Meson Structure at the EIC

ECCE Diffractive and Tagging WG

May 27th, 2021

Richard Trotta and the meson structure working group

Jefferson Lab

THE CATHOLIC UNIVERSITY OF AMERICA

Overview of Pion and Kaon Structure

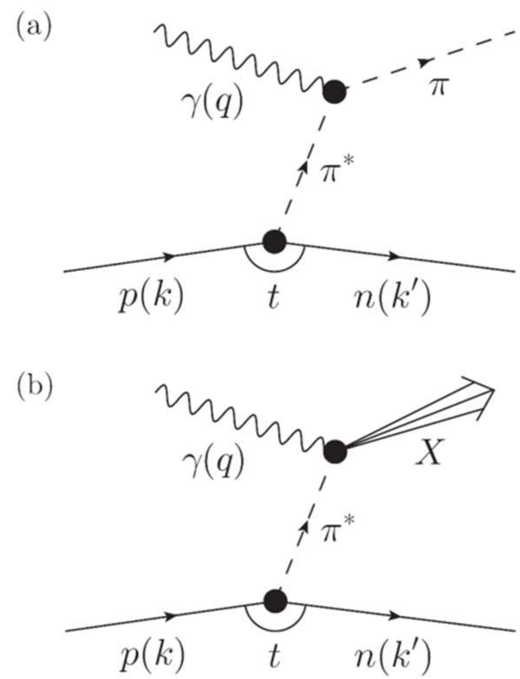
- The pion is both the lightest bound quark system with a valence $\bar{q}q$ structure and a Nambu-Goldstone boson

- 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 contrast (e.g. the CQM), bound state mass rises linearly with constituent mass - in the nucleon $m_Q \sim ⅓ m_N \sim 310$ MeV, in the pion $m_Q \sim ½ m_\pi \sim 70$ MeV, in the kaon (with one s quark) $m_Q \sim 200$ MeV (This is not real)
    - In both DSE and lQCD, the mass function of quarks is the same, regardless of what hadron the quarks reside in (This is real). It is the DCSB that makes the pion and kaon masses light.

- Pseudoscalar masses are generated dynamically

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

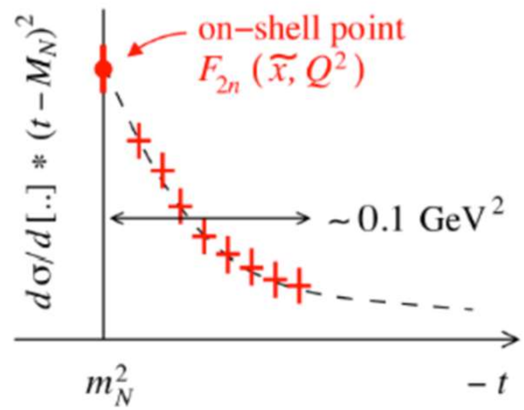


Pion cloud can access a) Elastic FF b) PDF

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

Off-Shell Considerations

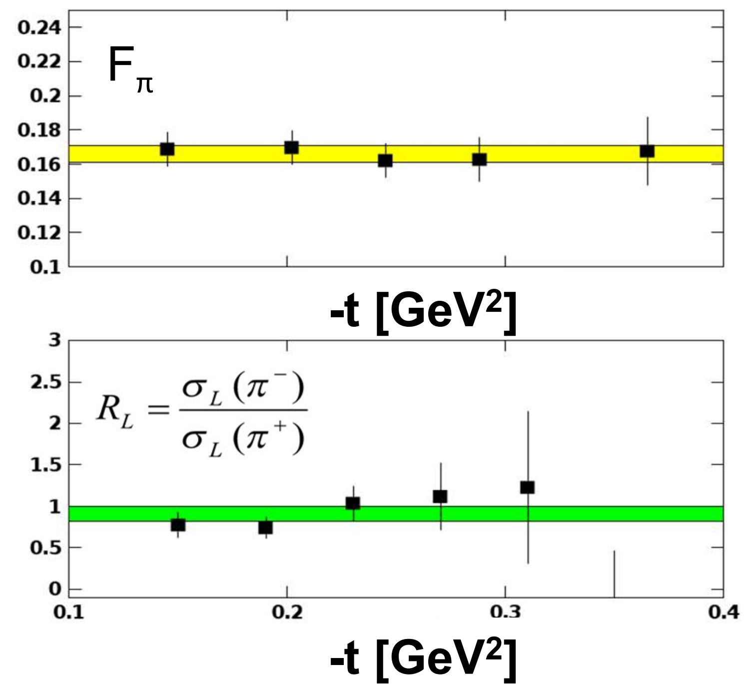
- The Sullivan process can provide reliable access to a meson target as t becomes space-like
- If the pole associated with the ground-state meson remains the dominant feature of the process
  - the structure of the related correlation evolves slowly and smoothly with virtuality
- Recent theoretical calculations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



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

Experimental Validation

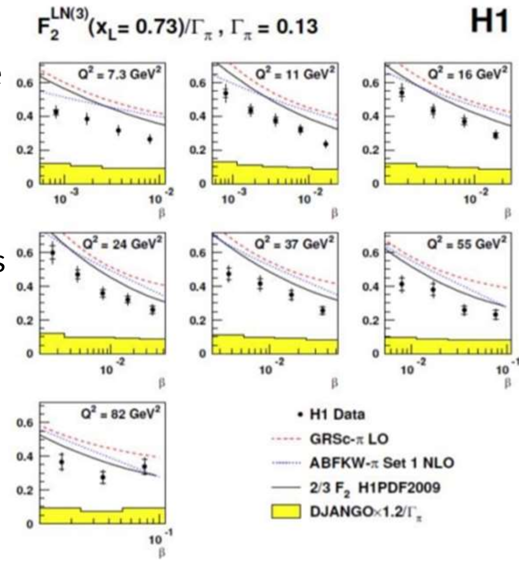
- To check these conditions are satisfied empirically...
  - data is taken covering a range in t
  - compare this data with phenomenological and theoretical expectations
    - F_π values do not depend on -t to give confidence in applicability of model to the kinematic regime of the data
  - Verify that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

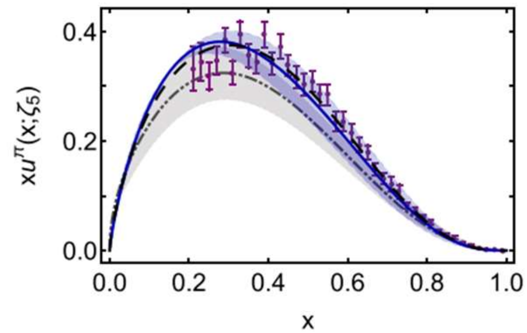


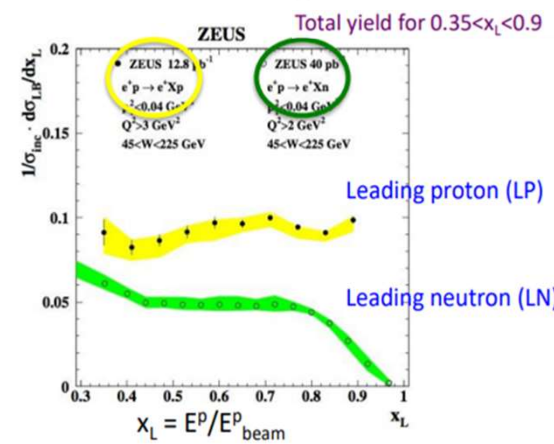
T. Horn, C.D. Roberts, J. Phys. G43 (2016) no.7, 073001
G. Huber et al, PRL112 (2014)182501
R. J. Perry et al., arXiV:1811.09356 (2019)

Pion Structure Function Measurements

- Knowledge of the pion structure function is very limited…
  - HERA TDIS data - at low x through Sullivan process (left)
  - Pionic Drell-Yan from nucleons in nuclei - at large x (right)
- 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…



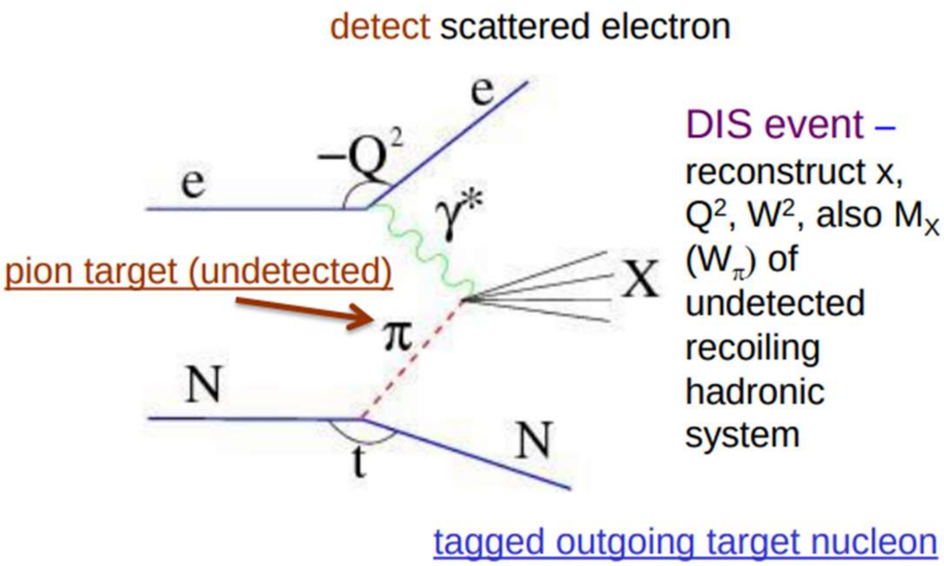


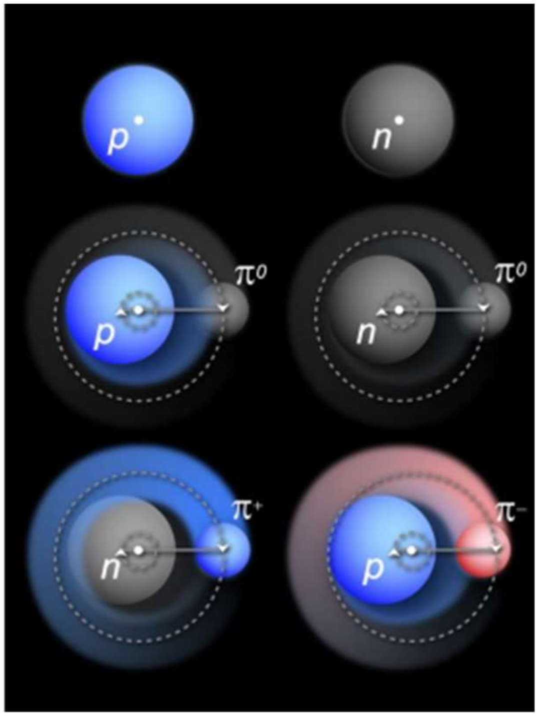


DESY 08-176 JHEP06 (2009) 74
Eur. Phy. J. C (2020) DOI:10.1140/epjc/s10052-020-08578-4

Tagged Deep Inelastic Scattering (TDIS)

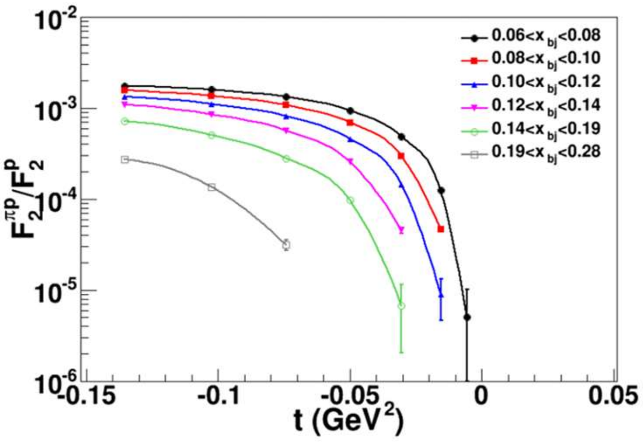
- Using the Sullivan process – scattering from nucleon-meson fluctuations





EIC Capabilities

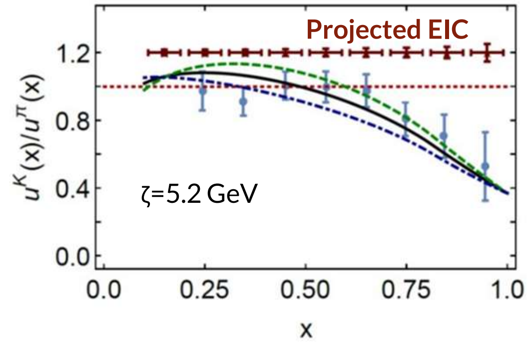
- $L_{EIC} = 10^{34}$ e-nucleons/cm²/s = 1000 x L_{HERA}
- Fraction of proton wave function related to pion Sullivan process is roughly 10^{-3} for a small −t bin (0.02)
  - pion data at EIC should be comparable or better than the proton data at HERA, or the 3D nucleon structure data at COMPASS
- By 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

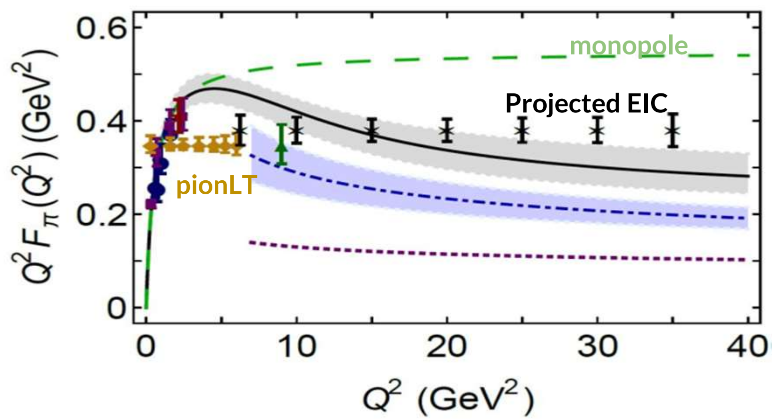


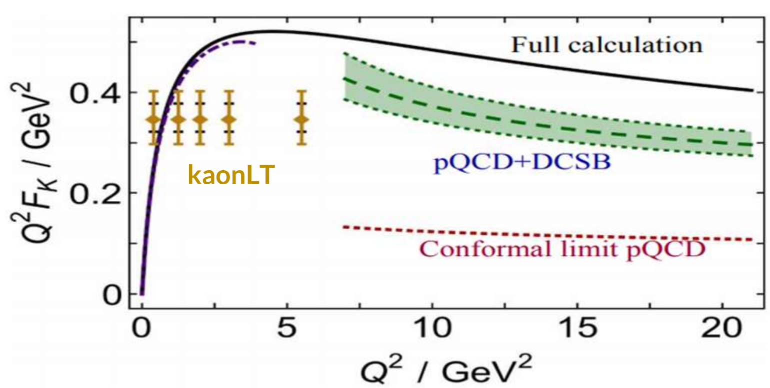
Jefferson Lab TDIS Collaboration, JLab Experiment C12-15-005 Proposal

2019 EPJA Pion and Kaon Structure Projections

- The EPJA paper projects a wide range of structure function data
- Projected Q^2 pion FF data up to 35 GeV^2
- Ratio of valence quark data projected at 1.2



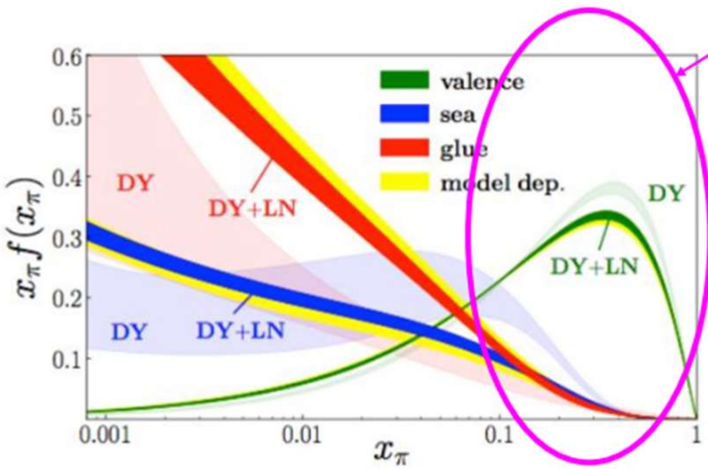




Arlene C. Aguilar, et al., Eur. Phy. J. A (2019) DOI:10.1140/epja/i2019-12885-0

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



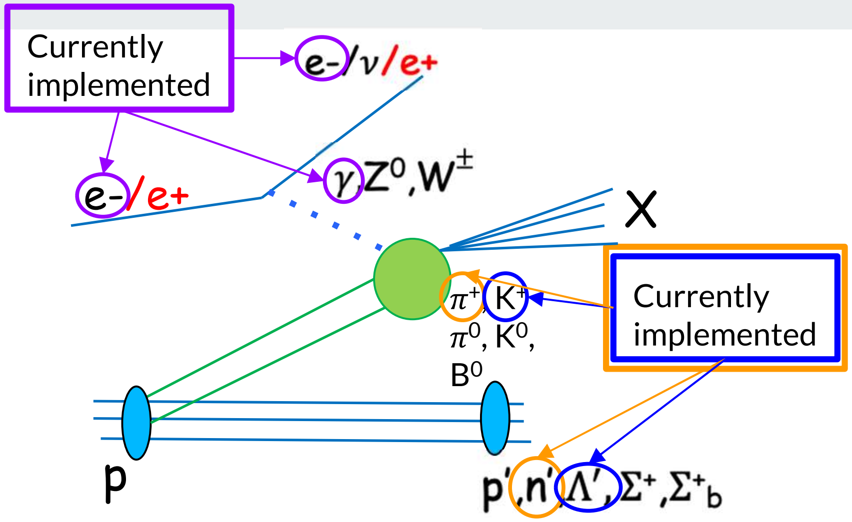
Barry, Sato, Melnitchouk, Ji (2018), Phys. Rev. Lett. 121 (2018) no.15, 152001

- ❑ 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

Structure Functions (SF)

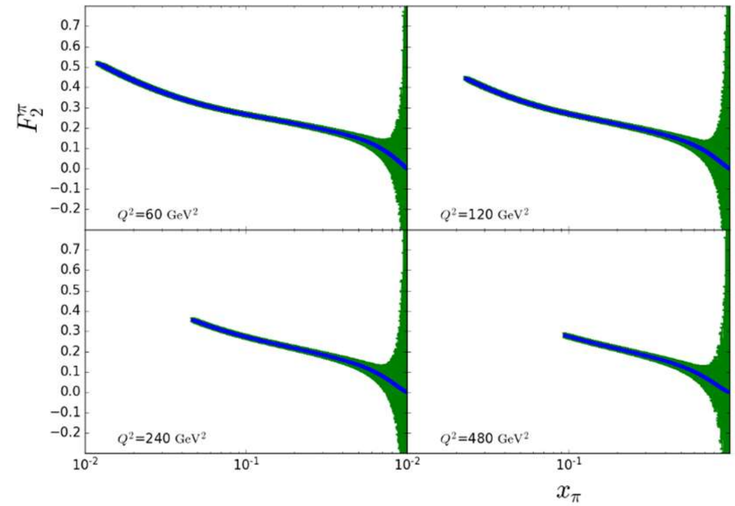


- For projections use a Fast Monte Carlo that includes the Sullivan process
  - PDFs, form factor, fragmentation function projections

- Progress with generator development since 2019 EPJA article:
  - now can make pion structure function (pion SF) projections
  - Published article in JPhysG (arXiv:2102.11788)

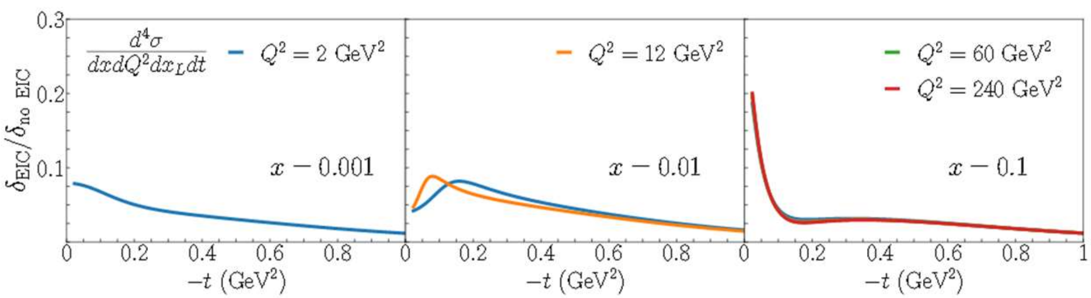
- π structure function: Measure DIS cross section with tagged neutron at small -t
- K structure function: Measure DIS cross section with tagged Λ/Σ at small -t
- Beam energies: 5 on 41, 5 on 100, 10 on 100, 10 on 135, 18 on 275
  - Only e-P currently implemented, but want to incorporate e-D

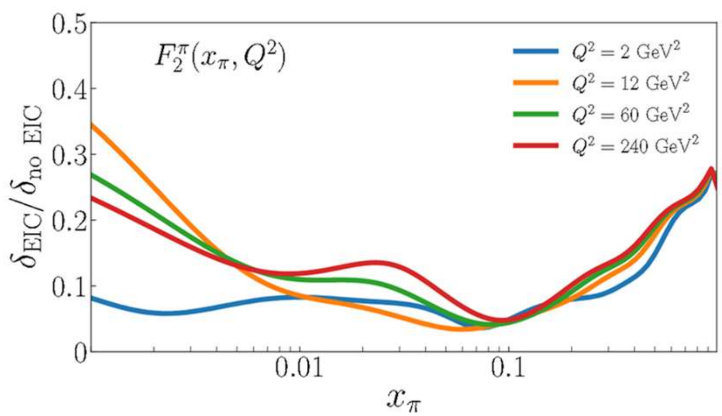
NLO through pion PDFs



Pion SF 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





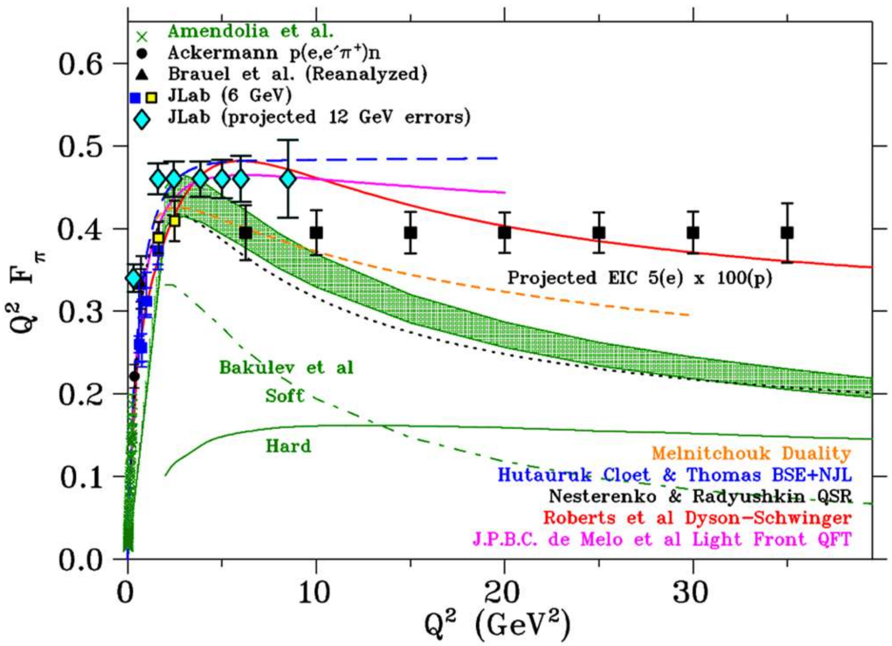
J Arrington, et al., J. Phys. G (2021) arXiv:2102.11788

π^+ Form Factors

- 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 difficult measurement to make
  - Using the events generated from DEMP
  - EIC software framework can assess the feasibility of the study with updated design parameters

π^+ Form Factor Projections

- Measurements of the p(e,e'π^+n) reaction at the EIC have the potential to extend the Q^2 reach of F_π measurements even further
- Note - y positioning of points arbitrary
- Preliminary pion studies featured in the yellow report
- Generator modifications for ECCE simulations in progress
- Generator will be extended to investigate F_K too
- Preliminary kaon studies in now in progress
- For F_K, need to study Σ reconstruction and detection too



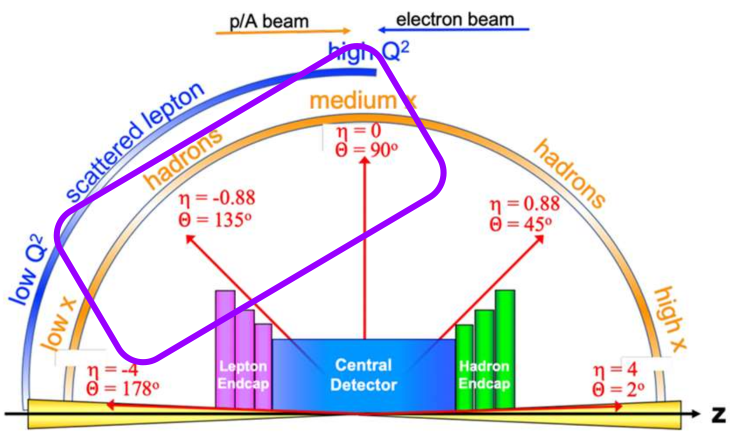
Geometric particle detection fractions

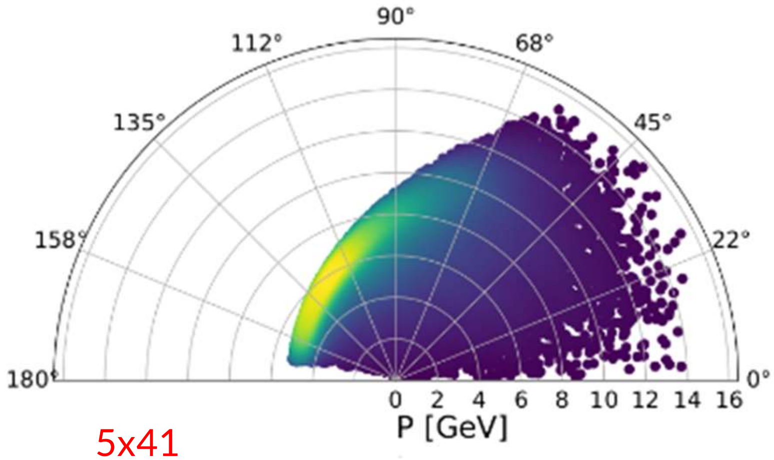
- For the pion structure function, the final state neutron moves with an energy near that of the initial proton beam
  - The Zero Degree Calorimeter (ZDC) must reconstruct the energy and position well enough to constrain both scattering kinematics and 4-momentum of pion
  - Constraining neutron energy 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

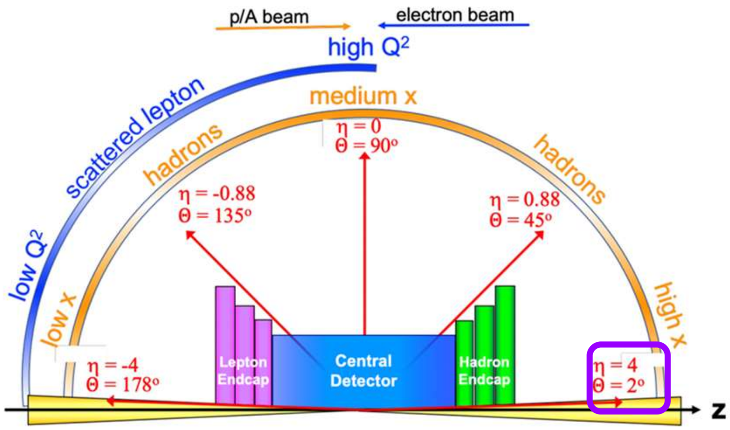
Meson Structure Functions – Scattered Electron

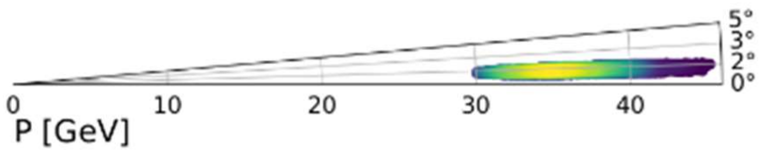




- Scattered electrons can be detected in the central detector

Meson Structure Functions – Forward Baryon

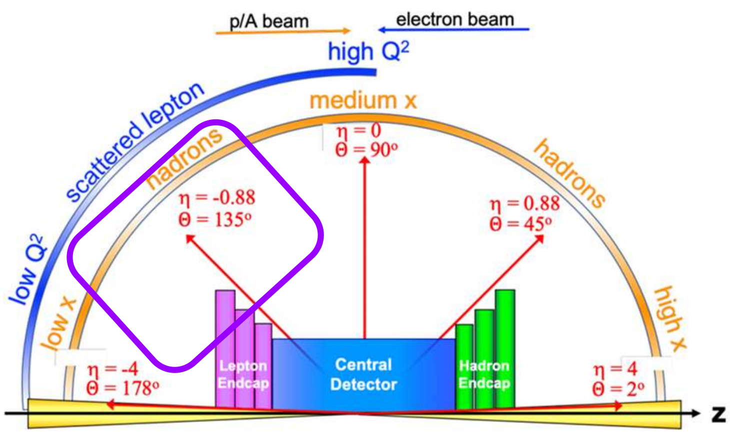


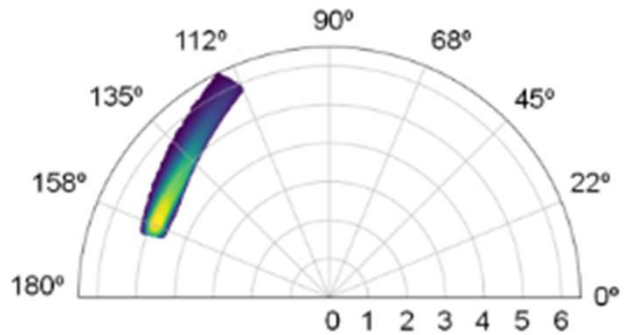


5x41

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

Meson Form Factor - Scattered Electron

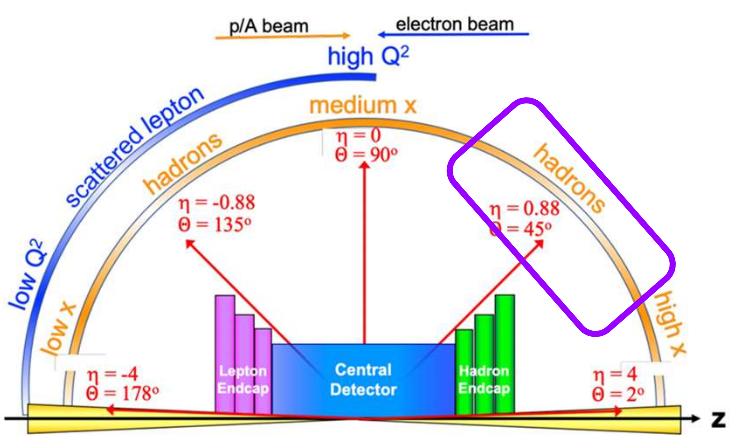


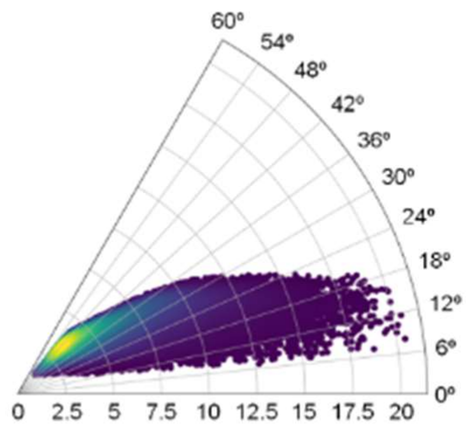


5x41

- The exclusive electron are stuck to a tighter band

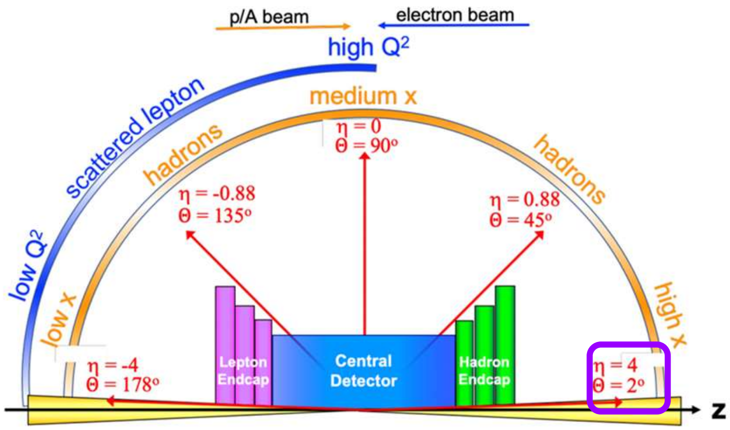
Meson Form Factor - Scattered π^+

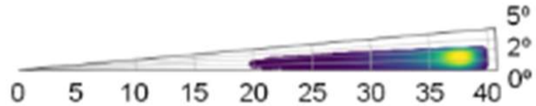




5x41

Meson Form Factor - Forward Neutron



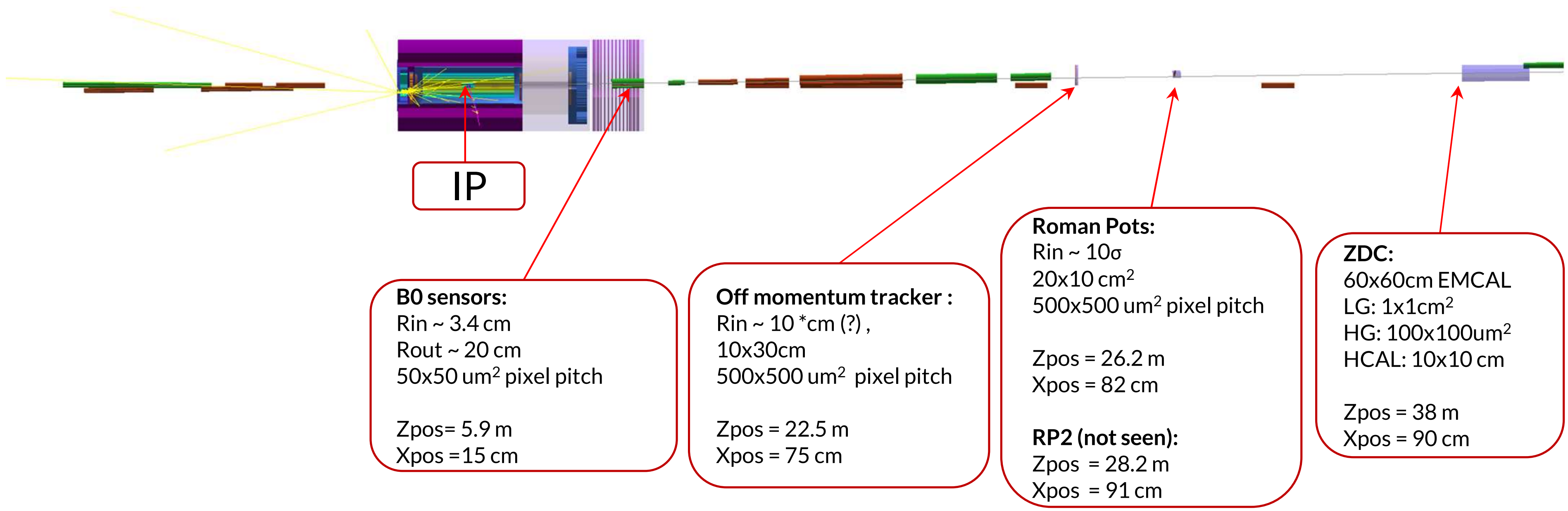


5x41

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

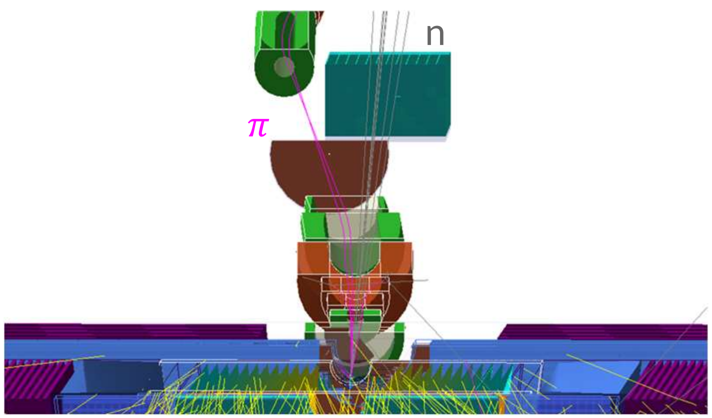
GEANT4 for EIC

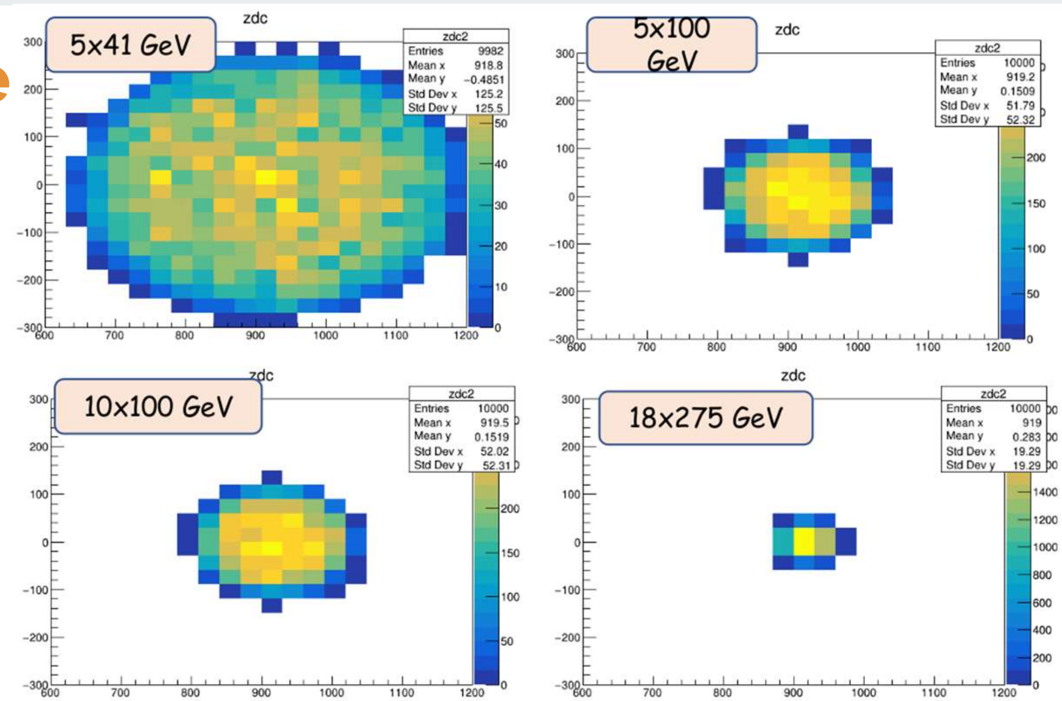
- Meson structure MC outputs lund files for use in GEANT4
    - Next goal is to include integration to Fun4All



Neutron Final State

- 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

Neutron Final State

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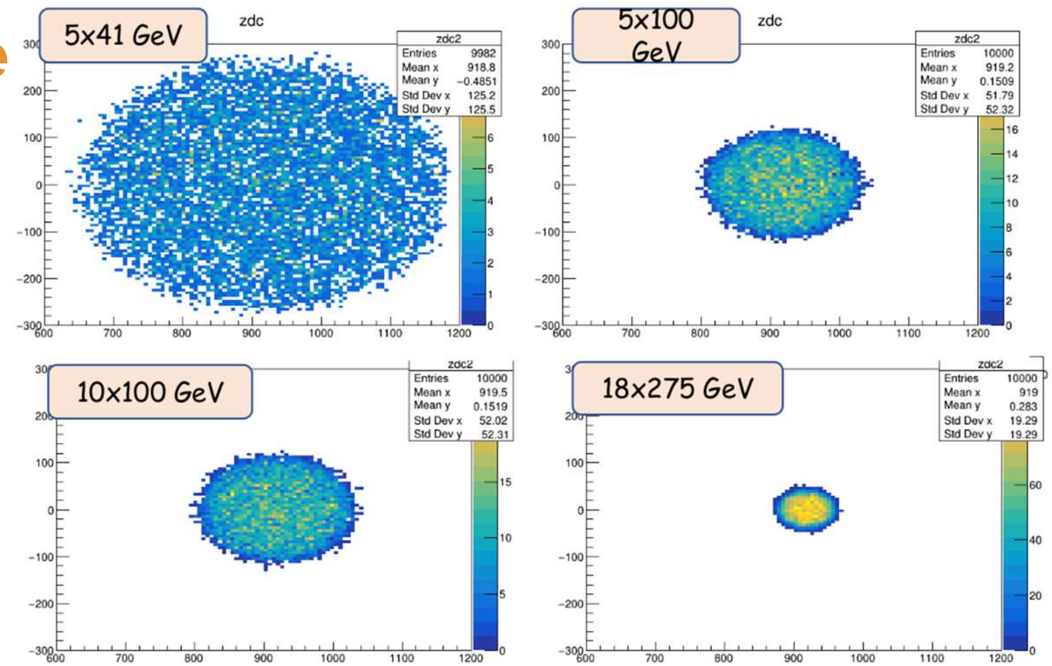
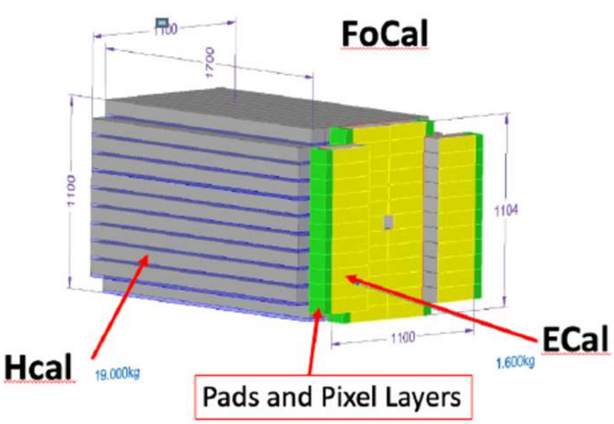




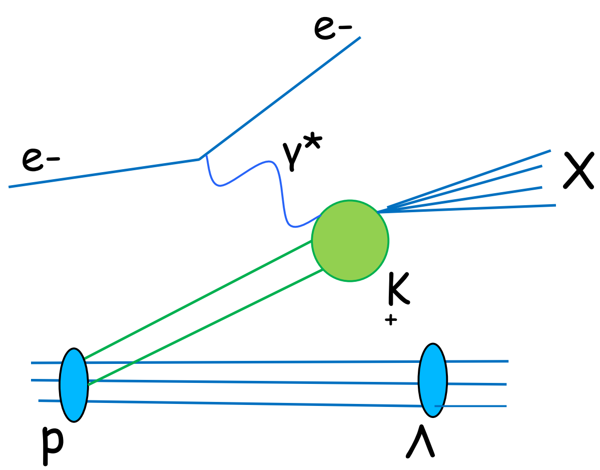
- ZDC: [60x60 cm, 100 bins → 0.6 cm towers]
- If we want energies over 100 GeV, we will need resolution of ~1 cm or better

Lambda Final State

- Λ has two primary decay modes...

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

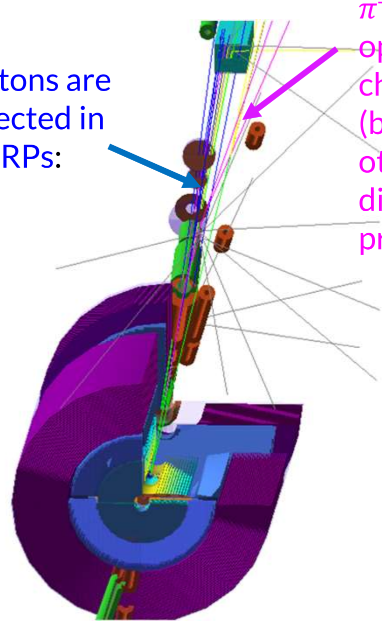
- Optimizing the detection efficiency of these decay products is critical for kaon studies
- The decay length of Λ is dependent on the initial proton beam energy
  - Proper choice of this beam energy is a must since decay lengths can reach past the forward spectrometer at higher energies



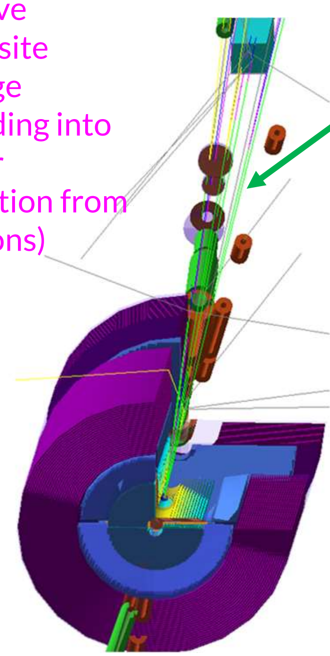
Lambda Final State

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

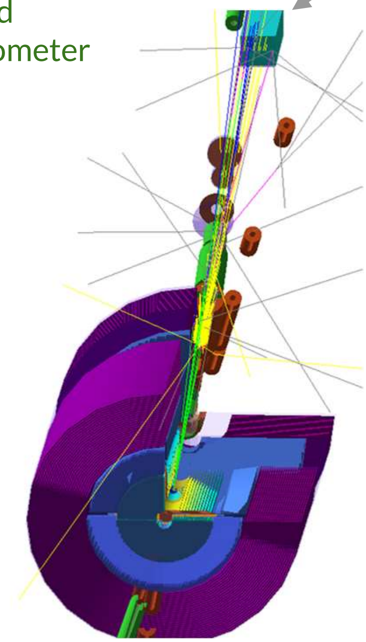
Protons are detected in the RPs:



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



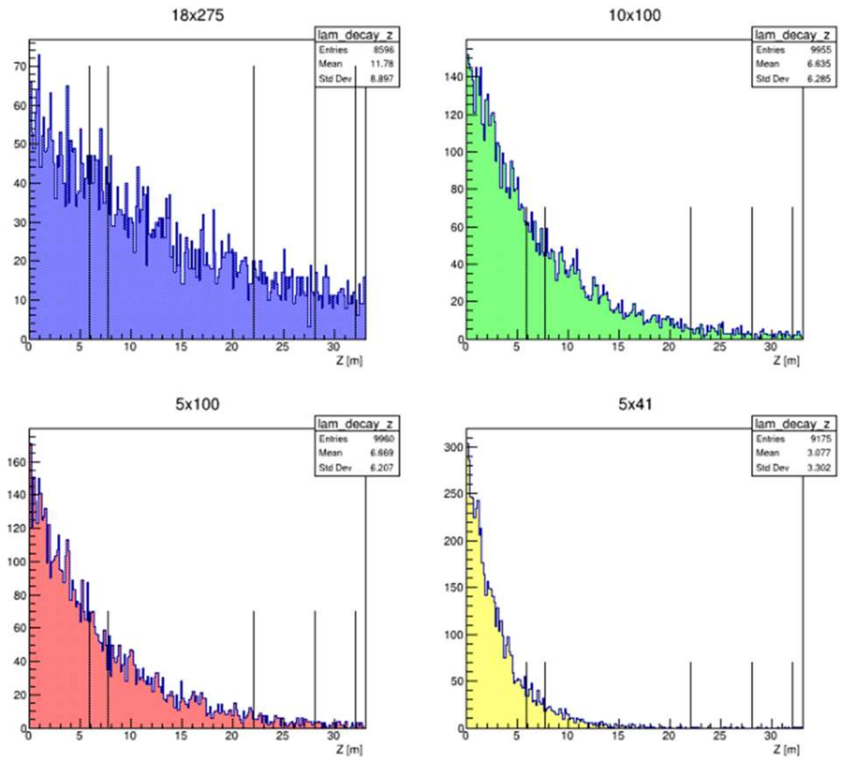
30% of Λ at high energy does not decay before forward spectrometer

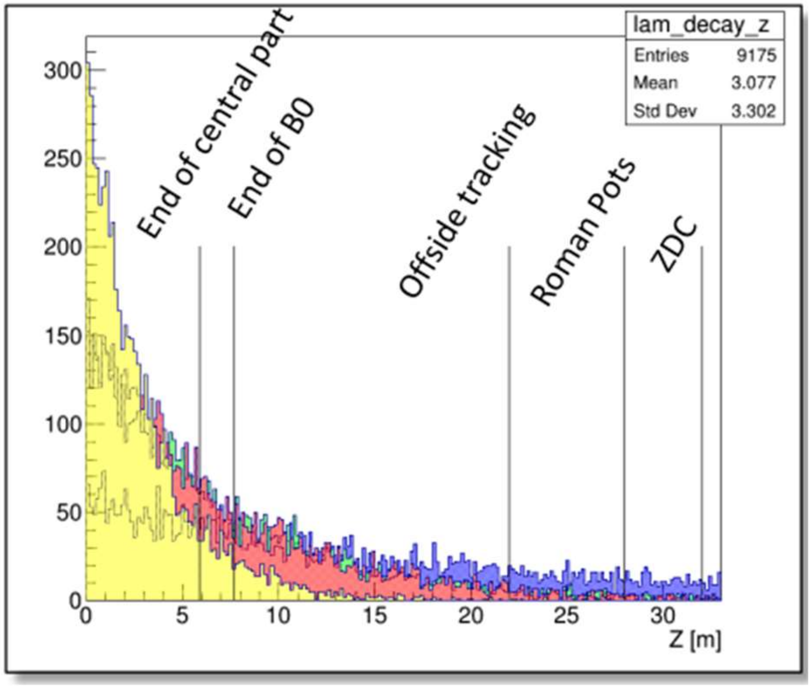


Neutrons and a fraction of π^{0} goes into ZDC

18 x 275

Decay Length





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

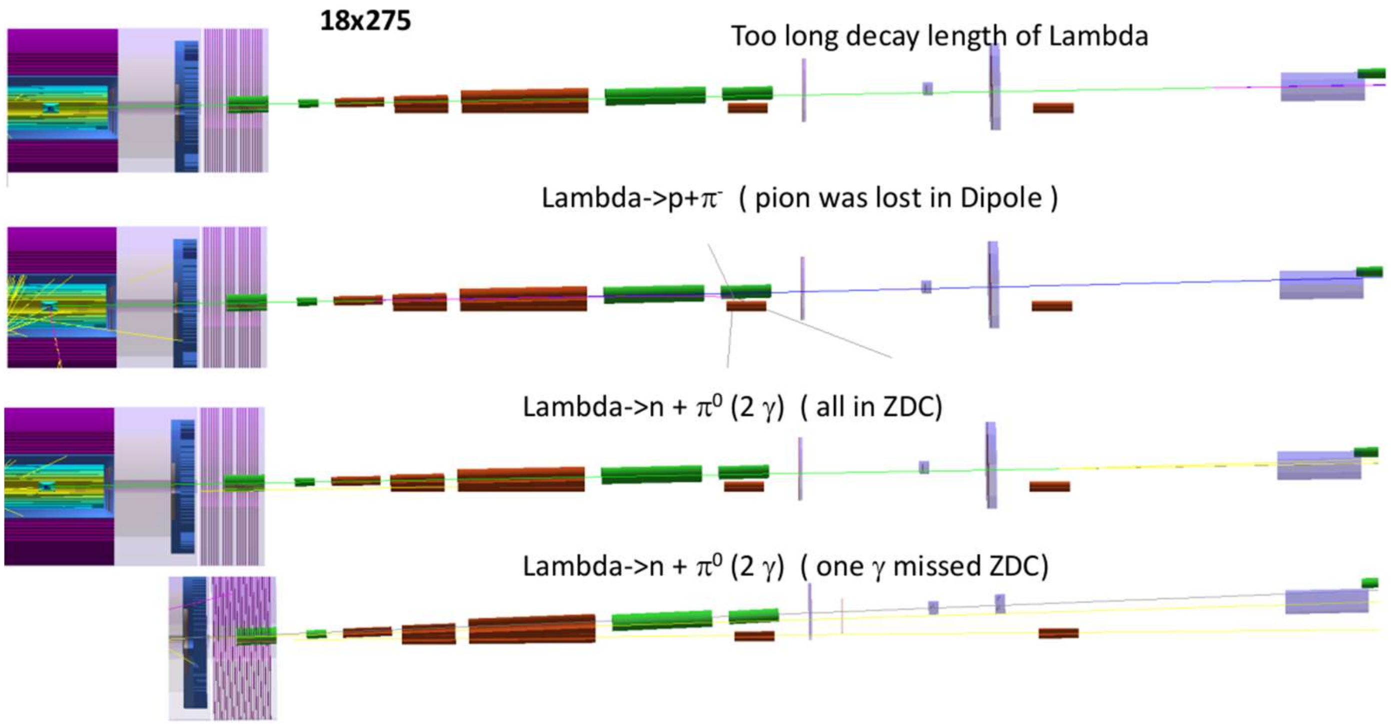
Lambda Final State

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

- need additional particle tracking between dipoles and ZDC

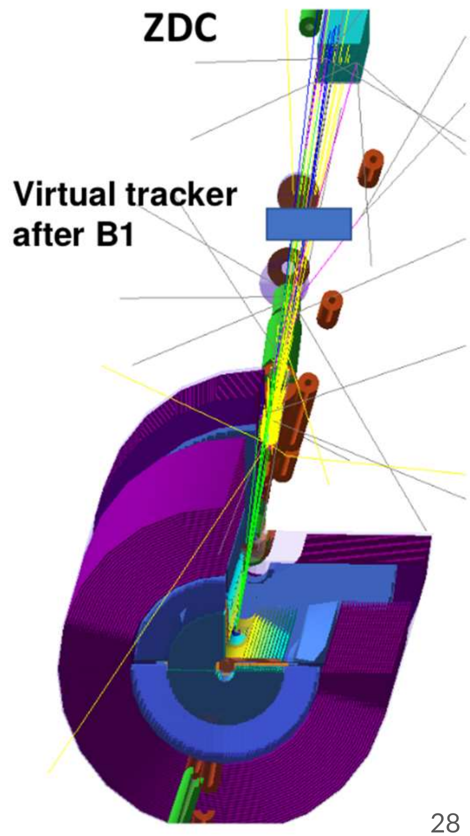
$\Lambda \rightarrow n + \pi^0$: looks promising

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



Summary of Detector Requirements

- For π^+/n...
  - For all energies, the neutron detection efficiency is ~100% with planned ZDC
  - Lower energies [5 on 41, 5 on 100], **require at least 60cmx60cm size** to access wider range of energies
- For π^+/n and K^+/Λ...
  - All energies need good ZDC angular resolution for the required t resolution
  - High energies [10 on 100, 10 on 135, 18 on 275] **require resolution of 1 cm or less**
- K^+/Λ benefits from low energies [5 on 41, 5 on 100] and also need...
  - $\Lambda \rightarrow n+\pi^0$: additional high-res/granularity
    - **EMCal+tracking before ZDC** (seems doable)
  - $\Lambda \rightarrow p+\pi^-$: additional trackers/veto in opposite charge direction on path to ZDC (more challenging)
- [In progress] Good hadronic calorimetry to obtain good x resolution at large x
- Next goal is a similar analysis for the 2nd IR



Future F_2^π projections

- Only ZEUS parameterization for F_2^π is currently implemented
  - next step would be checking with other pion SF parameterizations
  - parameterizations depend on how pion SF is regulated
  - varying theory inputs for models and checking how they fit MC pseudo-data

- Goal is to achieve more comprehensive control/quantification of theory/model uncertainties
  - explore limitations of Sullivan and single-pion exchange framework
  - implement additional contributions; e.g., Regge-theoretic modes
  - these uncertainties are entangled in simulations with the pion structure function (PDF) errors; the combined theory uncertainty must be mapped

Future F_2^K projections

- Goal is to extend to tagged kaon structure function
- Very limited data on F_2^K
- 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. A ***47*** *(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

Full talk at 2020 Pion/Kaon Workshop

1. 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 “X” and tagged Λ/Σ (K structure function)

2. Evaluated with simulations detector performance/requirements
   - Standard detection requirements
   - For the tagged neutron at all energies: ~100% detection efficiency
     - Low energies [5 on 41, 5 on 100] **require at least 60cmx60cm size** to access wider range of energies
     - High energies [10 on 100, 10 on 135, 18 on 275] **requires resolution of 1 cm or less**
   - For measuring the tagged Λ benefits from low energies [5 on 41, 5 on 100] and needs...
     - $\Lambda \rightarrow n + \pi^0$: additional high-res/granularity
       - **EMCal+tracking before ZDC** (seems doable)
     - $\Lambda \rightarrow p + \pi^-$: additional trackers/veto in opposite charge direction on path to ZDC (more challenging)
   - Next goal is a similar analysis for the 2nd IR and integrate Fun4All framework

Meson structure working group members!

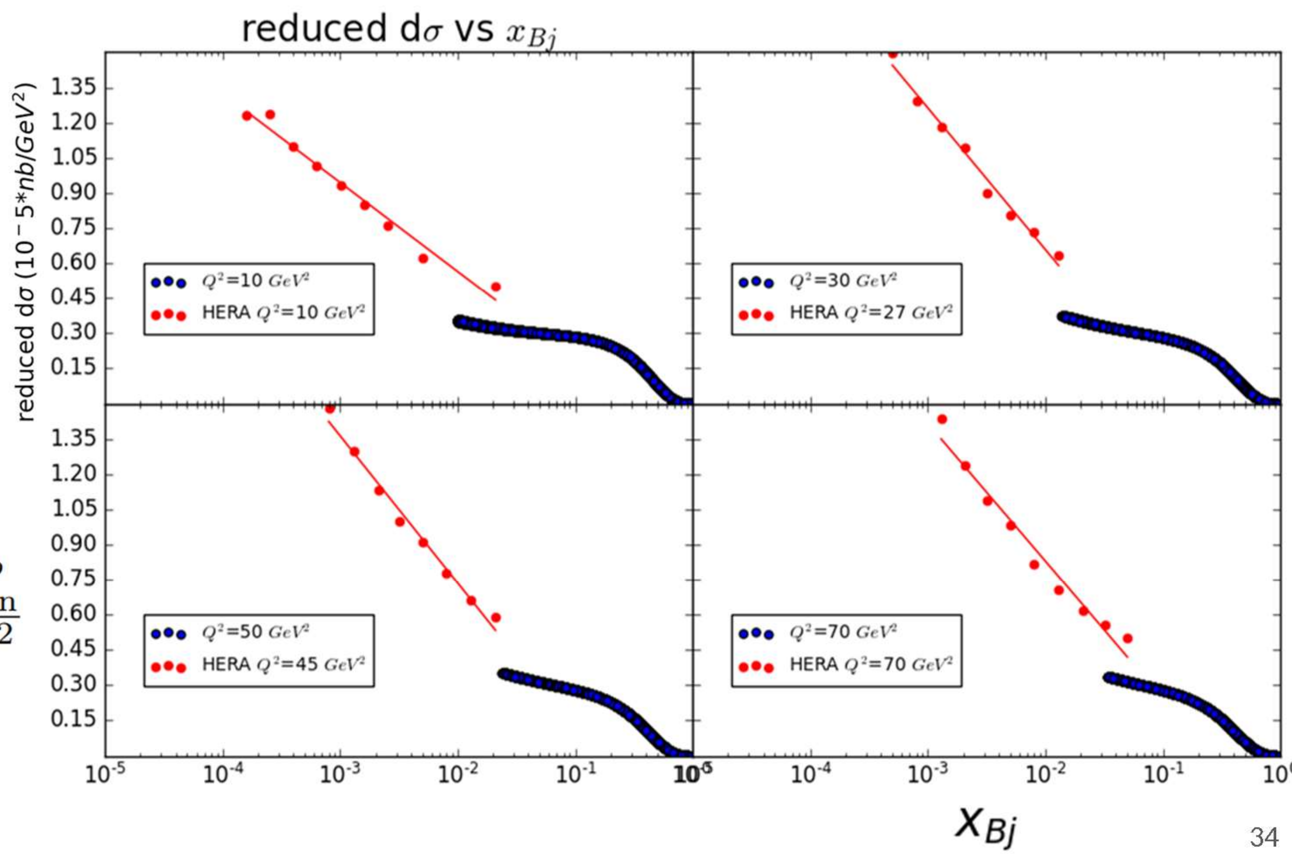
Daniele Binosi , Huey-Wen Lin, Timothy Hobbs, Arun Tadepalli, Rachel Montgomery, Paul Reimer, David Richards, Rik Yoshida, Craig Roberts, Garth Huber, Thia Keppel, John Arrington, Lei Chang, Stephen Kay, Ian L. Pegg, Jorge Segovia, Carlos Ayerbe Gayoso, Bill Li, Yulia Furletova, Dmitry Romanov, Markus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

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)

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



Kinematic Variables

$$Q^2 = Q^2_{max} uu + Q^2_{min}(1 - uu)$$

$$uu = ran3.Uniform(\,)$$

$$x_{Bj} = (x_{min})^{1-uu}(x_{max})^{uu}$$

$$x_\pi = \frac{x_{TDIS}}{1-(p2)_z}$$

$$(p2)_z = gRandom -> Uniform(1)$$

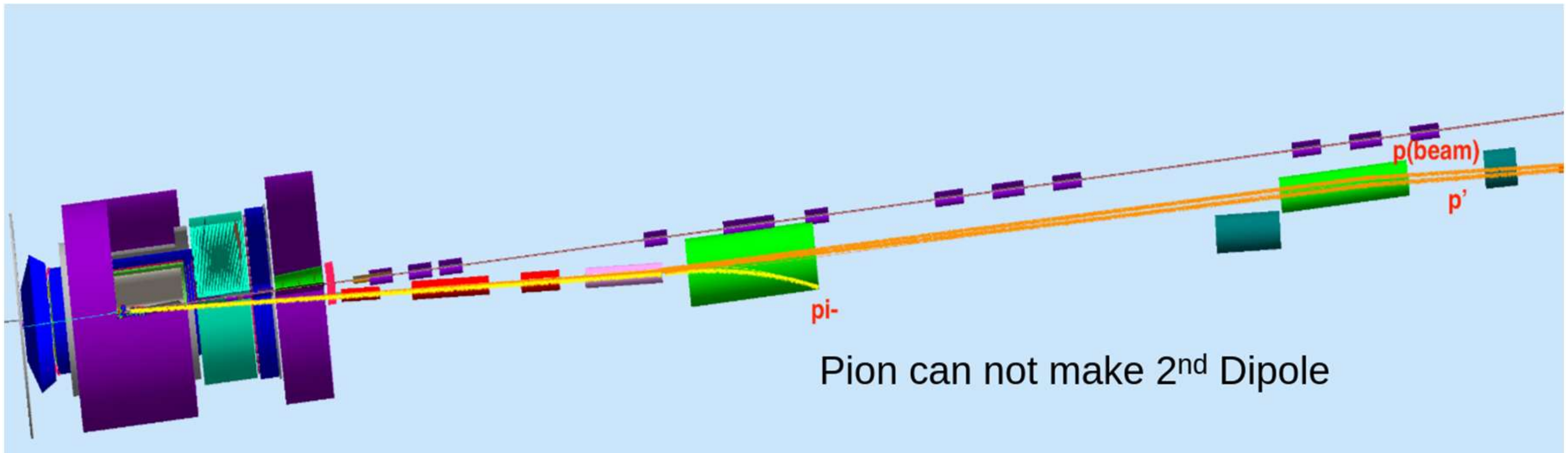
$$y_\pi = \frac{(pScatPion)_{rest}(qVirt)_{rest}}{(pScatPion)_{rest}(kIncident)_{rest}}$$

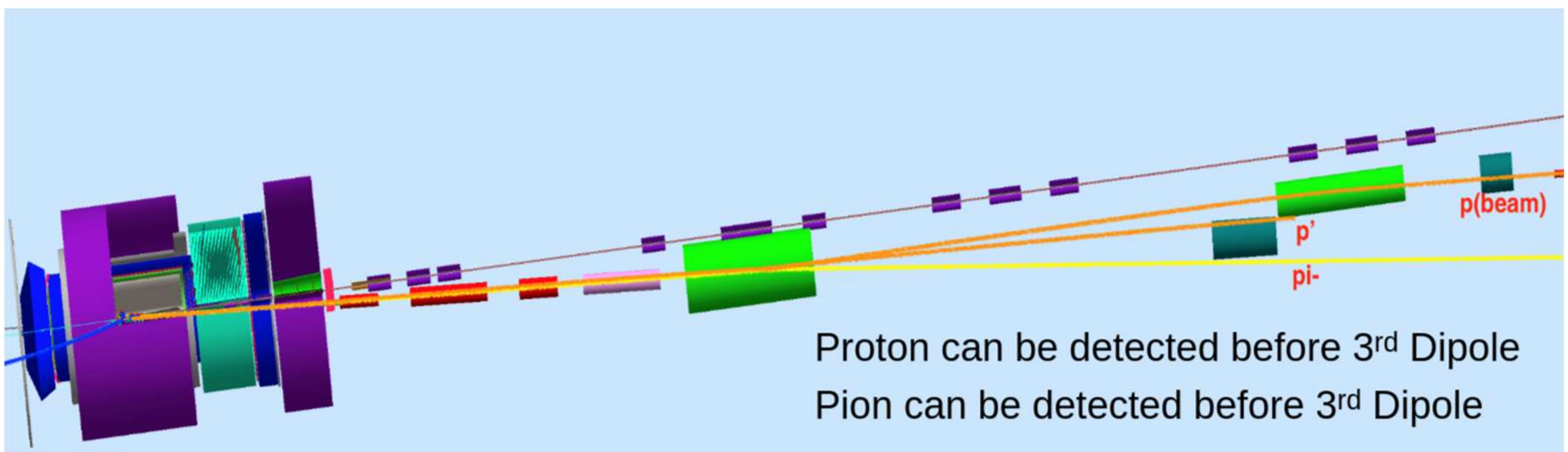
$$t_\pi = E^2_\pi - |pScatPion.v3|^2$$

$$x_D = x_{Bj}\left(\frac{M_{proton}}{M_{ion}}\right)$$

$$y_D = \frac{Q^2}{x_D(2p \bullet k)}$$

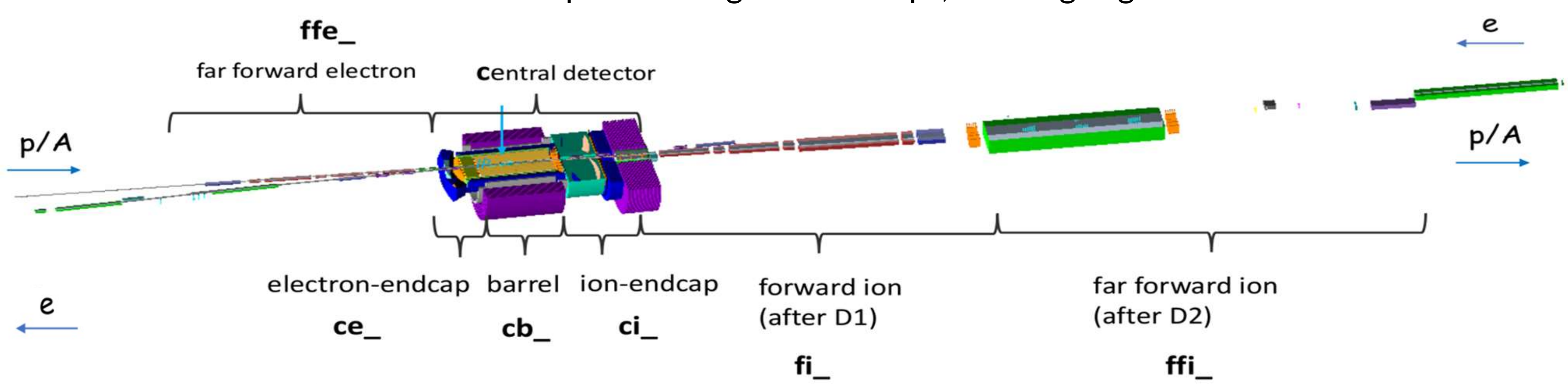
Detection of $^1H(e,e'K^+)\Lambda$, Λ decay to p + π^-



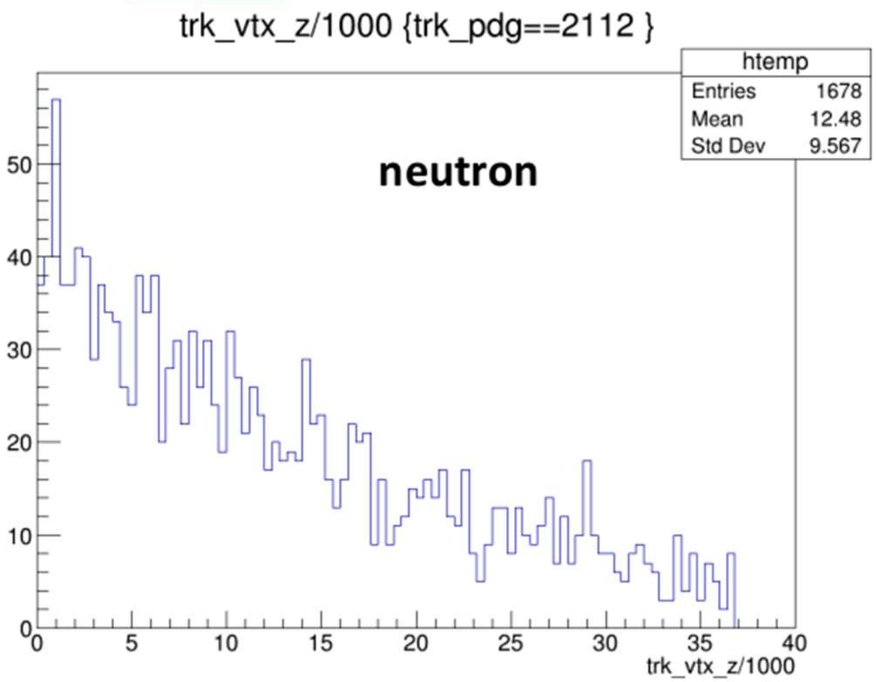


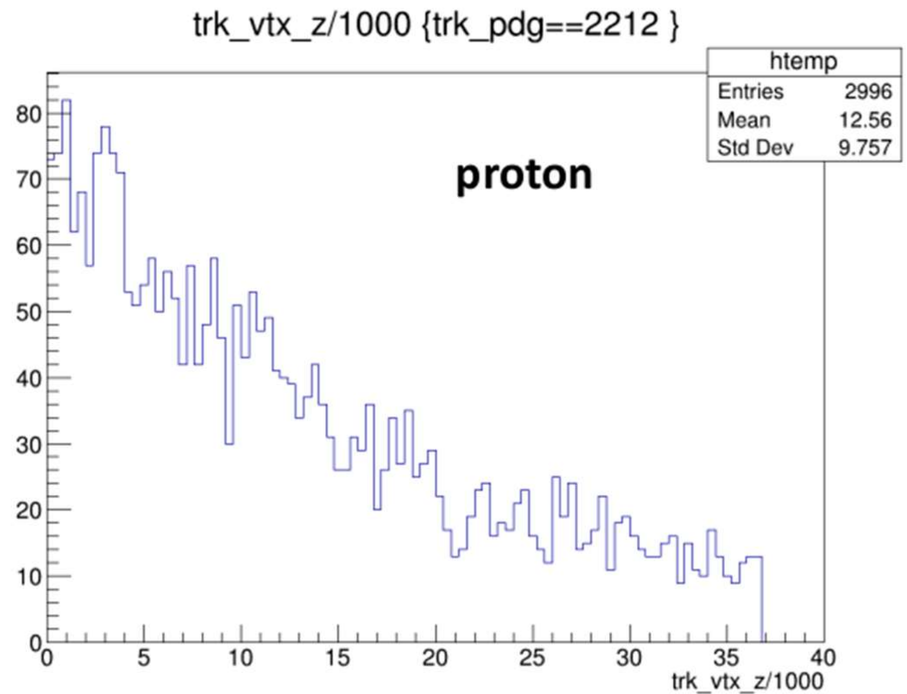
GEANT4 for EIC

- Meson structure MC outputs lund files for use in GEANT4
- Detector MC updated with eRHIC specifics (crossing angle changes primarily)
- Updates to electron beam line
  - Solenoid centered at zero - this cannot be changed as it affects the beamline
  - IR region was the same size for JLEIC and eRHIC design, so can use JLEIC detector in eRHIC beam line.
  - Modulo beam line required changes in end caps, crossing angles



Decay Length [p(e,e'$K^+\Lambda^0$)X]



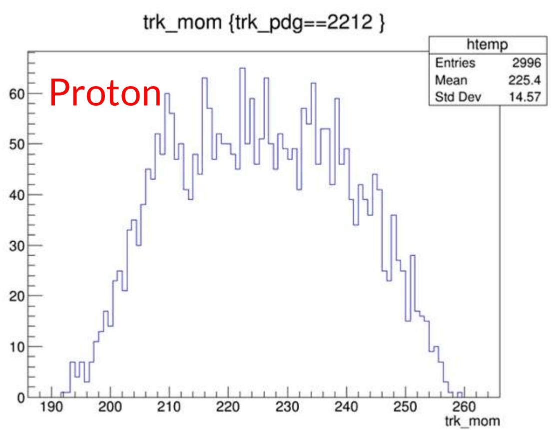


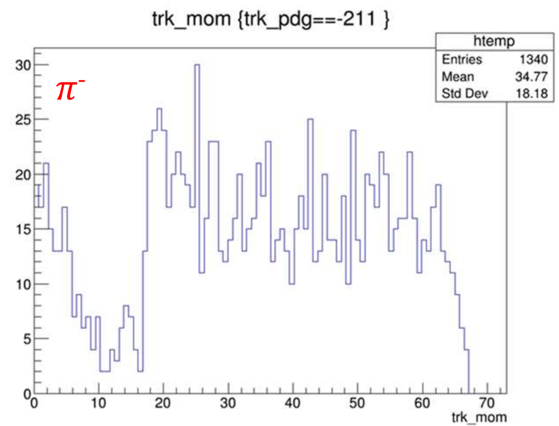
- 10k events → 3580 neutrons → ~47%
  - Need to add π^0 efficiency

- 10k events → 6390 protons → ~47%
  - Need to add π^- efficiency

Virtual planes [p(e,e’K⁺Λ⁰)X]

- Next step: Switch from virtual planes to the real size detector and check detector efficiency





Angular distribution for Proton