Meson Structure at the EIC

EIC Early Career Workshop
July 29th, 2021
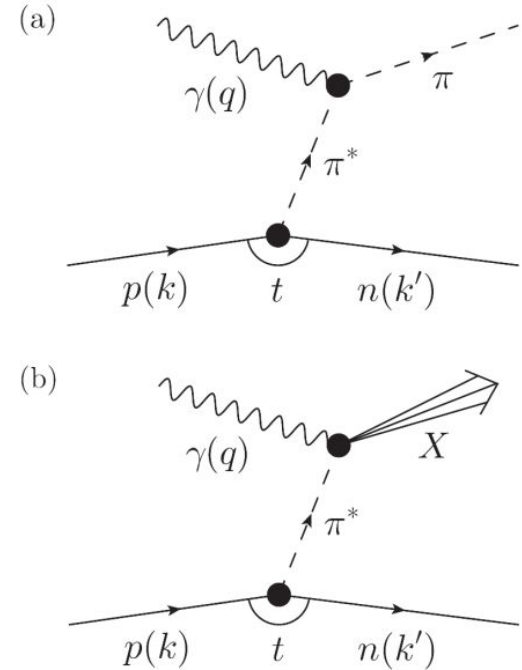
Richard Trotta and the meson structure working group

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 $\bar{q}q$ ucture 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
  - Quantum mechanical approaches to the bound-state problem of light hadrons, e.g. the constituent quark model, find important difficulties such as the description of pseudo-Goldstone bosons' masses which usually forces the practitioners to unrealistically fine tune the quark-(anti-)quark interaction.
  - 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

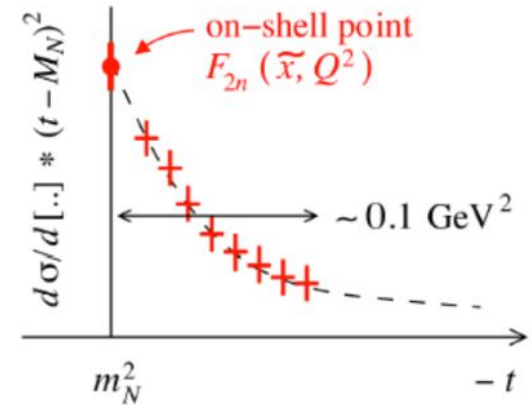# Accessing the Pion and Kaon Structure

- 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

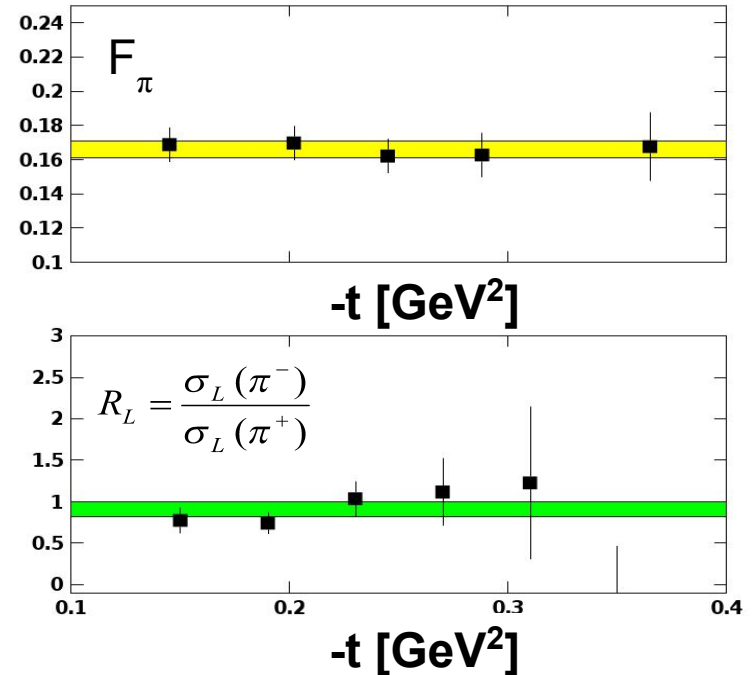Pion cloud can access a) Elastic FF b) PDF

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
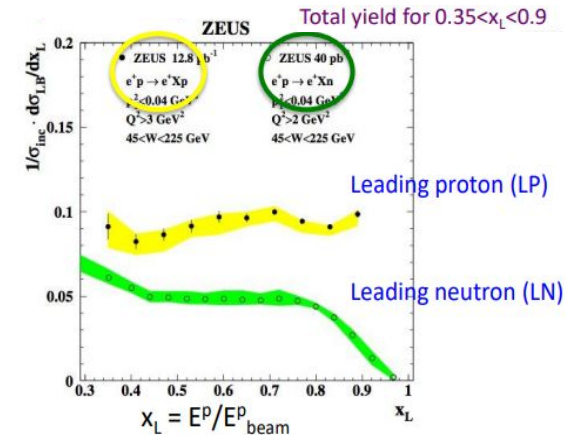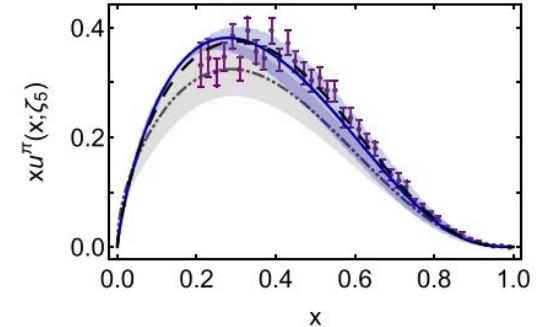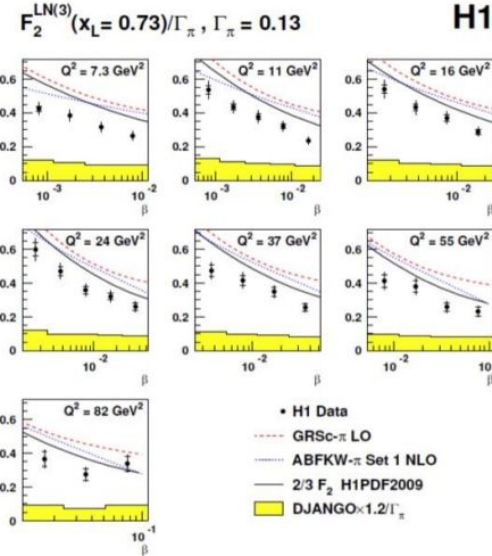
Experimental Validation

- 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

$$R_L = \frac{\sigma_L(\pi^-)}{\sigma_L(\pi^+)}$$

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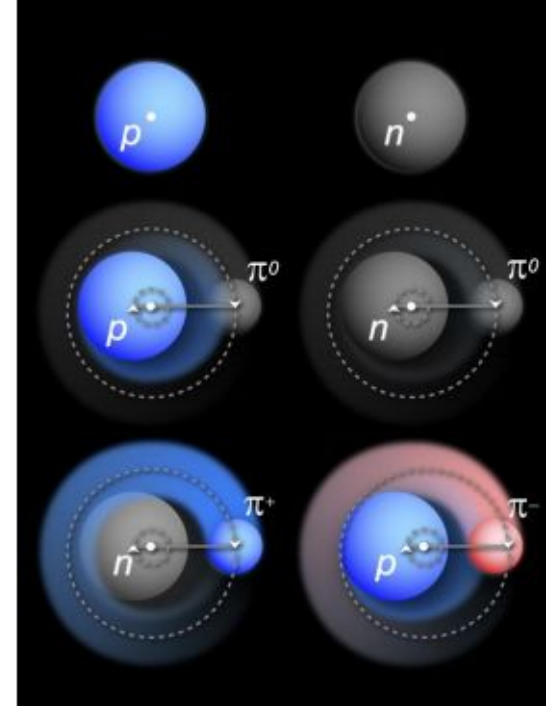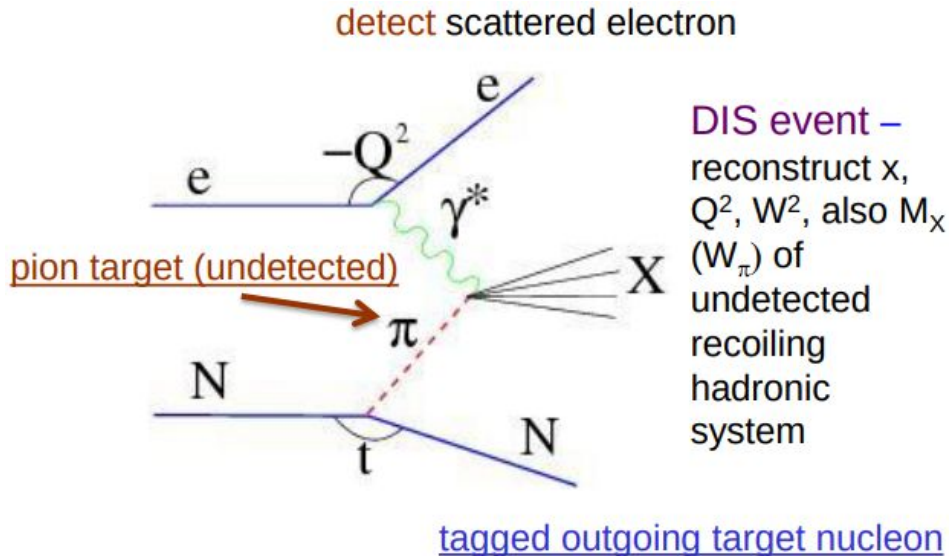R. J. Perry et al., arXiV:1811.09356 (2019)

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...
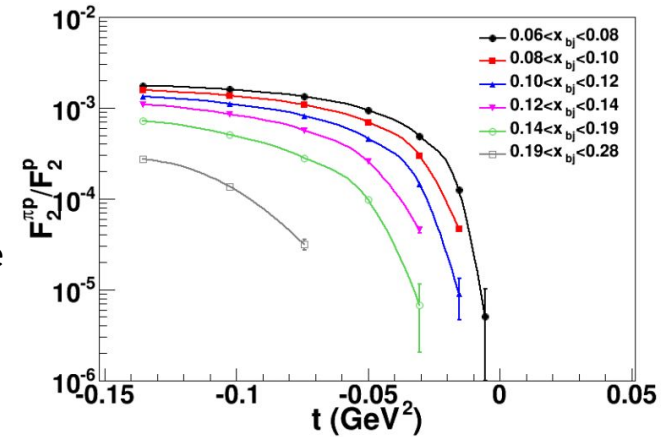

$F_2^{LN(3)}(x_L = 0.73)/\Gamma_\pi$, $\Gamma_\pi = 0.13$ **H1**

$Q^2 = 7.3$ GeV^2
$Q^2 = 11$ GeV^2
$Q^2 = 16$ GeV^2
$Q^2 = 24$ GeV^2
$Q^2 = 37$ GeV^2
$Q^2 = 55$ GeV^2
$Q^2 = 82$ GeV^2

- H1 Data
- - - GRSc-π LO
- · · · ABFKW-π Set 1 NLO
— 2/3 F_2 H1PDF2009
■ DJANGO×1.2/Γ_π

$xu^\pi(x;\zeta_5)$

Total yield for 0.35<x_L<0.9

ZEUS

ZEUS 12.8 b^{-1}
e$^+$p → e$^+$Xp
Q^2<0.04 GeV^2
Q^2>3 GeV^2
45<W<225 GeV

ZEUS 40 pb
e$^+$p → e$^+$Xn
Q^2<0.04 GeV^2
Q^2>2 GeV^2
45<W<225 GeV

Leading proton (LP)

Leading neutron (LN)

$x_L = E^p/E^p_{beam}$

$1/\sigma_{inc} \cdot d\sigma_{LB}/dx_L$

Tagged Deep Inelastic Scattering (TDIS)

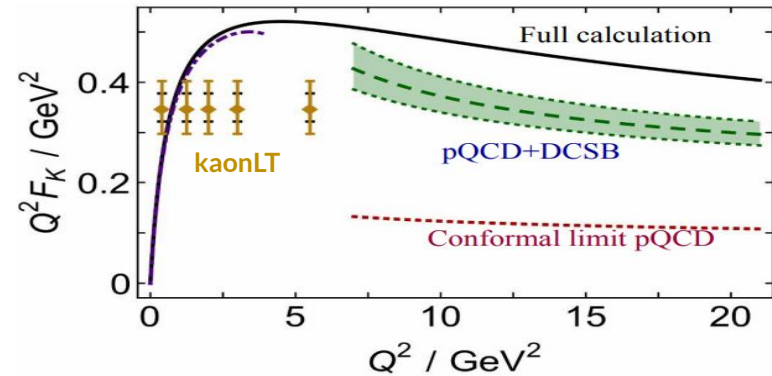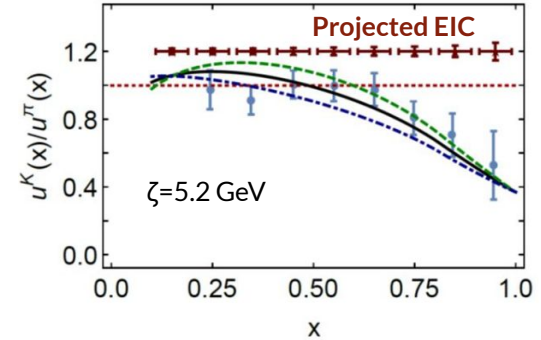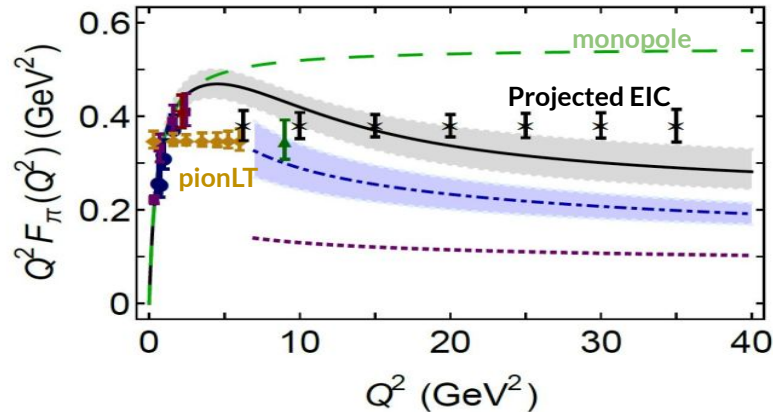- Using the Sullivan process – scattering from nucleon-meson fluctuations

detect scattered electron

pion target (undetected)

DIS event – reconstruct x, Q^2, W^2, also M_X (W_π) of undetected recoiling hadronic system

tagged outgoing target nucleon

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

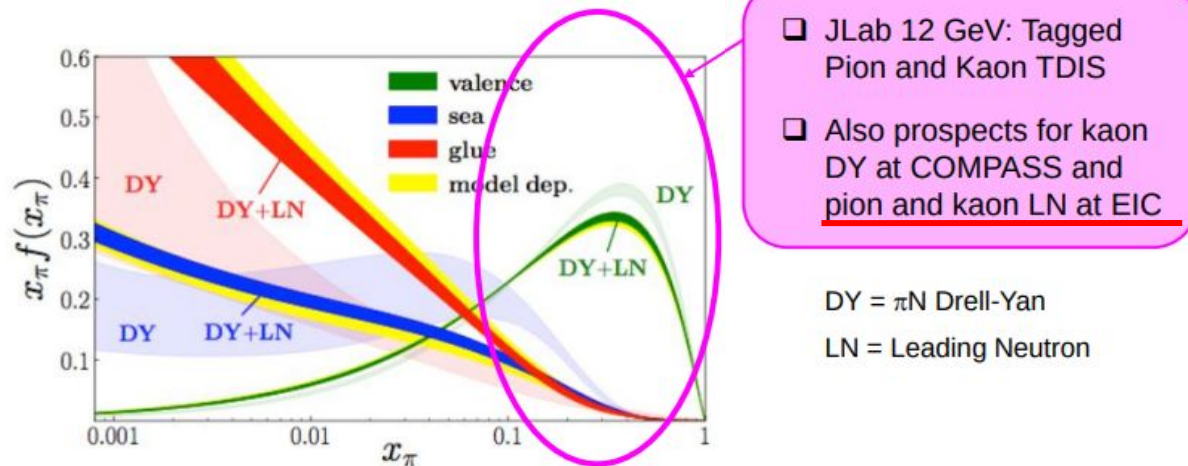*Jefferson Lab TDIS Collaboration, JLab Experiment C12-15-005 Proposal*

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

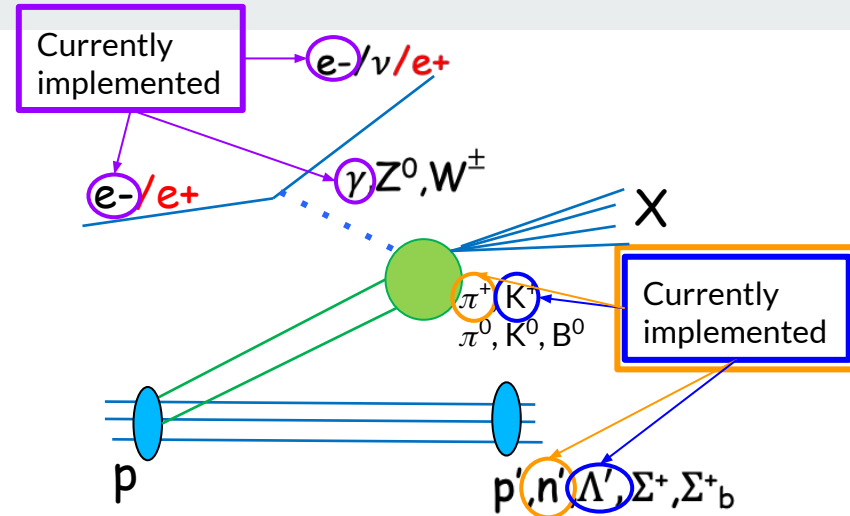*Arlene C. Aguilar,...**R. Trotta**, et al., Eur. Phy. J. A (2019) DOI:10.1140/epja/i2019-12885-0*

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
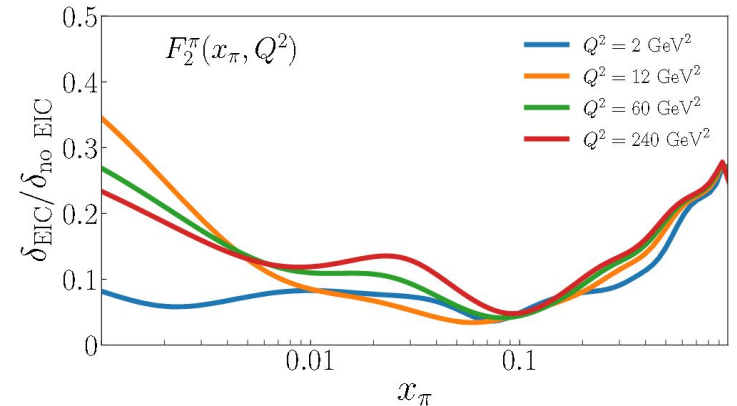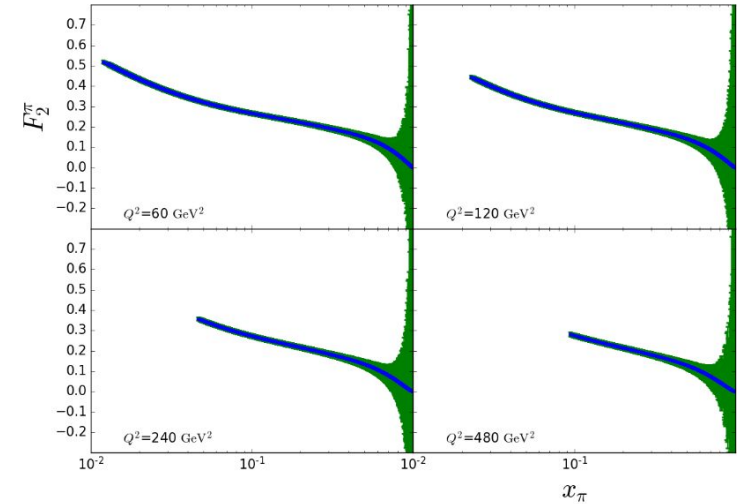 - Implications for "TDIS" (Tagged DIS) experiments at JLab

- 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

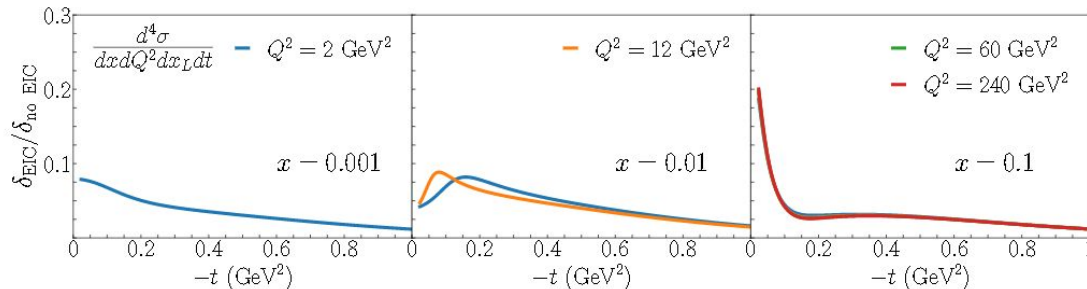*Barry, Sato, Melnitchouk, Ji (2018), Phys. Rev. Lett. 121 (2018) no.15, 152001*

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
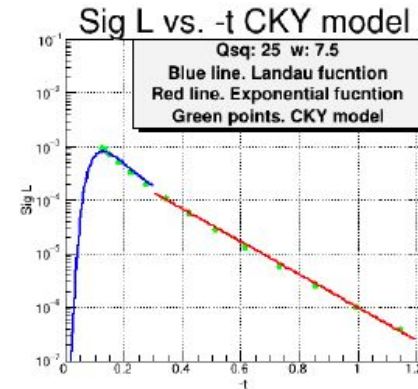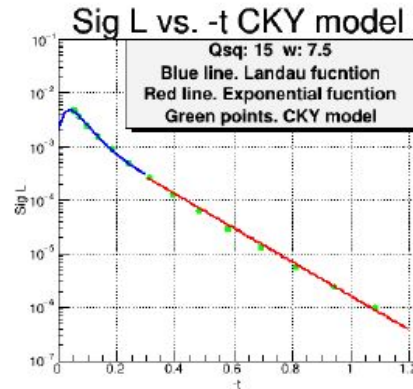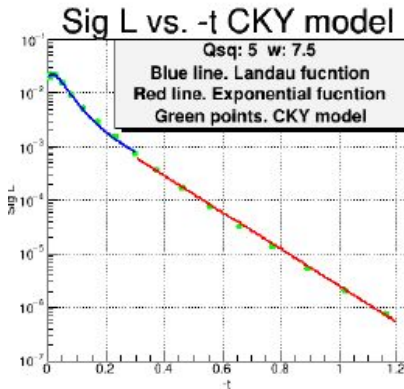 - Only e-P currently implemented, but want to incorporate e-D

11

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

12

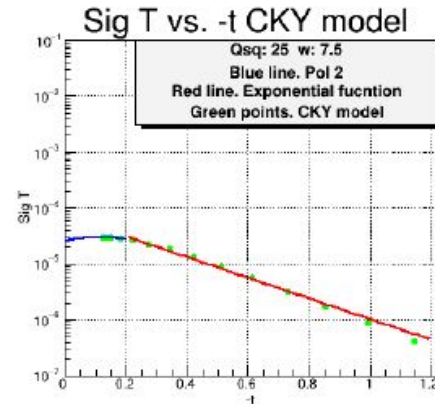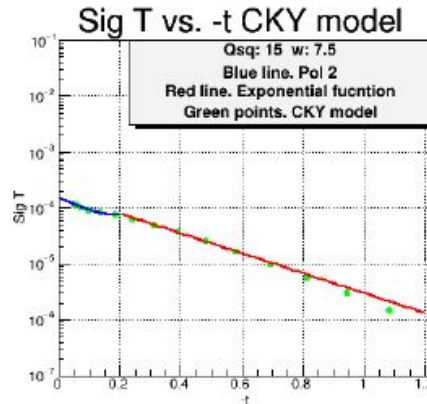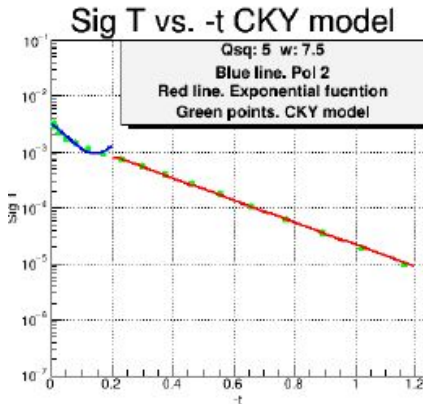# π^+ Form Factors

Analysis by Stephen Kay
and Ali Usman

- 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

13

π^+ Form Factors
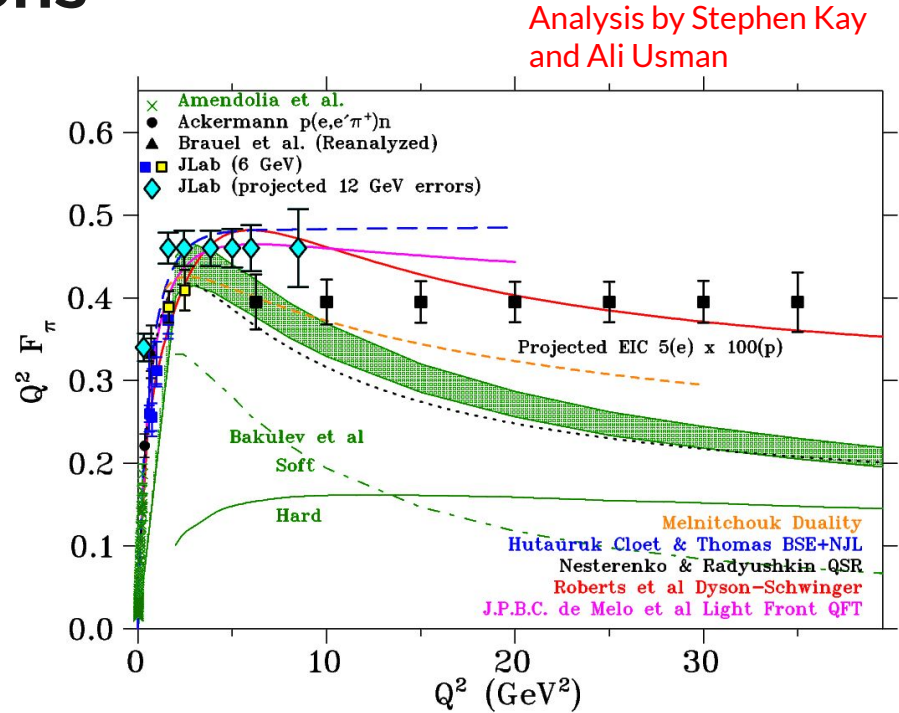
Analysis by Stephen Kay
and Ali Usman

- 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

14

π^+ Form Factor Projections

Analysis by Stephen Kay and Ali Usman

- 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
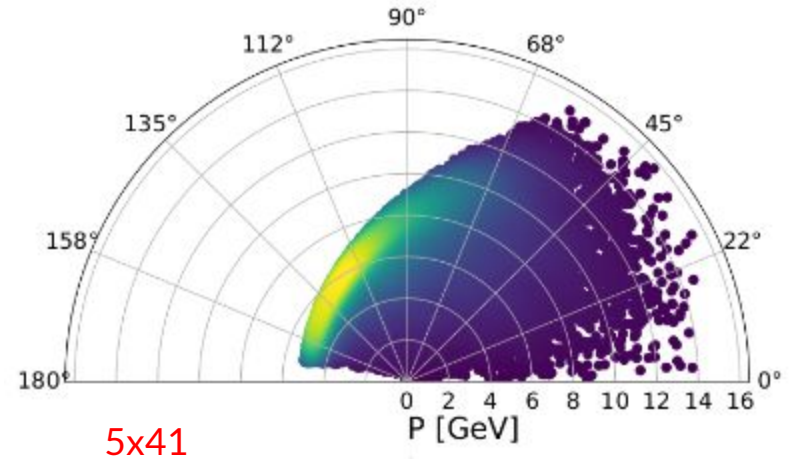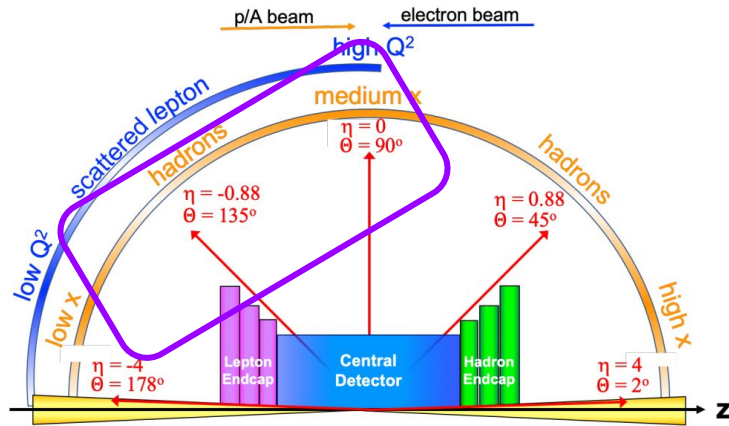- For F_K, need to study Σ reconstruction and detection too

15

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 $35\%/\sqrt{E}$ 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
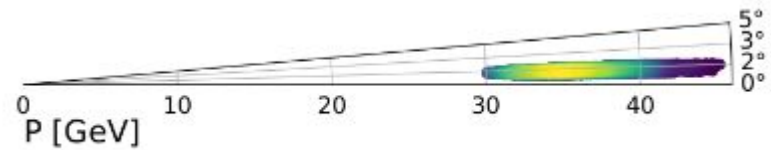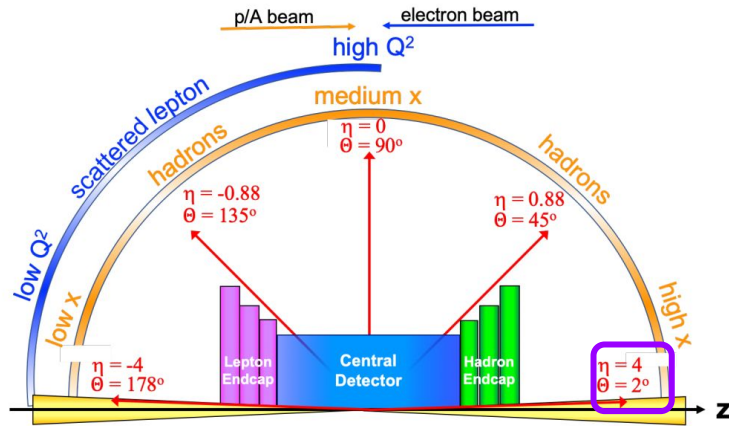 - Distinguishing decay products is crucial

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

Meson Structure Functions – Scattered Electron

5x41

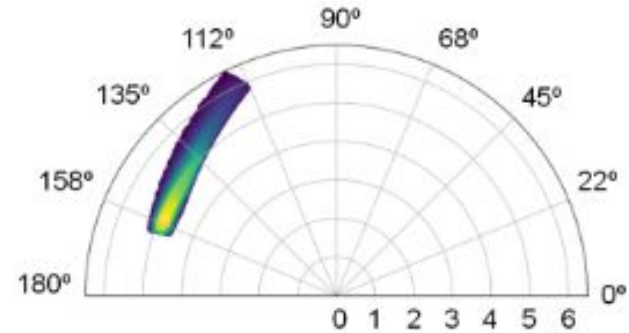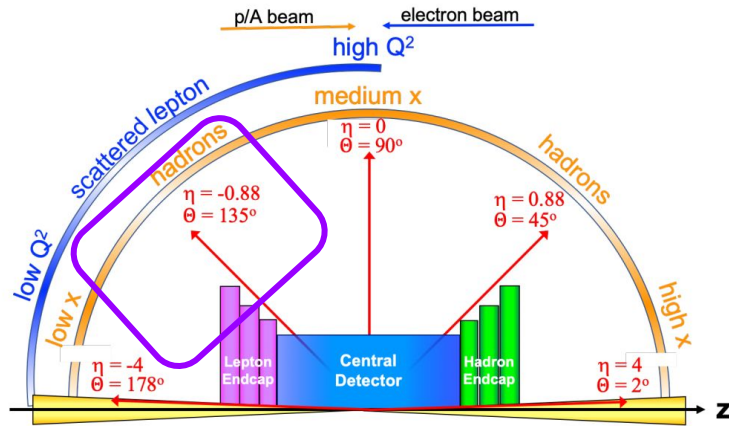- Scattered electrons can be detected in the central detector

Meson Structure Functions – Forward Baryon

5x41

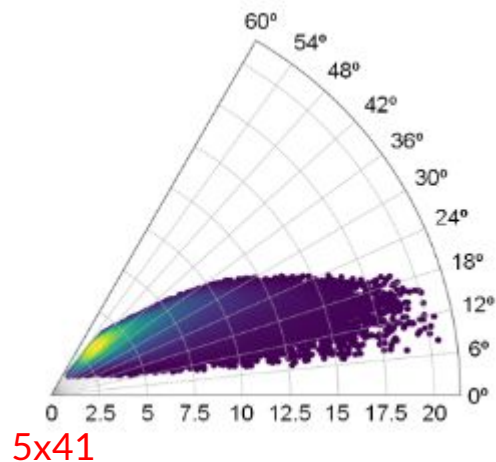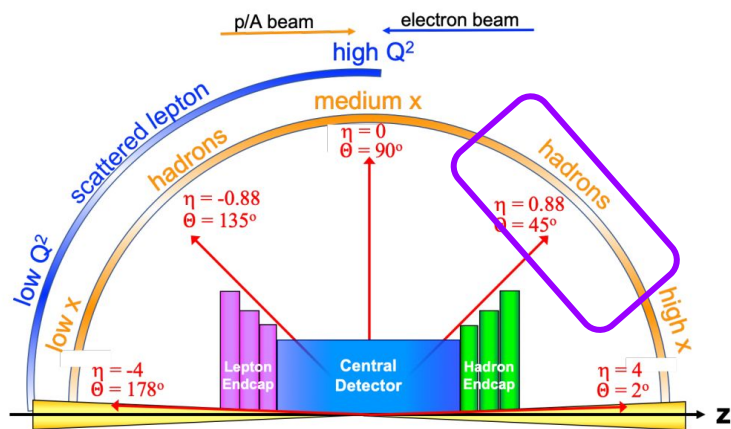- Baryon (neutron, lambda) at very small forward angles and nearly the beam momentum

Meson Form Factor - Scattered Electron
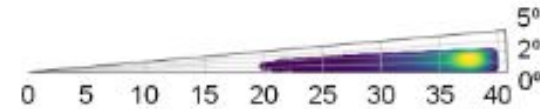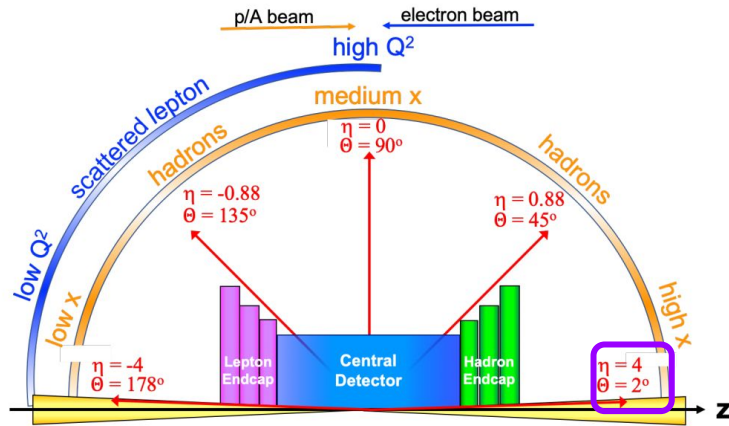

5x41

- The exclusive electron are stuck to a tighter band

Meson Form Factor - Scattered π^+
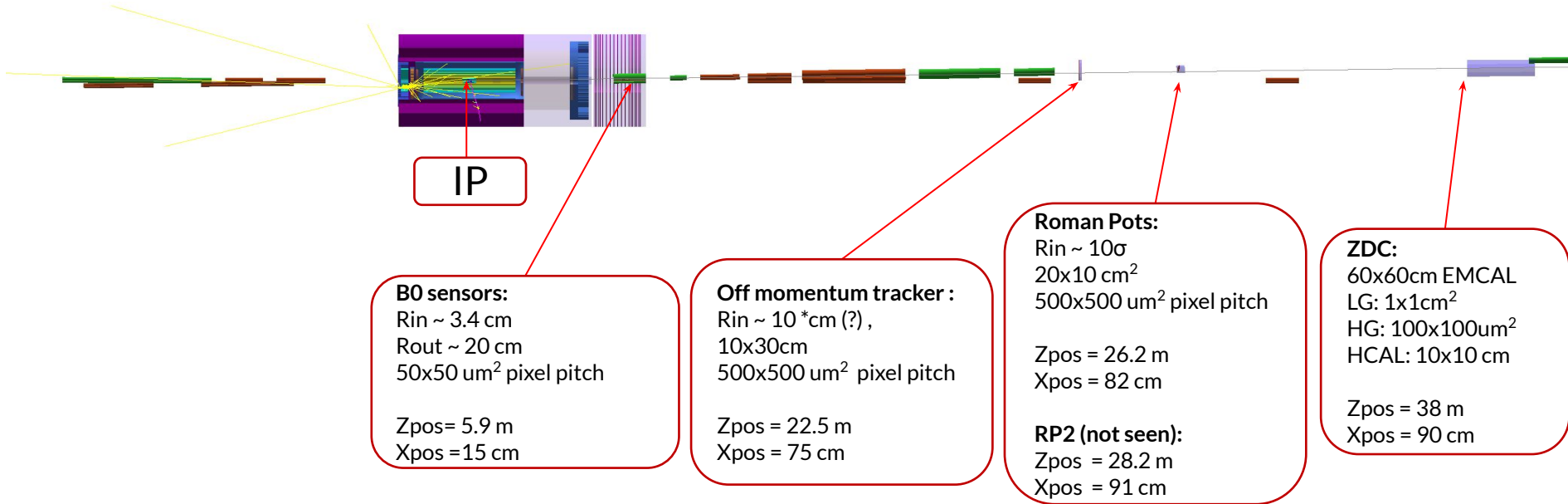

5x41

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

IP

B0 sensors:
Rin ~ 3.4 cm
Rout ~ 20 cm
50×50 um^2 pixel pitch

Zpos= 5.9 m
Xpos =15 cm

Off momentum tracker :
Rin ~ 10 *cm (?) ,
10×30cm
500×500 um^2 pixel pitch

Zpos = 22.5 m
Xpos = 75 cm

Roman Pots:
Rin ~ 10σ
20×10 cm^2
500×500 um^2 pixel pitch

Zpos = 26.2 m
Xpos = 82 cm

RP2 (not seen):
Zpos = 28.2 m
Xpos = 91 cm

ZDC:
60×60cm EMCAL
LG: 1×1cm^2
HG: 100×100um^2
HCAL: 10×10 cm

Zpos = 38 m
Xpos = 90 cm

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
- Example from Yellow Report
  - Work in progress with Alex, Dmitry, and Yulia

- 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
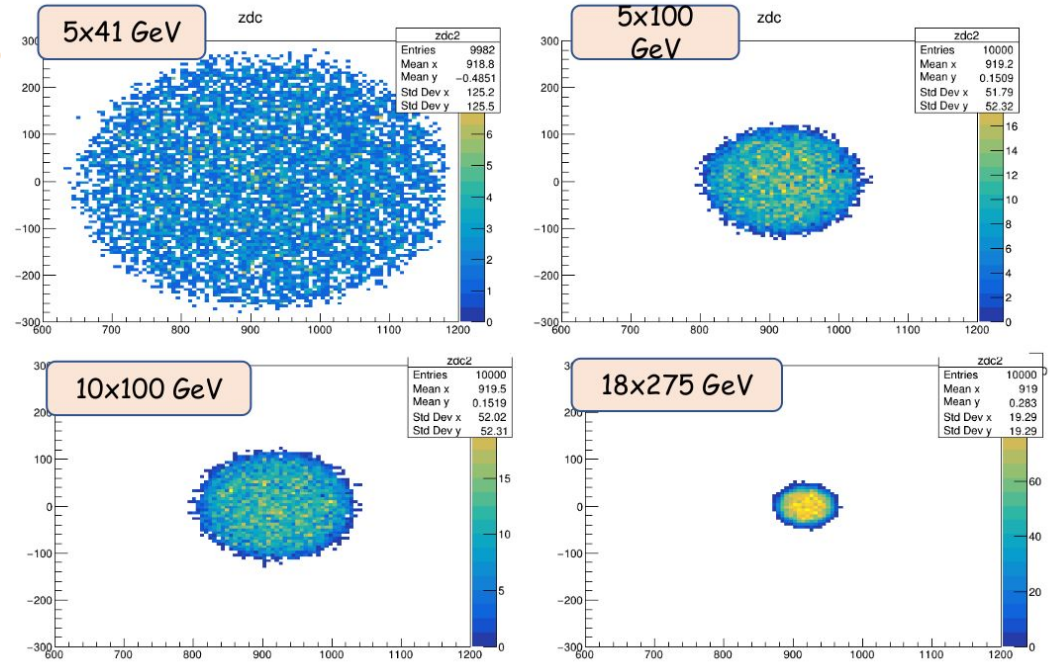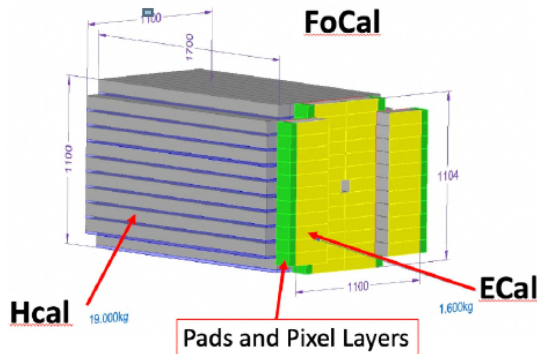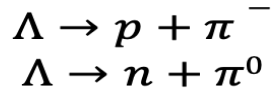
23

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
- Example from Yellow Report
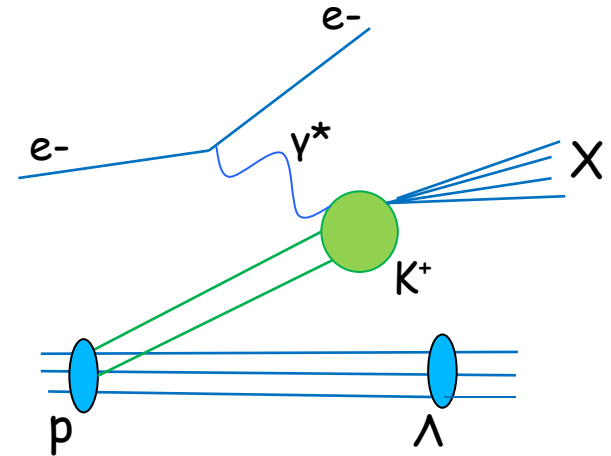 - Work in progress with Alex, Dmitry, and Yulia

- 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…

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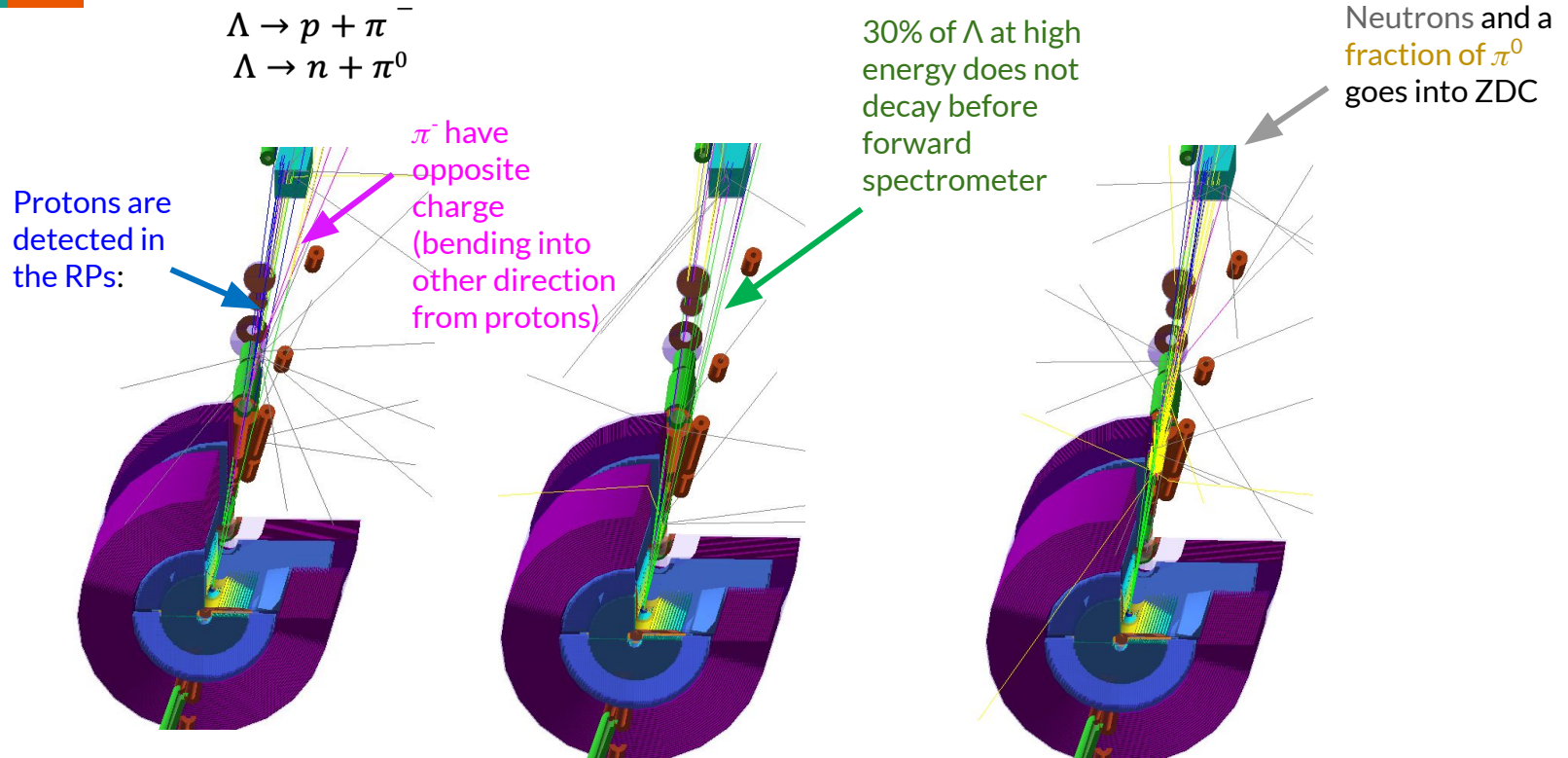$$\Lambda \to n + \pi^0$$

- 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

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

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

Neutrons and a fraction of π^0 goes into ZDC

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

Protons are detected in the RPs:
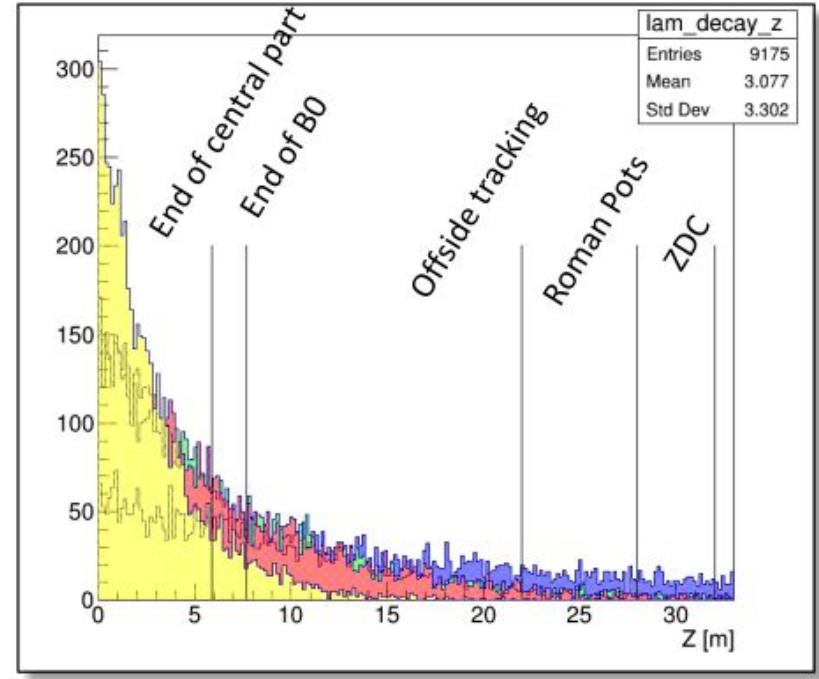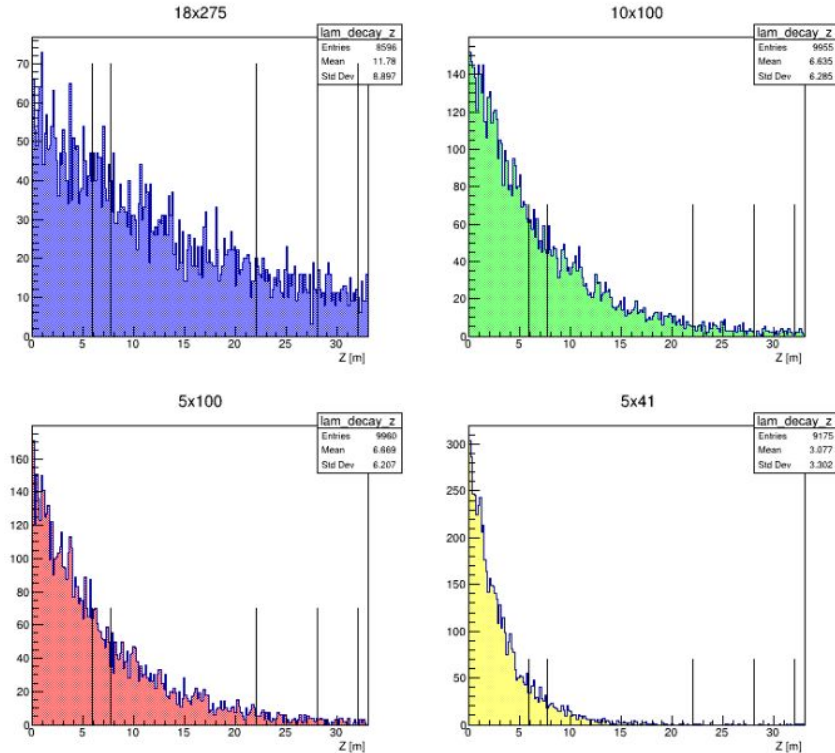
18 x 275

Decay Length

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

Lambda Final State

$\Lambda \to p + \pi-$: very challenging!
- ➤ need additional particle tracking between dipoles and ZDC

$\Lambda \to n + \pi^0$: looks promising
- ➤ need additional high-res/granularity EMCal+tracking before ZDC

18x275

Too long decay length of Lambda

Lambda->p+π^- (pion was lost in Dipole)

Lambda->n + π^0 (2 γ) (all in ZDC)

Lambda->n + π^0 (2 γ) (one γ missed ZDC)

Summary of Detector Requirements

- For π^+/n...
  - <u>For all energies</u>, the neutron detection efficiency is ~100% with planned ZDC
  - <u>Lower energies</u> [5 on 41, 5 on 100], **require at least 60cmx60cm size** to access wider range of energies
- For π^+/n and K$^+$/Λ...
  - <u>All energies</u> need good ZDC angular resolution for the required t resolution
  - <u>High energies</u> [10 on 100, 10 on 135, 18 on 275] **require resolution of 1 cm or less**
- K$^+$/Λ benefits from <u>low energies</u> [5 on 41, 5 on 100] and also need...
  - Λ → n+π^0 : additional high-res/granularity
    - **EMCal+tracking before ZDC** (seems doable)
  - Λ → p+π^- : 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 (IP8)

ZDC

Virtual tracker after B1
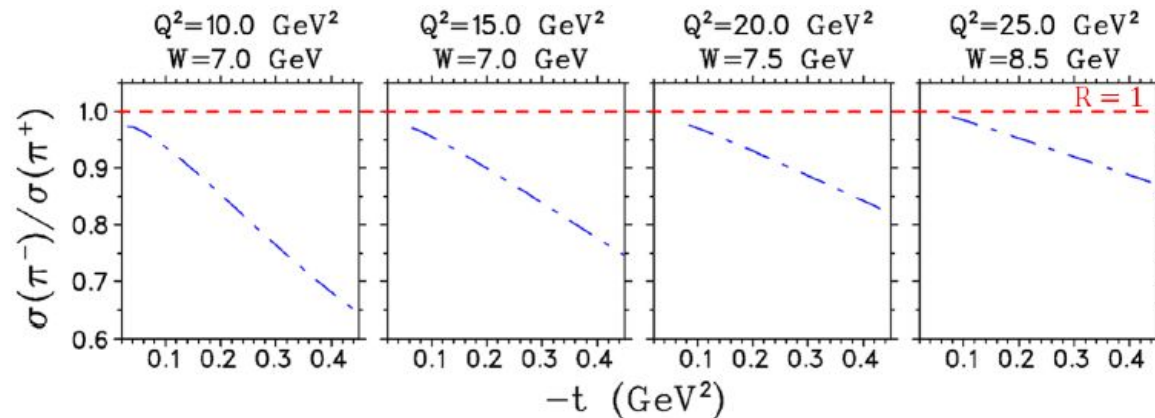
Plans for F_2^π projections

- 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

Plans for π^+ Form Factors

Analysis by Stephen Kay

- QCD scaling predicts $\sigma_L \propto Q^{-6}$ and $\sigma_T \propto Q^{-8}$
- Can attempt to extract σ_L by using a model to isolate dominant $d\sigma_L/dt$ from measured $d\sigma_{UNS}/dt$
- Critical to confirm the validity of the model used!
- R will be diluted if σ_T or small or if there are significant non-pole contributions to σ_L
- Compare R to model expectations

31

Plans for 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
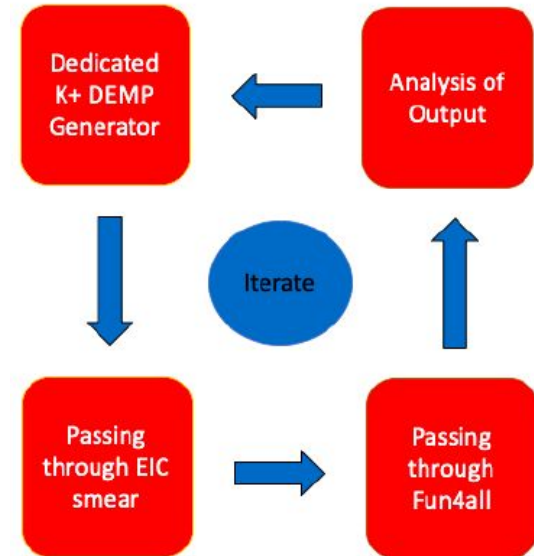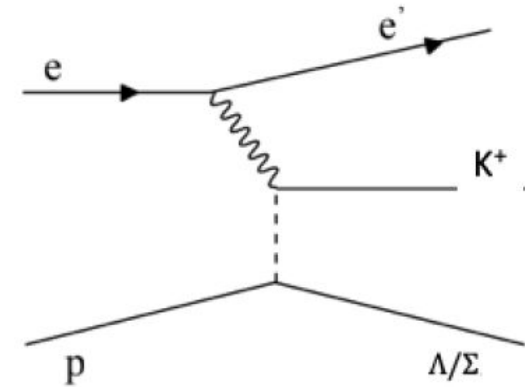
S. Goloskokov and P. Kroll, Eur.Phys.J. A**47** (2011) 112:

$g_{\pi NN}$=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 $g_{\pi NN}$)

Plans for K⁺ Form Factors

Analysis by Ali Usman

- If the pole process dominates, ratio of Λ and Σ^0 should behave like $g_{KN\Lambda}/g_{KN\Lambda\Sigma0}$
- K⁺ DEMP Generator
  - Modifying the existing π^+ DEMP generator
  - Need to include both Λ and Σ^0 channels
  - Modification of K⁺ kinematics ($Q^2, W \rightarrow -t$)
- Four step iterative process
- Need to accurately detect γ in far-forward detectors
  - Only distinction between Λ and Σ^0 ($\Sigma^0 \rightarrow \Lambda\gamma$)
- Charged final states ($\Lambda \rightarrow \pi^- + p$) are difficult

33

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/Σ (K form factor)
        - Measure "X" and tagged Λ/Σ (K structure function)

- Next steps are to...
    - Develop analysis plugin for both form factor and structure function studies
    - Simulate KΛ and KΣ events
    - Extend π to K structure function
    - 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, Jorge Segovia, Carlos Ayerbe Gayoso, Bill Li, Yulia Furletova, Dmitry Romanov, Markus Diefenthaler, Richard Trotta, Tanja Horn, Rolf Ent, Tobias Frederico, Ali Usman
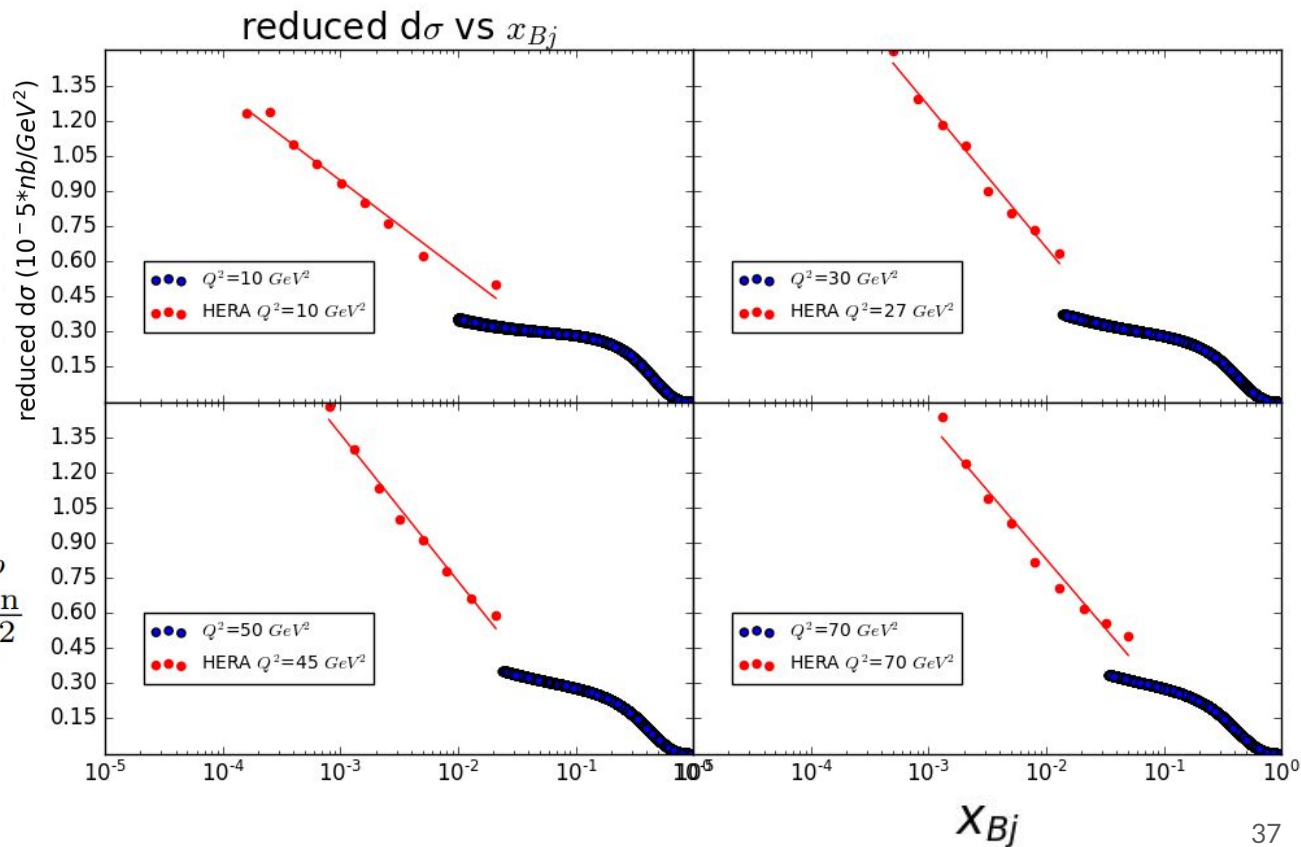
EXTRA

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)

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

reduced dσ vs x_{Bj}

x_{Bj}

Kinematic Variables

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

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

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

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

$$(p2)_z = gRandom \rightarrow Uniform(1)$$

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

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

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

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

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

Pion can not make 2nd Dipole

Proton can be detected before 3rd Dipole
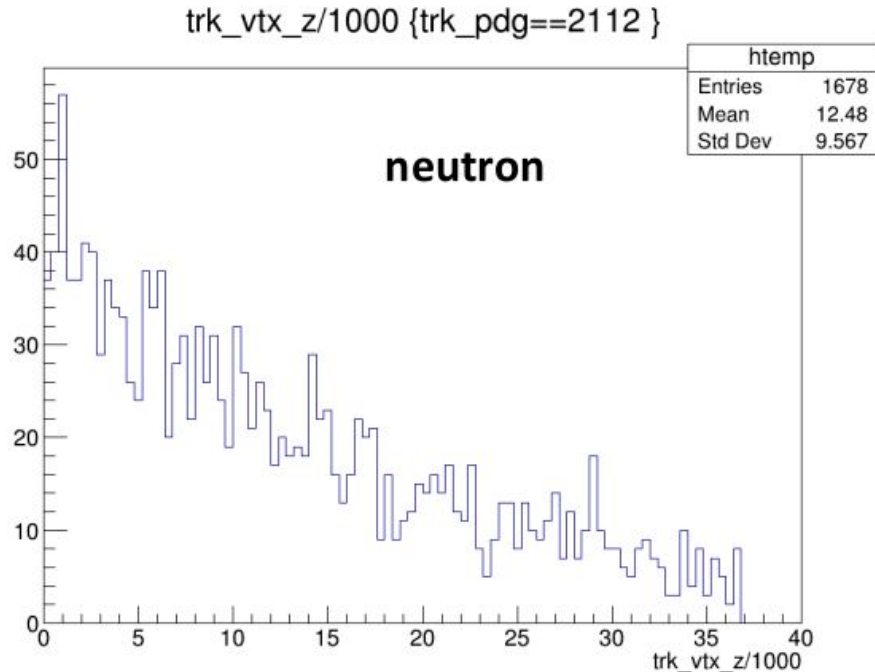Pion can be detected before 3rd Dipole
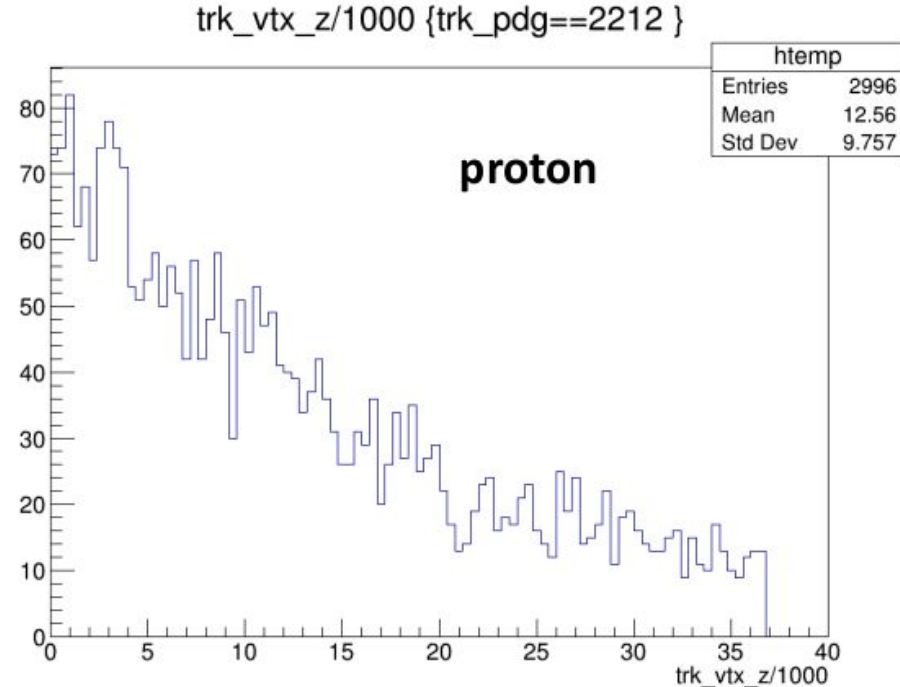
GEANT4 for EIC

- 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

ffe_

far forward electron

central detector

p/A

e

e

p/A

electron-endcap   barrel   ion-endcap

ce_   **cb_**   **ci_**

forward ion
(after D1)

fi_

far forward ion
(after D2)

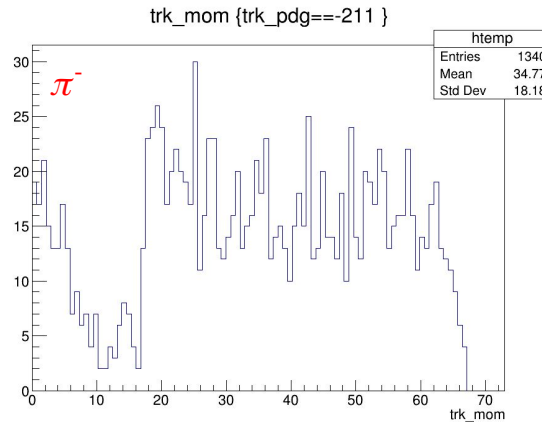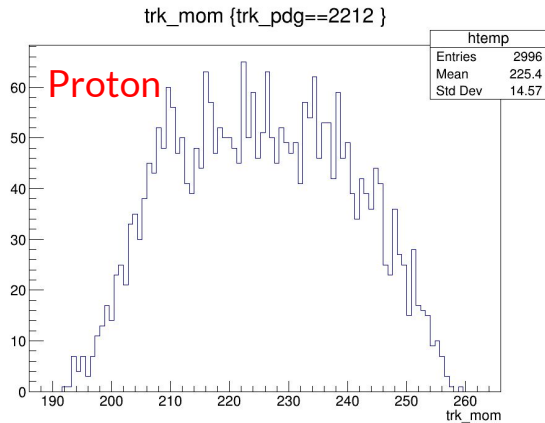**ffi_**

Decay Length [p(e,e′K⁺Λ⁰)X]

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

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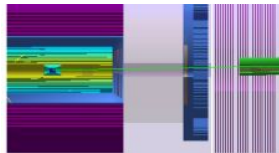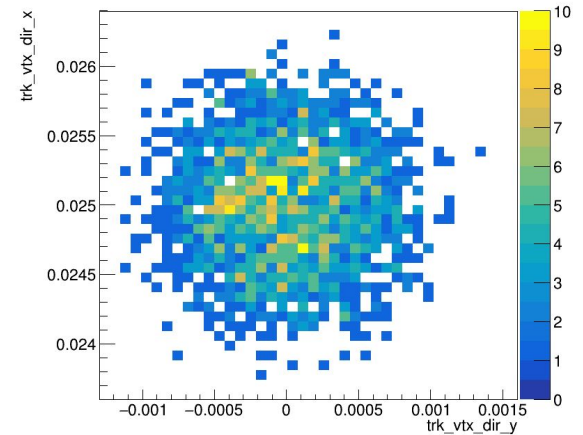 - Need to add π^- efficiency

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

Virtual planes