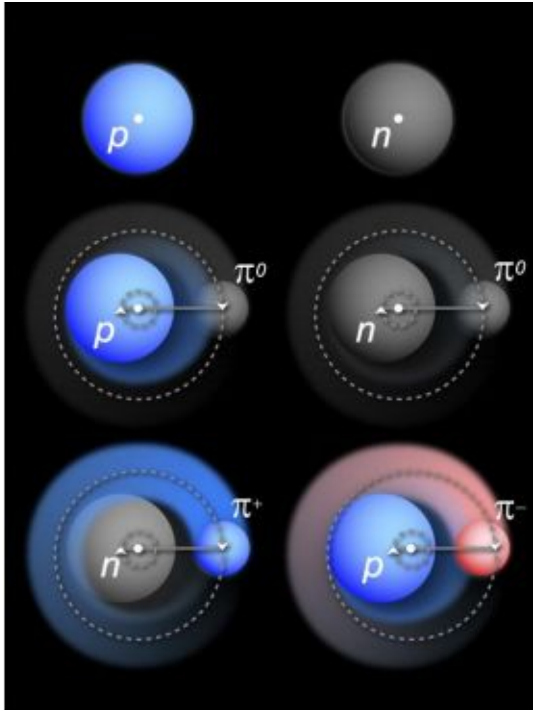


DESY 08-176 JHEP06 (2009) 74
Eur. Phy. J. C (2020) DOI:10.1140/epjc/s10052-020-08578-4

Tagged Deep Inelastic Scattering (TDIS)

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

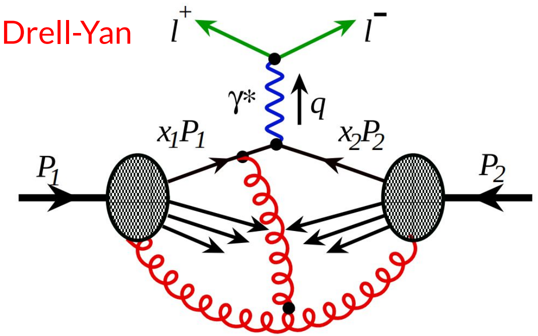


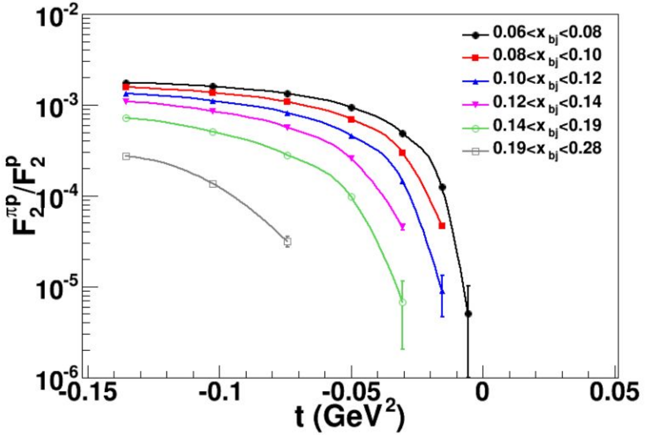


EIC Capabilities

- $L_{EIC} = 10^{34}$ e-nucleons/cm²/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) GeV², 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

Drell-Yan

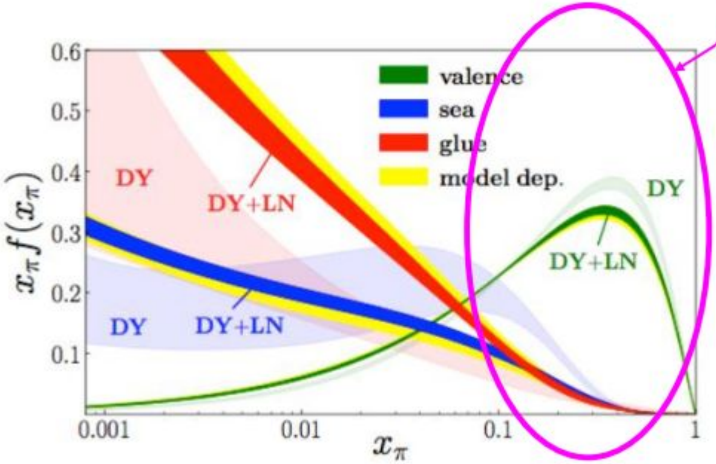




Jefferson Lab TDIS Collaboration, JLab Experiment C12-15-005
Journal of Physics G (2021) arXiv:2102.11788

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



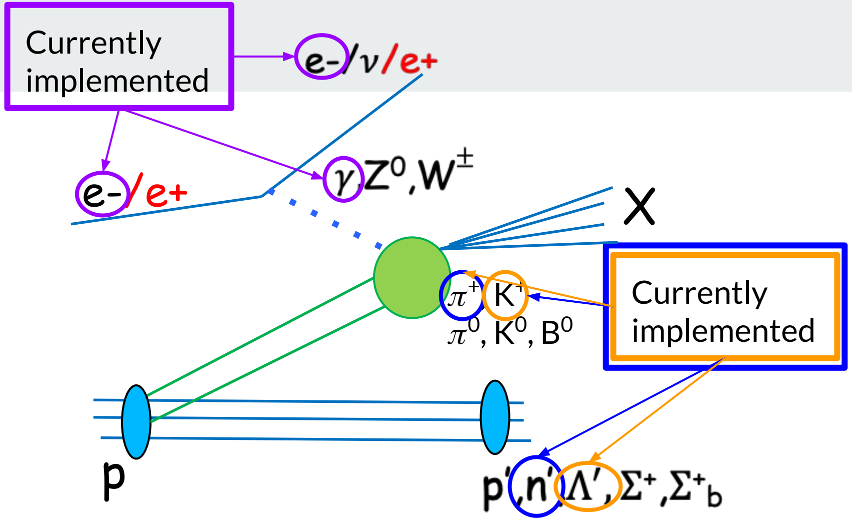
- ❑ JLab 12 GeV: Tagged Pion and Kaon TDIS
- ❑ Also prospects for kaon DY at COMPASS and pion and kaon LN at EIC

DY = πN Drell-Yan

LN = Leading Neutron

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

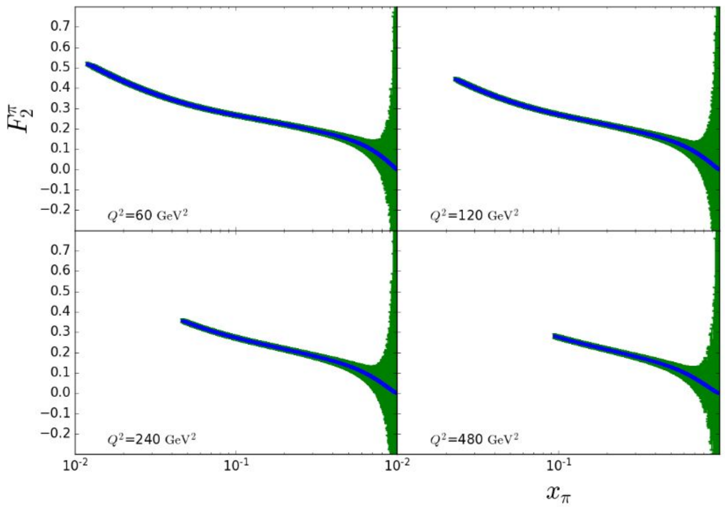
π^+ Structure Functions (F^{π}_2)

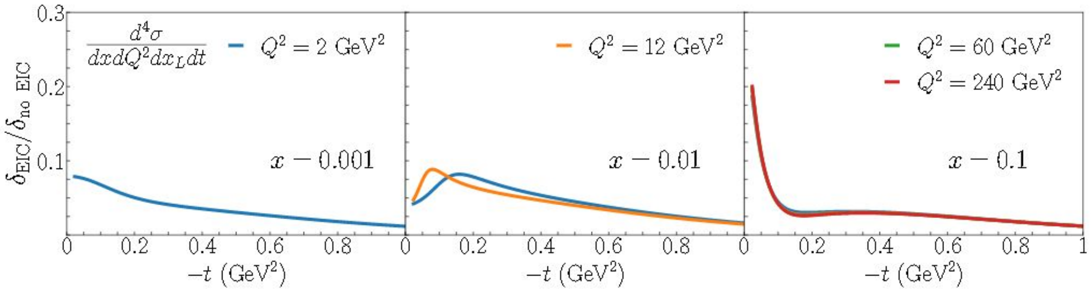


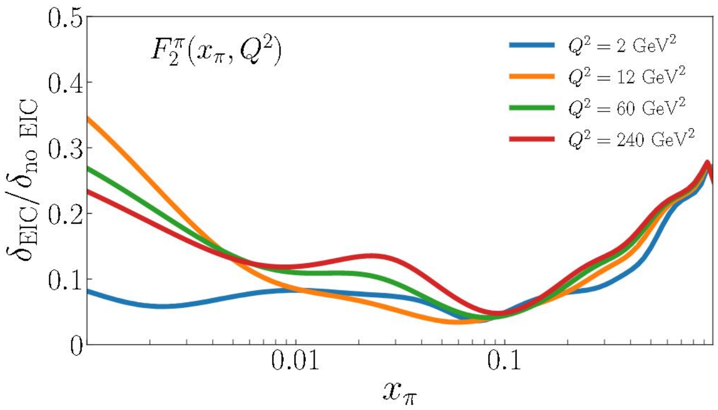
- For projections use a Fast Monte Carlo that includes the Sullivan process
  - PDFs, form factor, fragmentation function projections
- Progress made with generator documented in the following publications…
  - Feasibility of structure function data [2019 EPJA article (DOI:10.1140/epja/i2019-12885-0)]
  - Pion structure function (pion SF) projections [2021 JPhysG (arXiv:2102.11788)]
  - Over the last year projections were made in the context of the EIC detector proposals. Those for the ECCE configuration is anticipated to appear in NIM this year
- 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
  - Only e-P currently implemented, but want to incorporate e-D

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

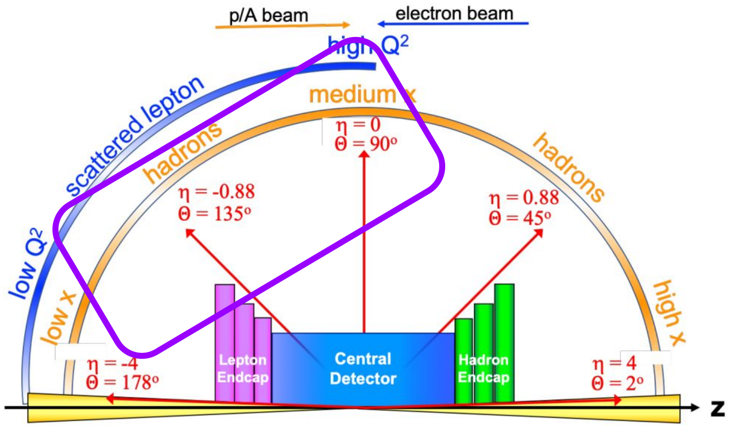


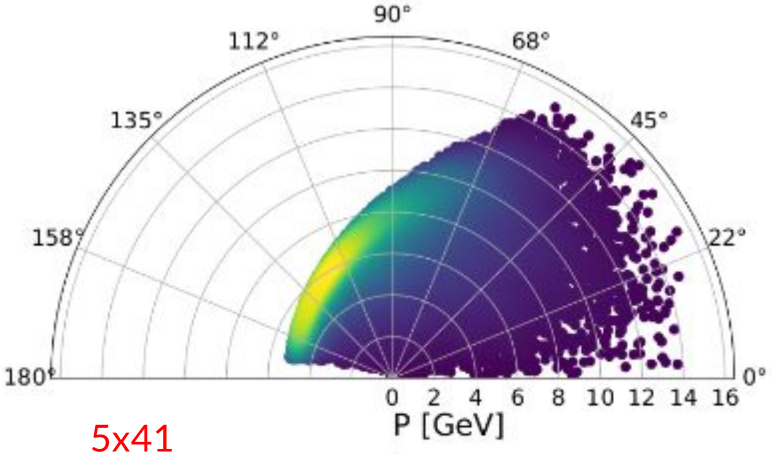




J Arrington, et al., J. Phys. G (2021) arXiv:2102.11788

Meson Structure Functions – Scattered Electron

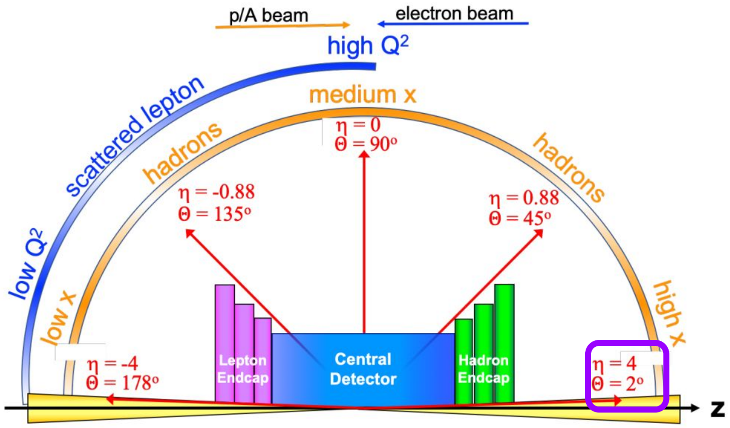


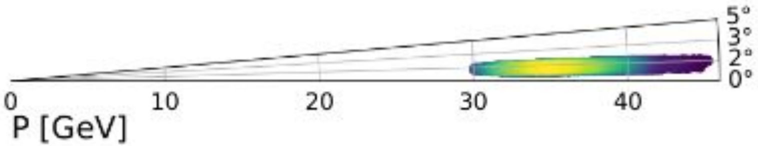


5x41

- Scattered electrons can be detected in the central detector

Meson Structure Functions – Forward Baryon



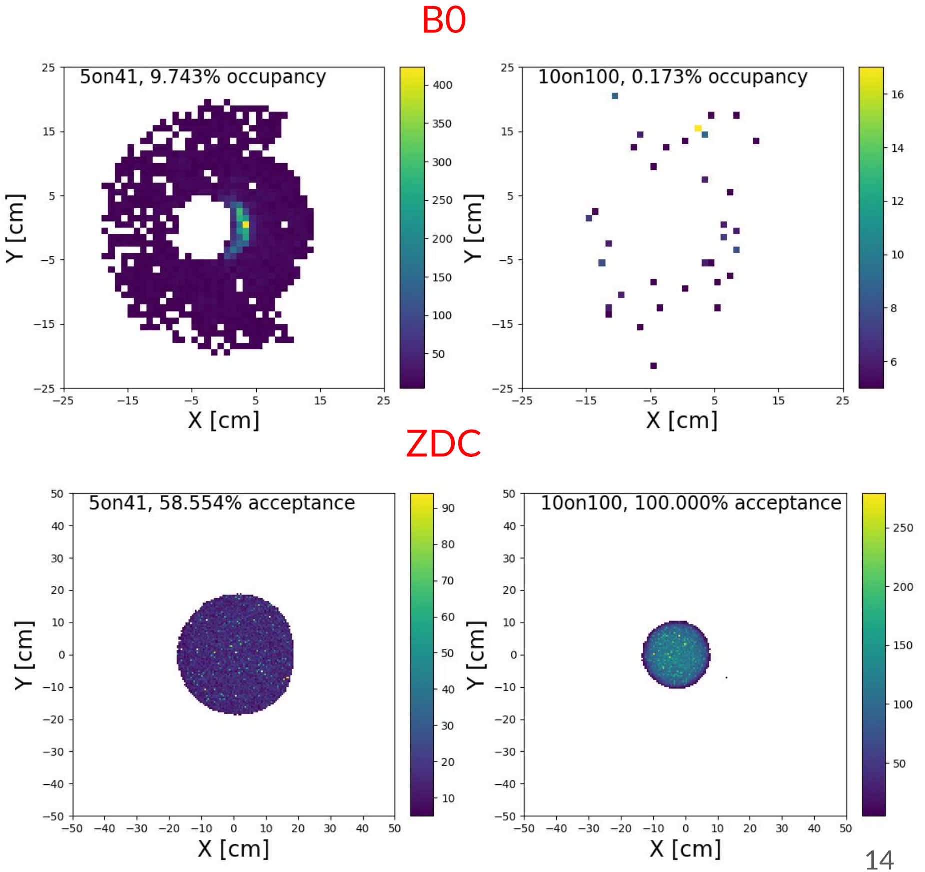


5x41

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

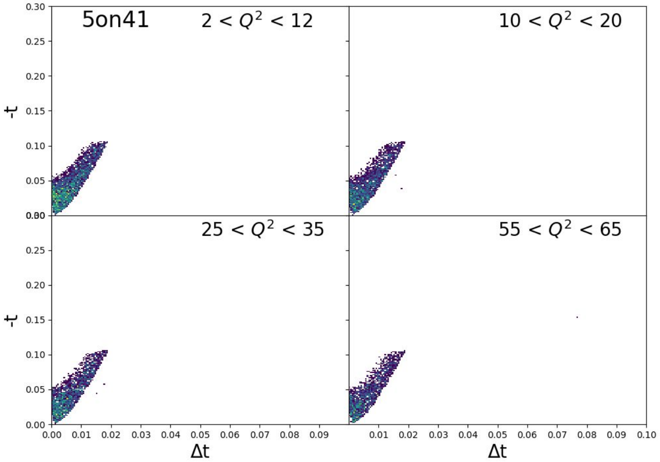
F^{π}_{2} Neutron Final State

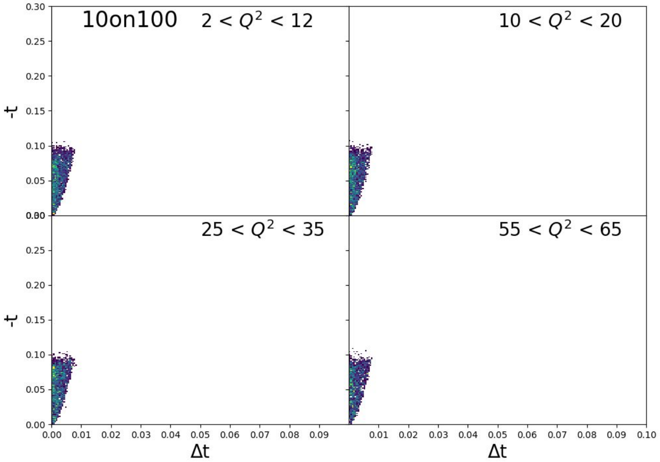
- Neutron final state uses Zero Degree Calorimeter (ZDC)
- Constraining neutron energy around 50%/√E will assure an achievable resolution in x
- The ZDC must reconstruct the energy and position well enough to constrain both scattering kinematics and 4-momentum of pion
- Acceptance ~100% for energies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



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, Δt = t − tT ruth, 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





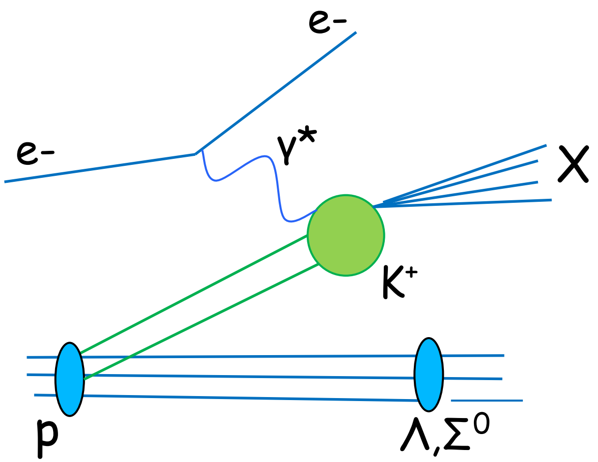
K^+ Structure Functions (F^K_2)

- 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



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 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
- To determine projected kaon structure function data from pion structure function projections
  - one method...scale the pion to the kaon case with the coupling constants while taking the geometric detection efficiencies into account

*S. Goloskokov and P. Kroll, Eur.Phys.J. **A47** (2011) 112:*

$g_{\pi NN}$=13.1 $g_{Kp\Lambda}$=-13.3 $g_{Kp\Sigma^0}$=-3.5

(these values can vary depending on what model one uses, so sometimes a range is used, *e.g.*, 13.1-13.5 for $g_{\pi NN}$)

Summary

- Produced initial physics deliverables, physics objects, and kinematic plots/coverage
  - Physics deliverables: π/K structure function plots
  - Physics objects:
    - scattered electron
    - Measure "X" and tagged neutron (π structure function)
    - Measure "X" and tagged Λ/Σ (K structure function)

- Next steps are to...
  - Simulate KΛ and KΣ events
  - Extend π to K structure function
  - Continue far-forward analysis and extend to the 2nd IR (ie IP8)
    - Early results for F^{π}_{2} at IP8 will be available in the upcoming ECCE NIM paper

Meson structure working group members!

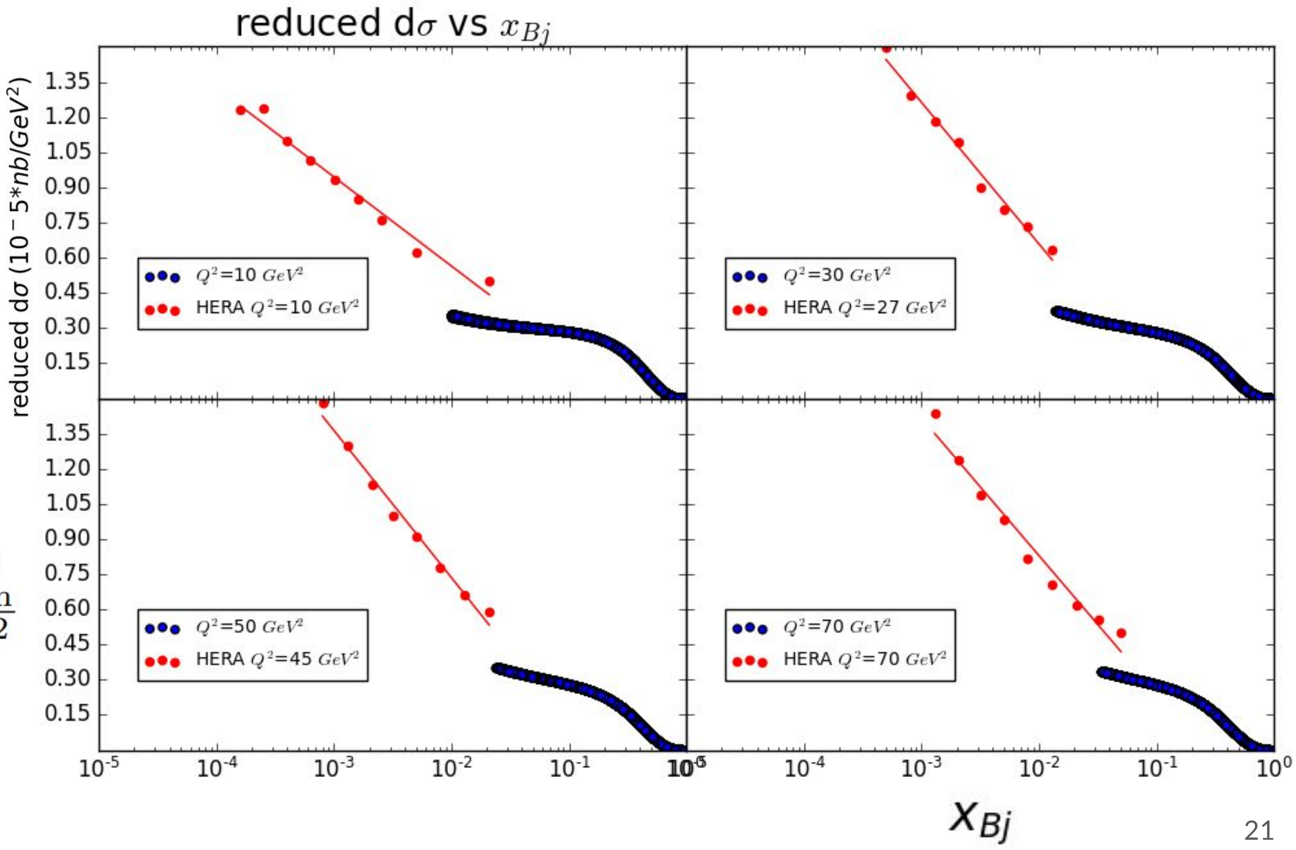
Daniele Binosi , Huey-Wen Lin, Timothy Hobbs, Arun Tadepalli, Rachel Montgomery, Paul Reimer, David Richards, Rik Yoshida, Craig Roberts, Garth Huber, Thia Keppel, John Arrington, Lei Chang, Stephen Kay, Ian L. Pegg, Love Preet, Jorge Segovia, Carlos Ayerbe Gayoso, Bill Li, Yulia Furletova, Dmitry Romanov,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

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)

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



F_{π} -> Selecting Good Simulated Events

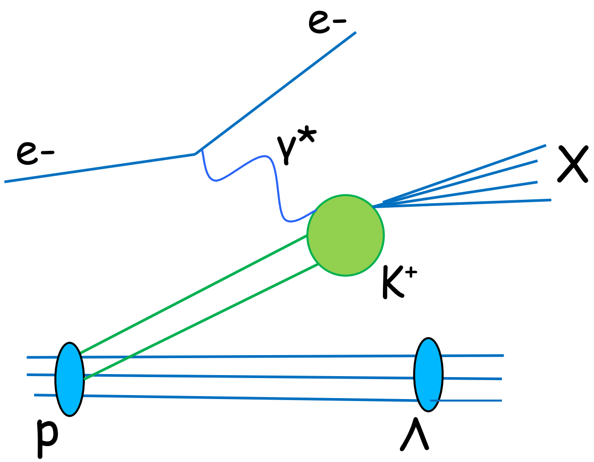
- Pass through a full Geant4 simulation (ECCE)
  - More realistic estimates of detector acceptance/performance than earlier studies
- Identify $e'\pi^{+}n$ triple coincidences in the simulation output
- For a good triple coincidence event, require -
  - Exactly two tracks
    - One positively charged track going in the +z direction (π+)
    - One negatively charged track going in the −z direction (e')
  - At least one hit in the zero degree calorimeter (ZDC)
  - For 5 (e', GeV) on 100 (p, GeV) events, require that the hit has an energy deposit over 40 GeV
- Both conditions must be satisfied
- Determine kinematic quantities for remaining events

Lambda Final State

- 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

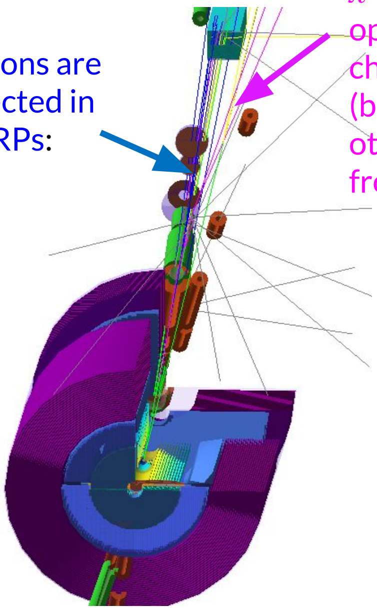
$$\Lambda \rightarrow p + \pi^{-}$$
$$\Lambda \rightarrow n + \pi^{0}$$

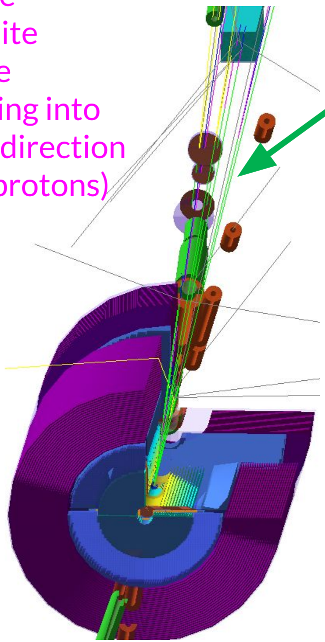
Protons are detected in the RPs:

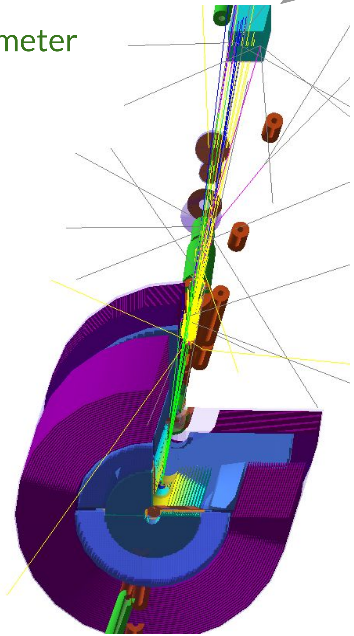
π^{-} have opposite charge (bending into other direction from protons)

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

Neutrons and a fraction of π^{0} goes into ZDC

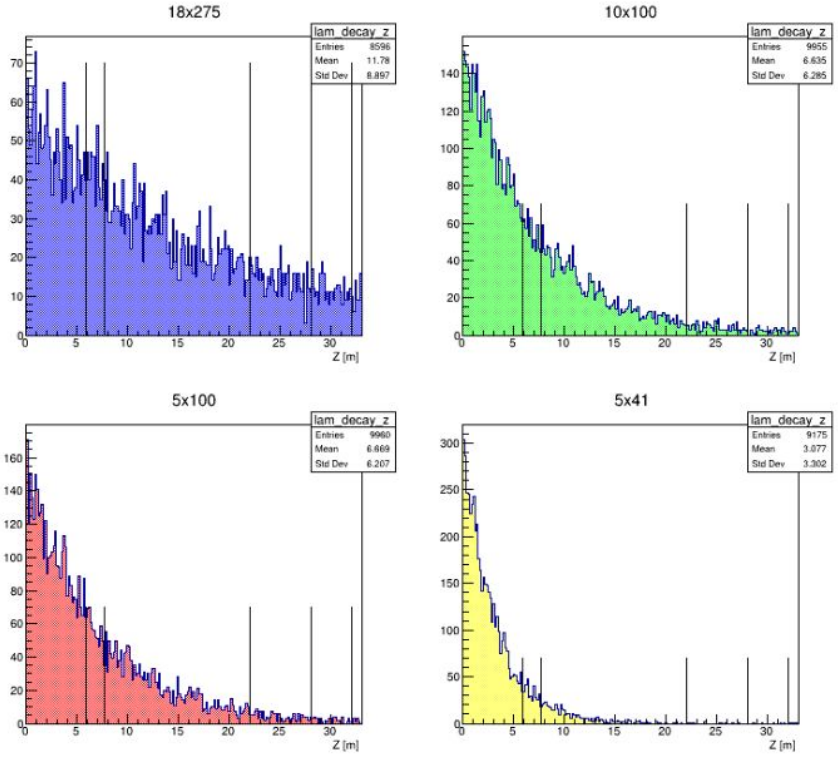


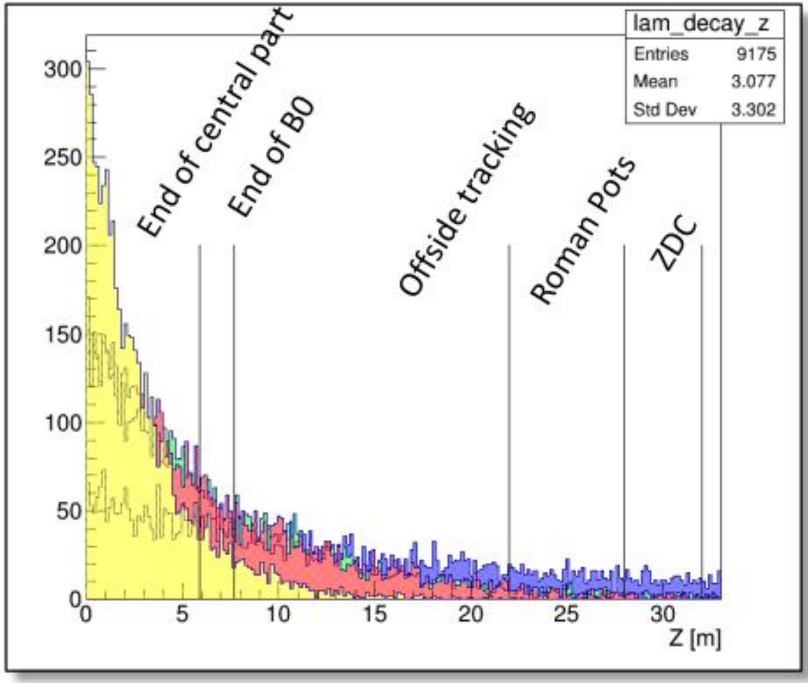




18 x 275

Decay Length





- There are some advantages for lower proton energy for K-Λ detection

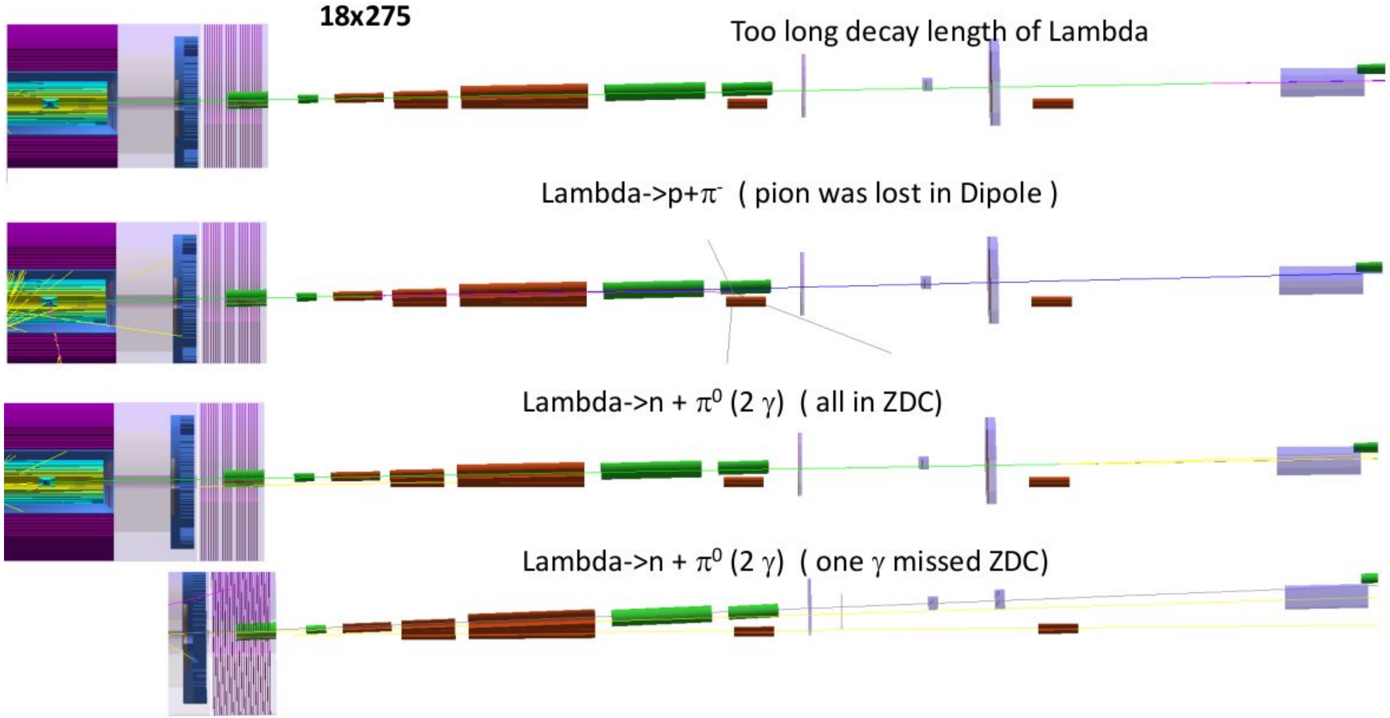
Lambda Final State

$\Lambda \rightarrow p+\pi-$: very challenging!

- need additional particle tracking between dipoles and ZDC

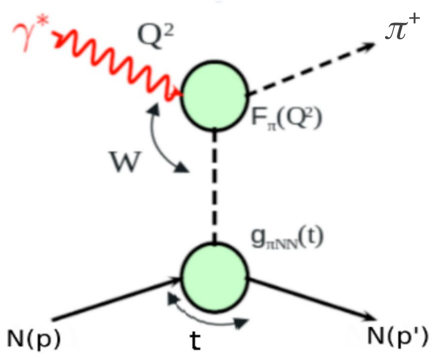
$\Lambda \rightarrow n+\pi^0$: looks promising

- need additional high-res/granularity EMCal+tracking before ZDC



π^+ Form Factors (F_π)

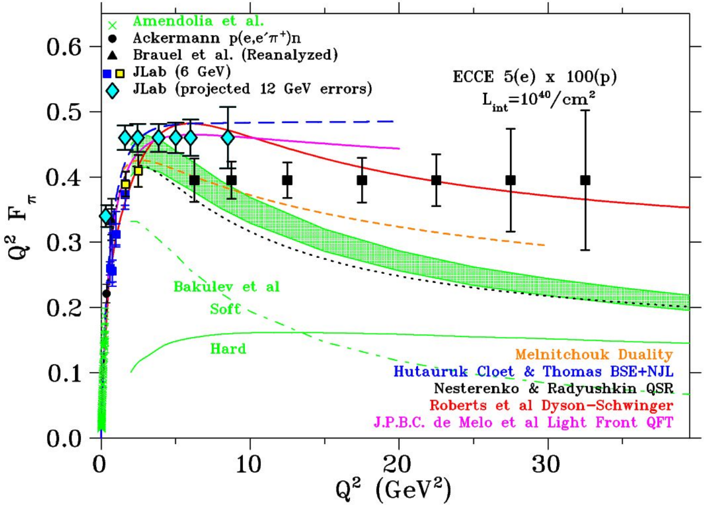
- Measurements of the p(e, e'π^+n) reaction at the EIC can potentially extend the Q^2 reach of F_π measurements even further
- A challenging measurement however
  - Need good identification of p(e, e'π^+n) triple coincidences
  - Conventional L-T separation not possible → would need lower than feasible proton energies to access low
  - Need to use a model to isolate $d\sigma_L/dt$ from $d\sigma_{uns}/dt$
- Utilize new EIC software framework to assess the feasibility of the study with updated design parameters
  - Feed in events generated from a DEMP event generator
  - Multiple detector concepts to evaluate



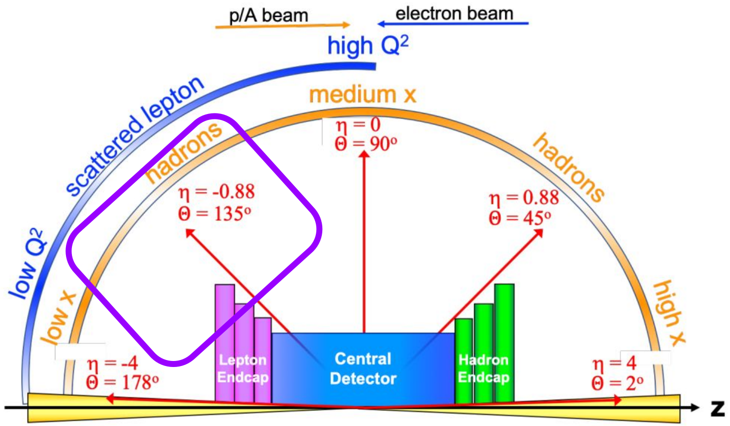
F_π Projections

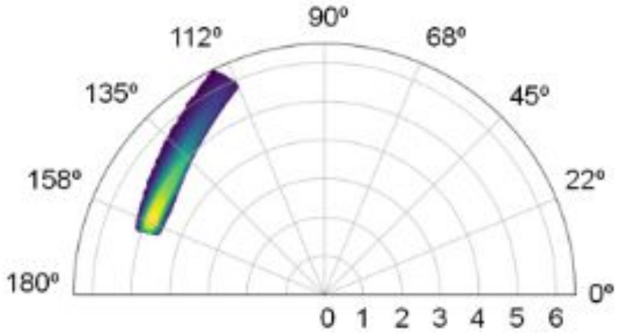
Analysis by Stephen Kay

- ECCE appears to be capable of measuring F_π to
  - $Q^2 \sim 32.5\ GeV^2$
- 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 upcoming ECCE NIM paper



Meson Form Factor - Scattered Electron

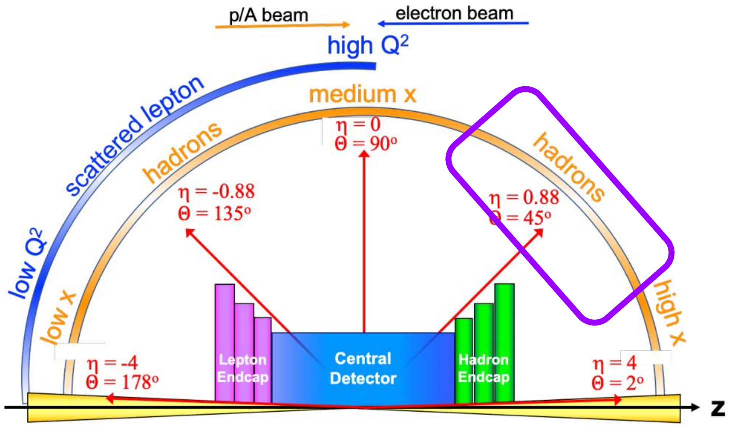


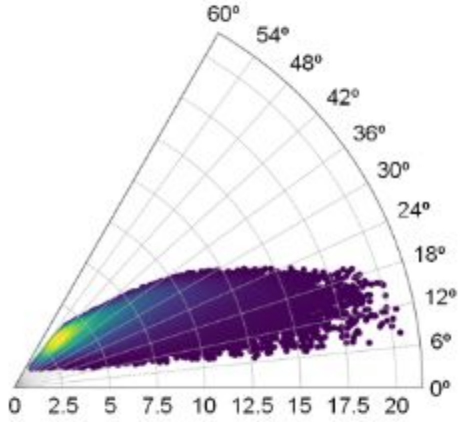


5x41

- The exclusive electron are stuck to a tighter band

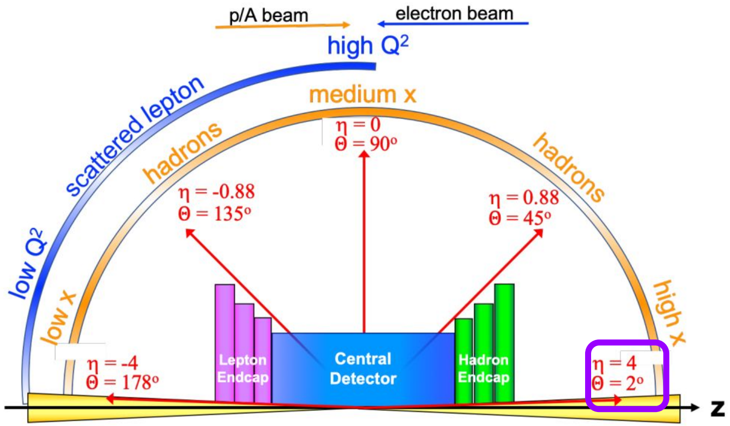
Meson Form Factor - Scattered π^+

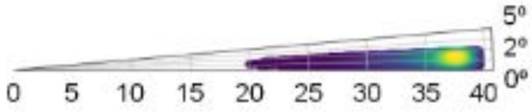




5x41

Meson Form Factor - Forward Neutron





5x41

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

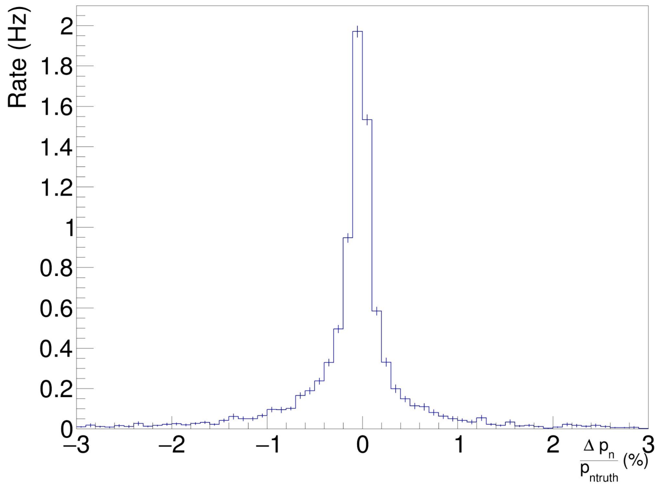
F_{π} Neutron Reconstruction

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

- 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

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

- 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



Plans for F_K projections

- Need to update DEMP with a kaon module
- URegina MSc student (Love Preet) is working on this module
  - Parameterization based upon previous data
  - Vrancx/Ryckebusch Regge model guidance
  - http://rprmodel.ugent.be/calc/
- Use similar approach to pion model in generator
  - Need Λ and Σ modules
- In parallel, will begin studies of Λ reconstruction in ZDC
  - Can use particle gun
  - May need to use likelihood analysis for Λ reconstruction
  - Should also examine charged decay channel
- Kaon model updates and simulations will be focus over the summer