Meson Structure at the EIC

Pavia EIC User Meeting

May 21st, 2020

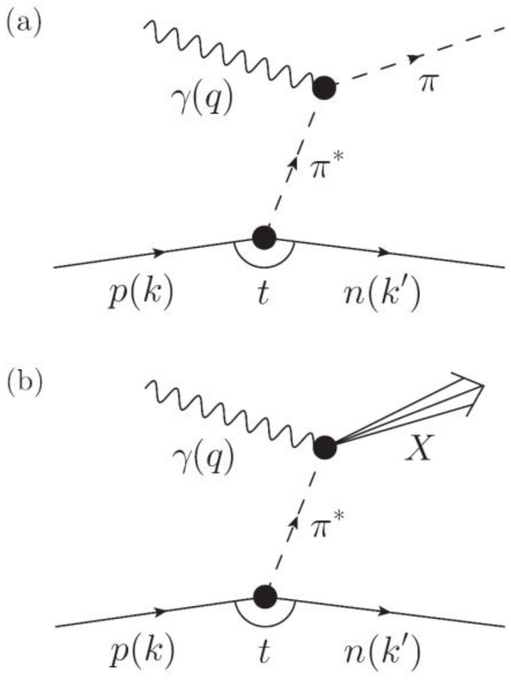
Richard Trotta and the meson structure working group

Jefferson Lab

The Catholic University of America

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

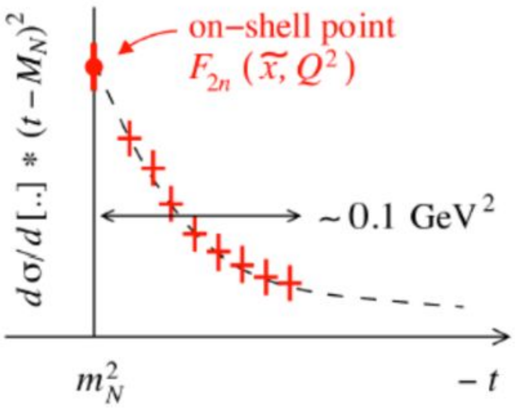


Pion cloud can access a) Elastic FF b) PDF

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

Pion and Kaon Sullivan Process

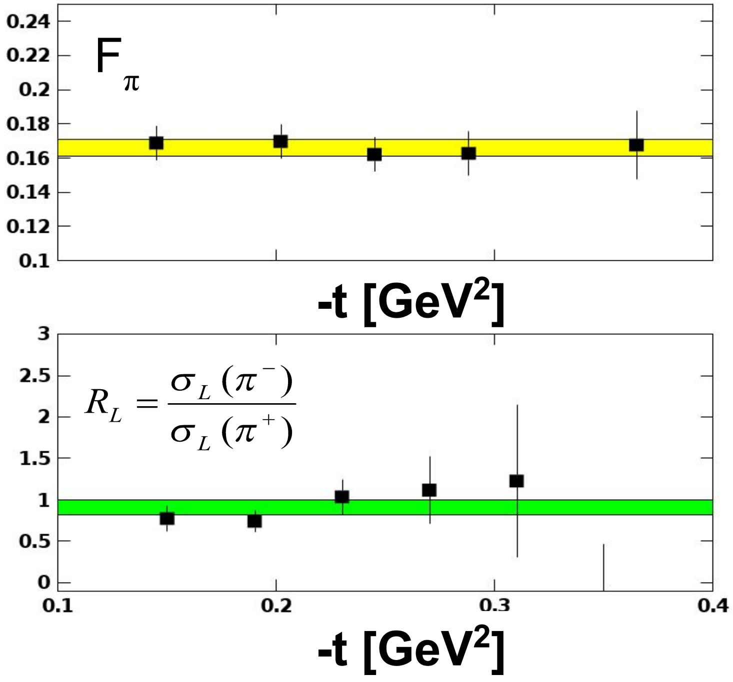
- The Sullivan process can provide reliable access to a meson target as t becomes space-like
- If the pole associated with the ground-state meson remains the dominant feature of the process
  - the structure of the related correlation evolves slowly and smoothly with virtuality
- Recent theoretical calculations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



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

Experimental Validation

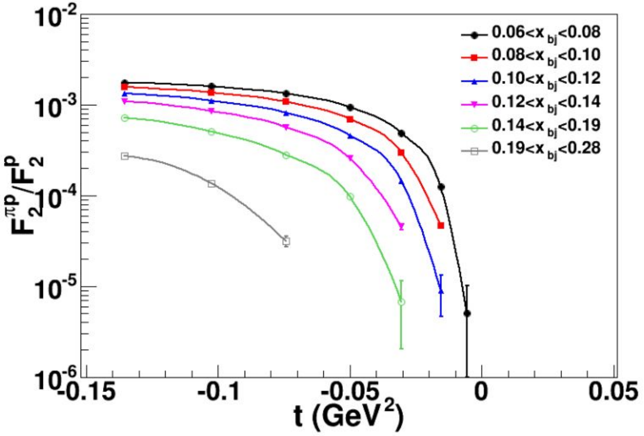
- To check these conditions are satisfied empirically...
  - data taking covering a range in t
  - comparing data with phenomenological and theoretical expectations
    - F_π values do not depend on -t to give confidence in applicability of model to the kinematic regime of the data
  - Verify that the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

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) 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 Proposal

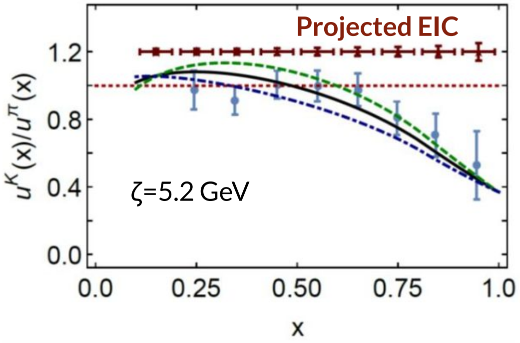
5 key EIC measurements

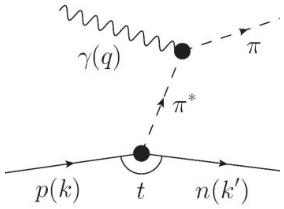
Arlene C. Aguilar, et al., Eur. Phy. J. A (2019) DOI:10.1140/epja/i2019-12885-0

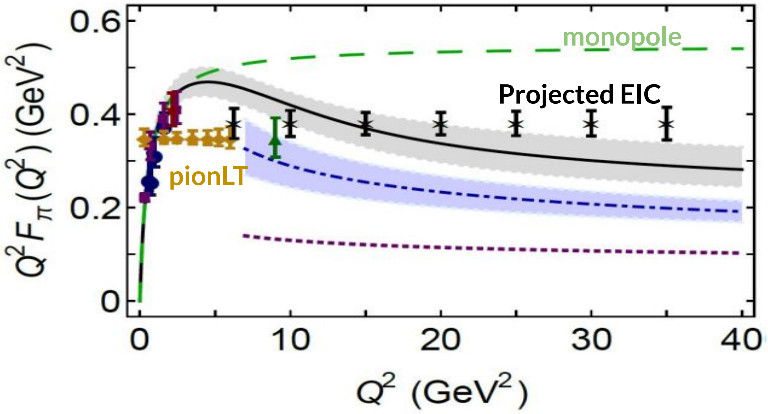
1. Measurement of pion and kaon structure functions and their GPDs
   - insights into quark and gluon energy contributions to hadron masses
2. Measurement of open-charm production
   - settle question of whether gluons persist or disappear within pions in the chiral limit
3. Measurement of the charged-pion form factor up to $Q^2 \sim 35\ GeV^2$
   - Quantitatively related to emergent-mass acquisition from DCSB
4. Measurement of the behavior of (valence) u-quarks in the pion and kaon
   - quantitative measure of the contributions of gluons to NG boson masses and differences between the impacts of emergent and Higgs-driven mass generating mechanisms
5. Measurement of the fragmentation of quarks into pions and kaons
   - a timelike analog of mass acquisition, which can potentially reveal relationships between DCSB and confinement mechanism

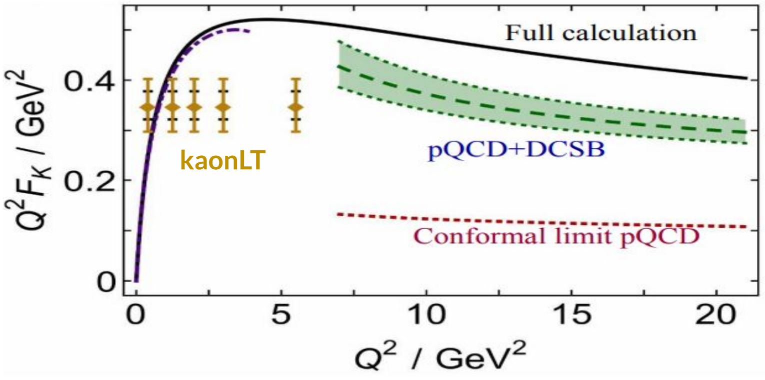
2019 EPJA Pion and Kaon Structure Projections

- 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









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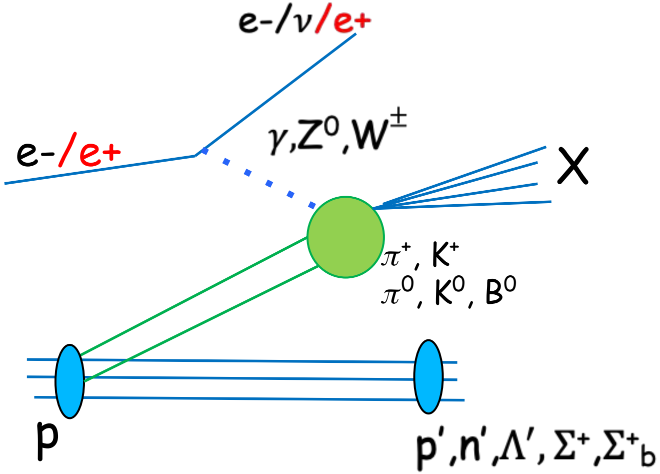
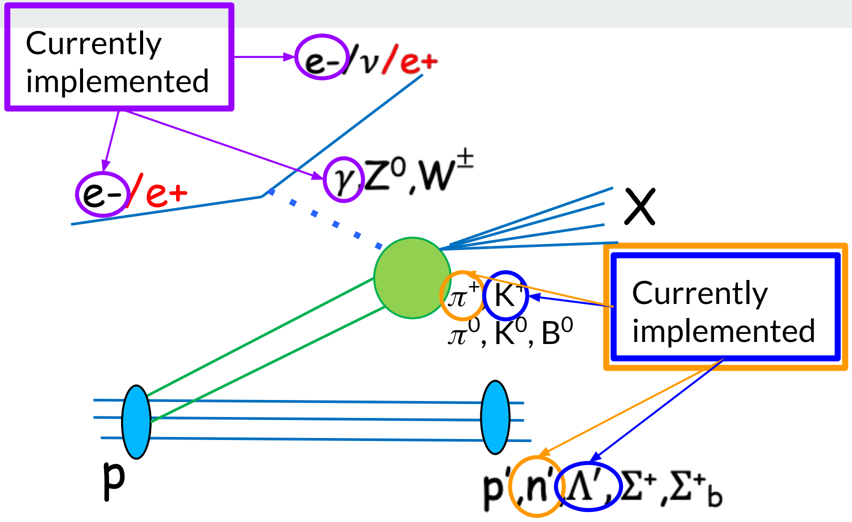
Structure functions

- 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:
  - fixes made in generator to remove fixed-target leftovers
  - now can make pion structure function (pion SF) projections

Structure functions



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  - fixes made in generator to remove fixed-target leftovers
  - now can make pion structure function (pion SF) projections

- 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

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*)
$^1H(e, e' \pi^+)\, n$	n	>20%
$^1H(e, e' K^+)\, \Lambda$	Λ	50%
$^1H(e, e' K^+)\, \Sigma$	Σ	17%

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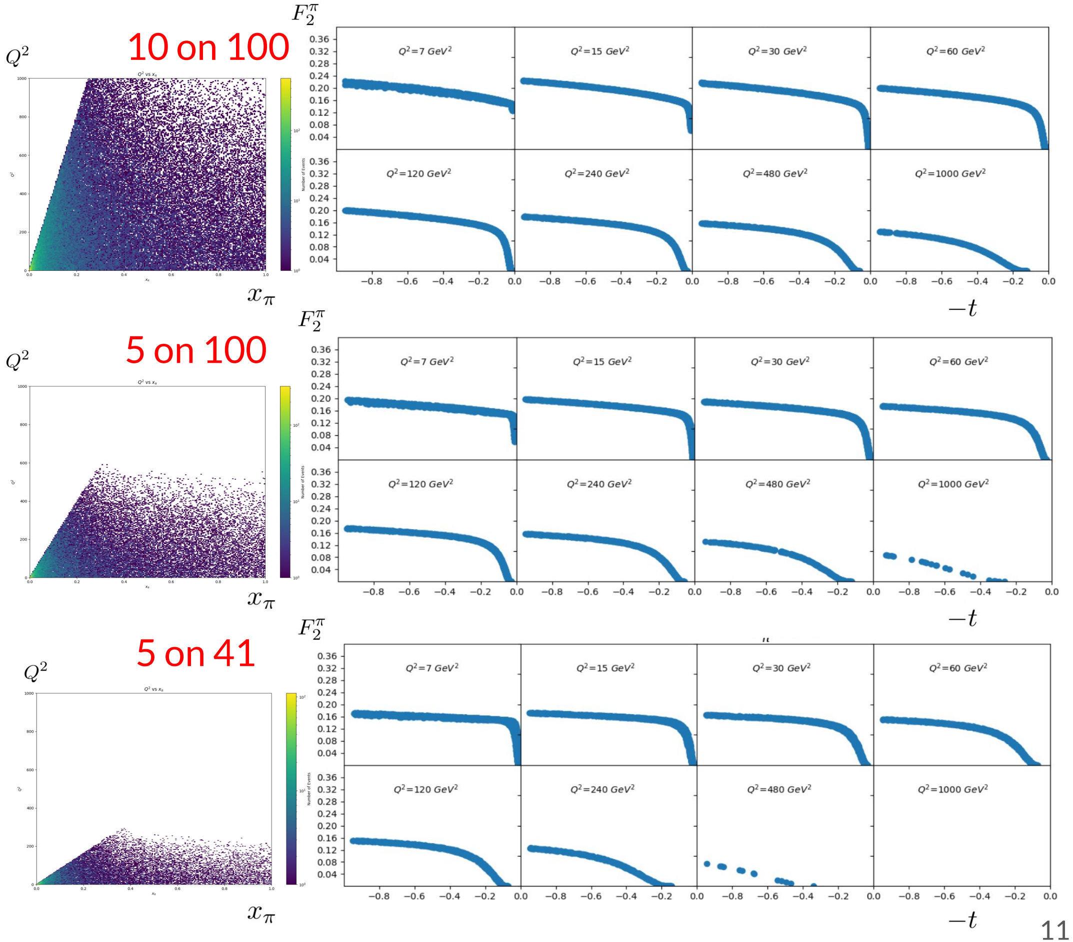
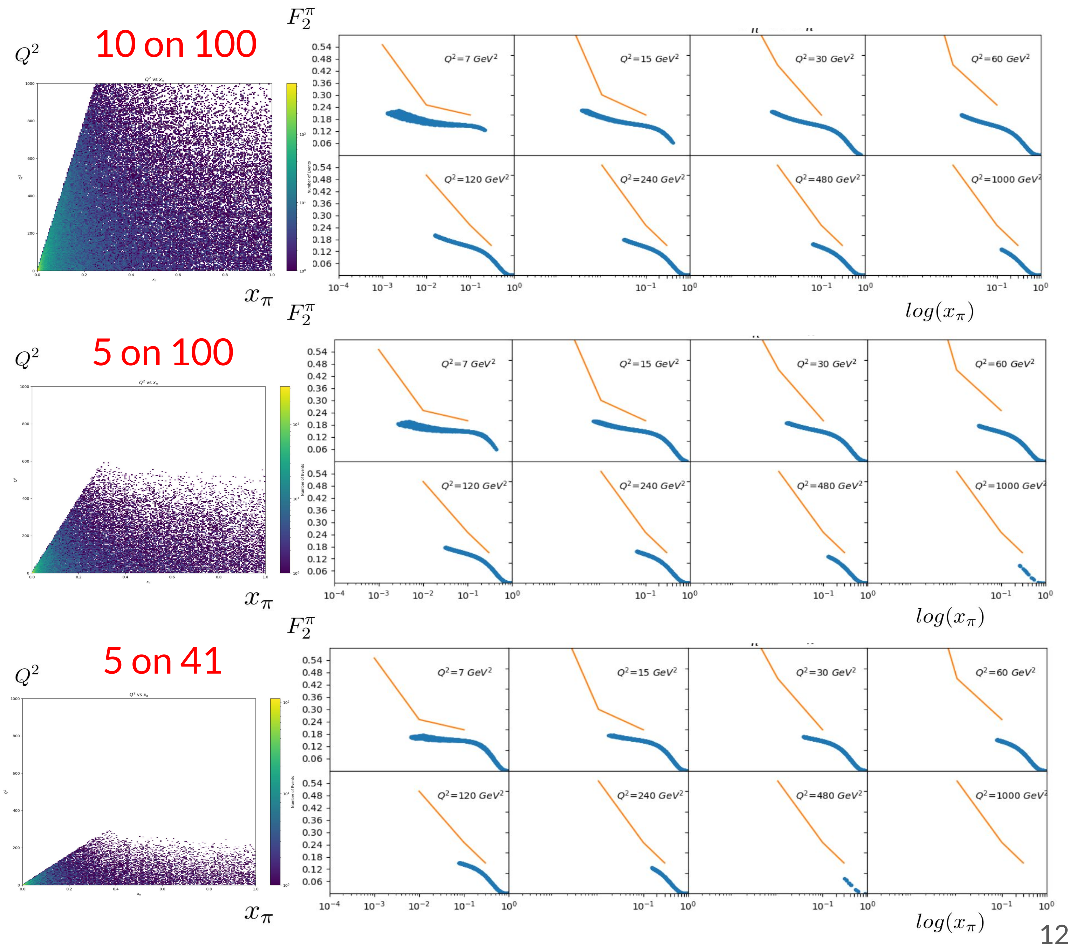
Pion Structure Function Projections

- e-P collision
- MC:[x(0.001-1.0),Q2(1,1000)]
  - Cuts:[(0.01 < y < 0.95)]
- $F^{\pi}_{2} = (0.361)*F^{P}_{2}$
  - ZEUS Parameterization
  - GRV fit
  - $L=10\ fb^{-1}$
- -t coverage is similar for the various beam energies, as expected

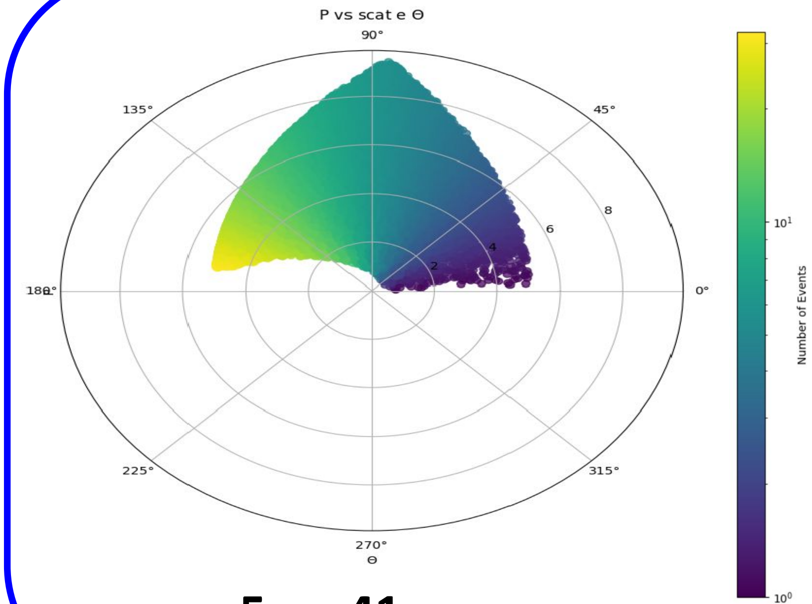


Pion Structure Function Projections

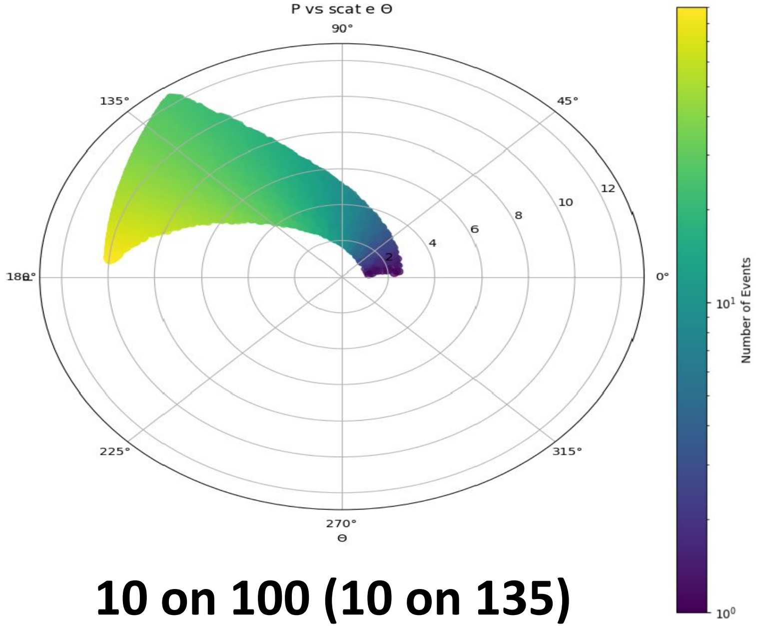
- To reach the large x region at a certain intermediate Q^2, the lowest possible energy is normally best
- For high beam energies this area requires y to be low
- 5 on 100 can access more acceptance at high-x, but lose acceptance to the low-x region
- Even more for 5 on 41
  - There are some advantages for lower proton energy for K-Λ detection



Meson Structure Functions – Scattered Electron



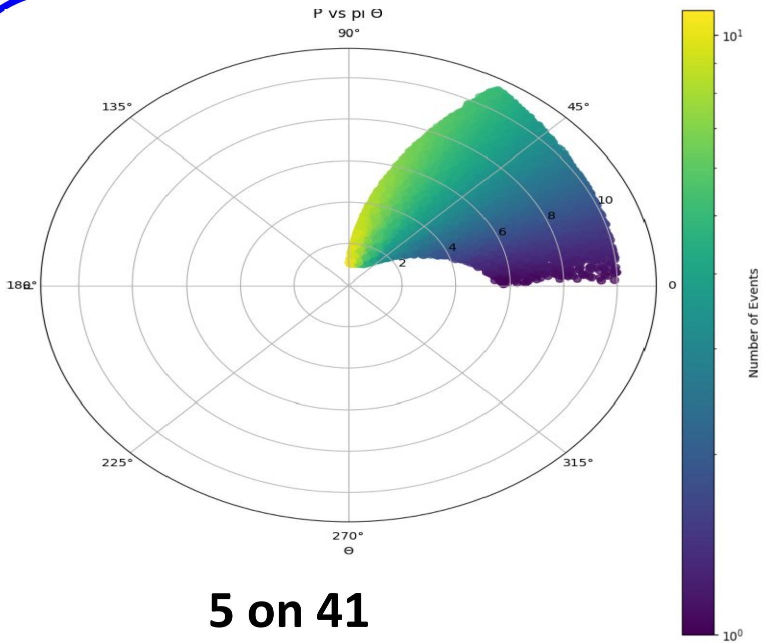
5 on 41



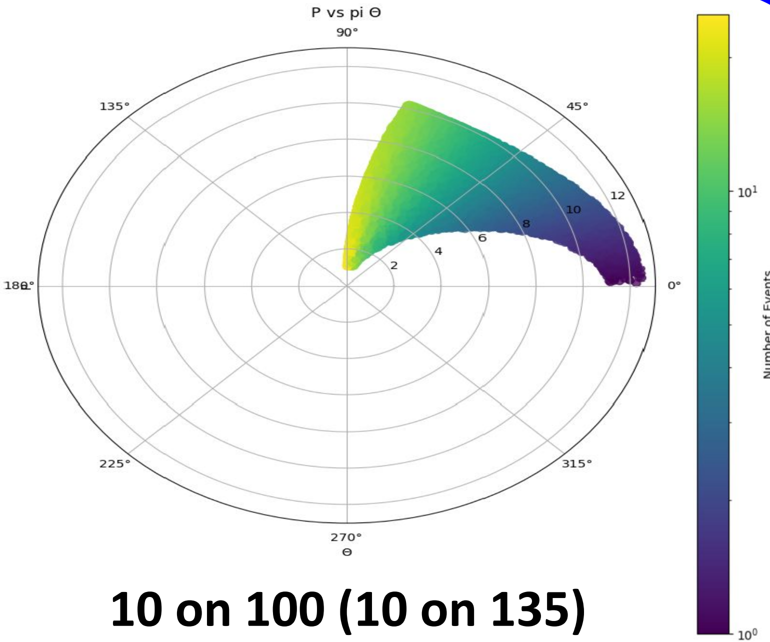
10 on 100 (10 on 135)

- Scattered electrons can be detected in the central detector

Meson Structure Functions – Scattered Meson

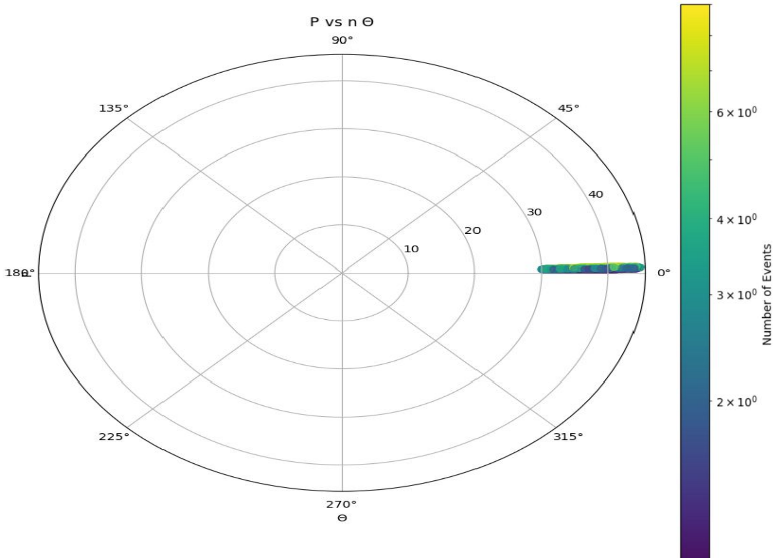


5 on 41

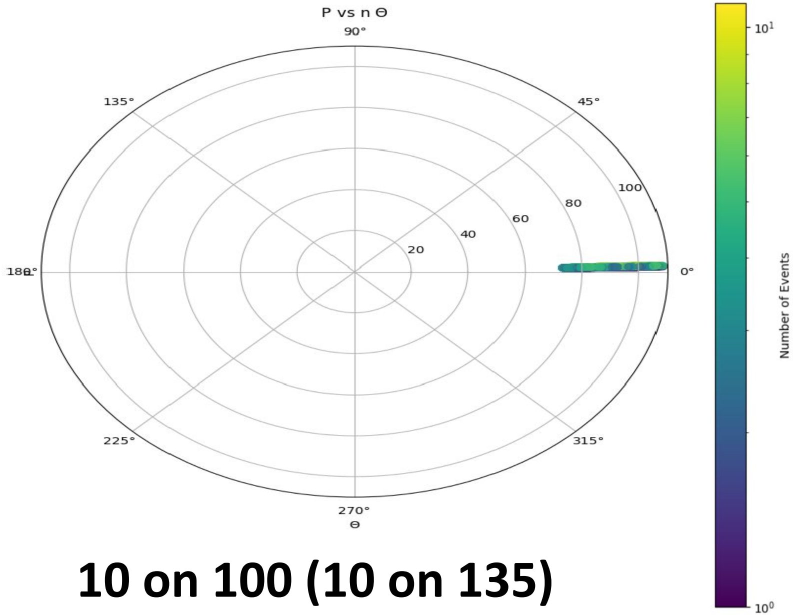


10 on 100 (10 on 135)

Meson Structure Functions – Forward Baryon



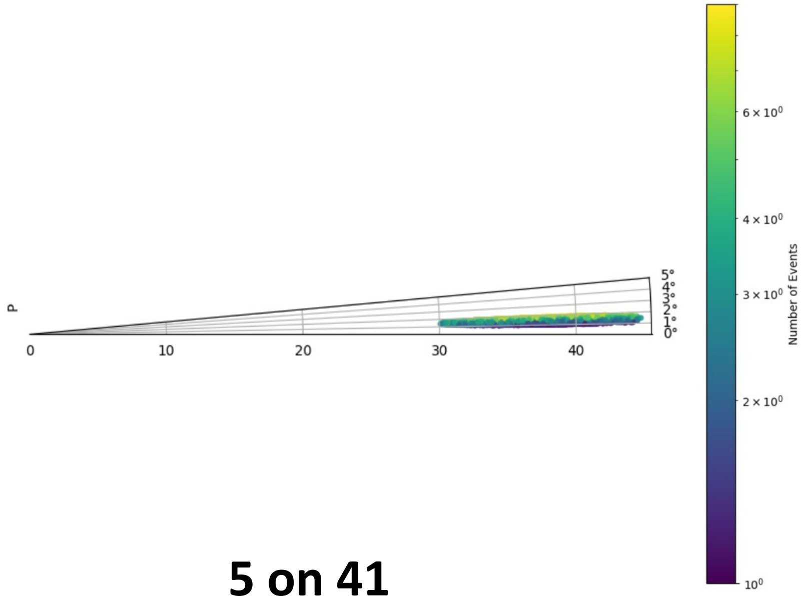
5 on 41



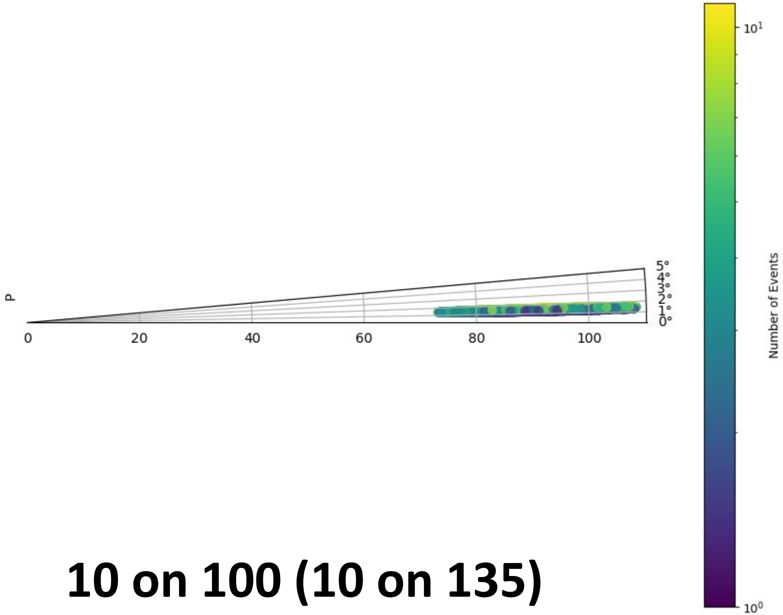
10 on 100 (10 on 135)

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

Meson Structure Functions – Forward Baryon



5 on 41

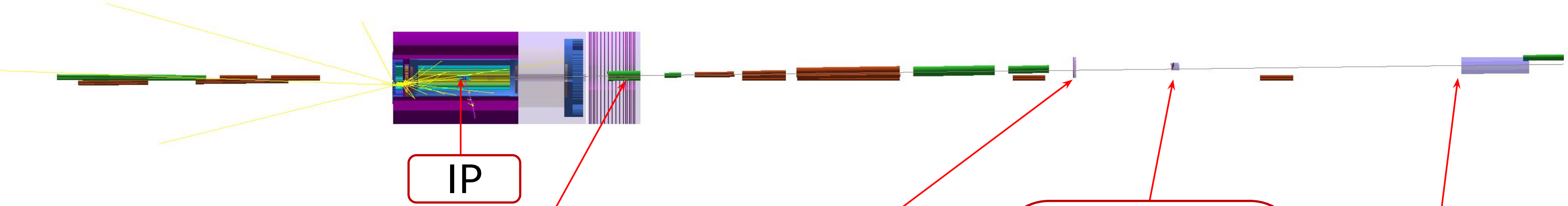


10 on 100 (10 on 135)

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

GEANT4 for EIC

- Meson structure MC outputs lund files for use in GEANT4



B0 sensors:
Rin ~ 3.4 cm
Rout ~ 20 cm
50x50 um^2 pixel pitch

Zpos= 5.9 m
Xpos =15 cm

Off momentum tracker :
Rin ~ 10 *cm (?) ,
10x30cm
500x500 um^2 pixel pitch

Zpos = 22.5 m
Xpos = 75 cm

Roman Pots:
Rin ~ 10σ
20x10 cm^2
500x500 um^2 pixel pitch

Zpos = 26.2 m
Xpos = 82 cm

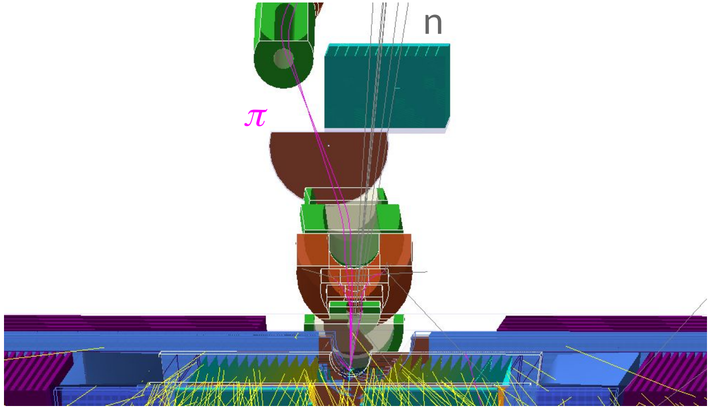
RP2 (not seen):
Zpos = 28.2 m
Xpos = 91 cm

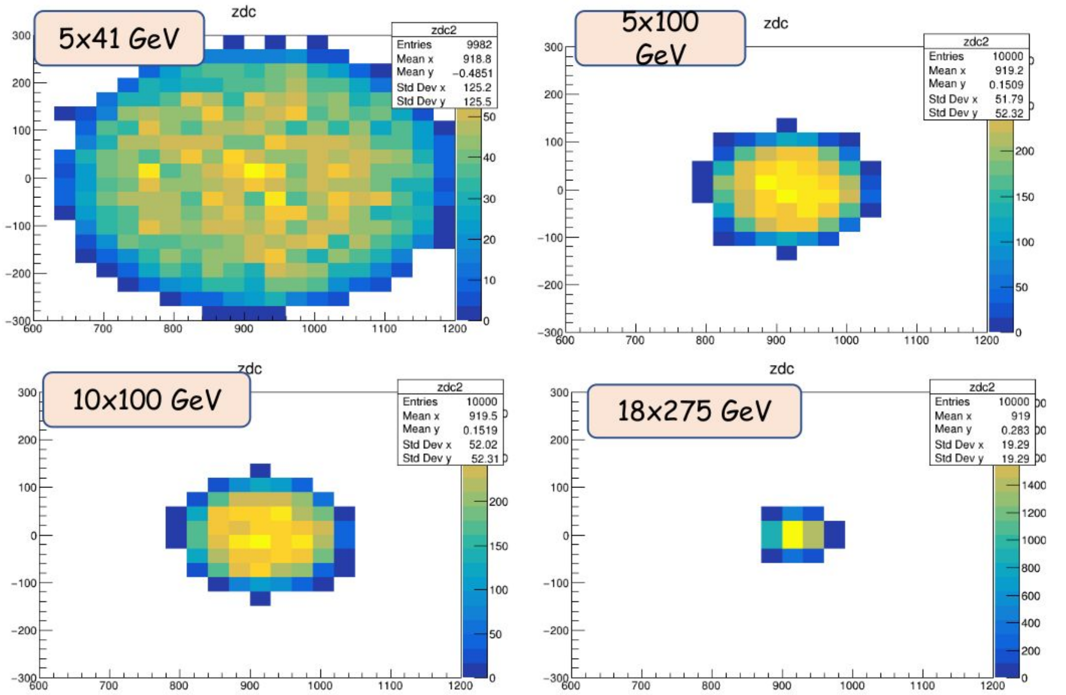
ZDC:
60x60cm EMCAL
LG: 1x1cm^2
HG: 100x100um^2
HCAL: 10x10 cm

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





- 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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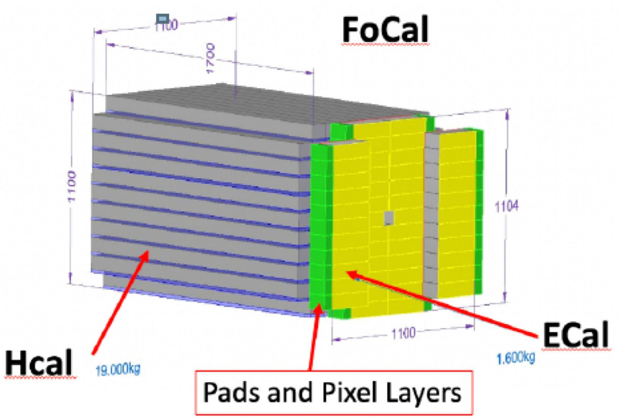
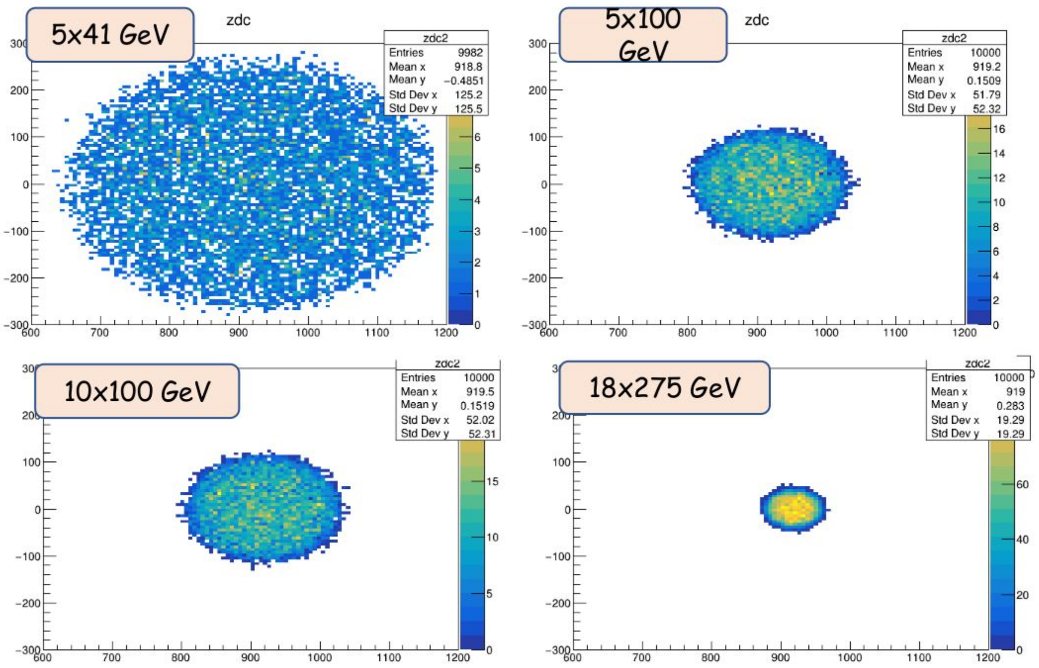




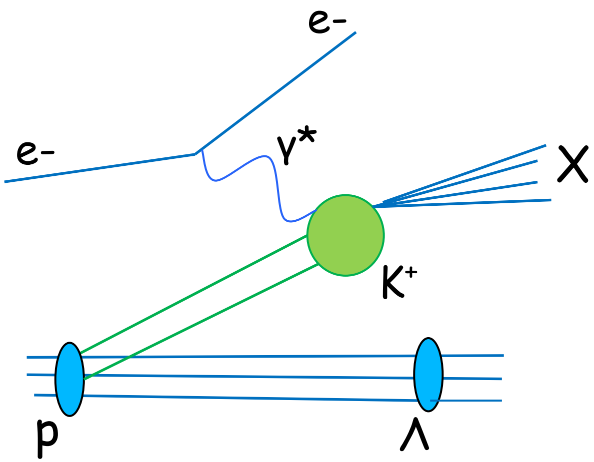
- ZDC: [60x60 cm, 100 bins → 0.6 cm towers]
- If we want energies over 100 GeV, we will need resolution of ~1 cm or better

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

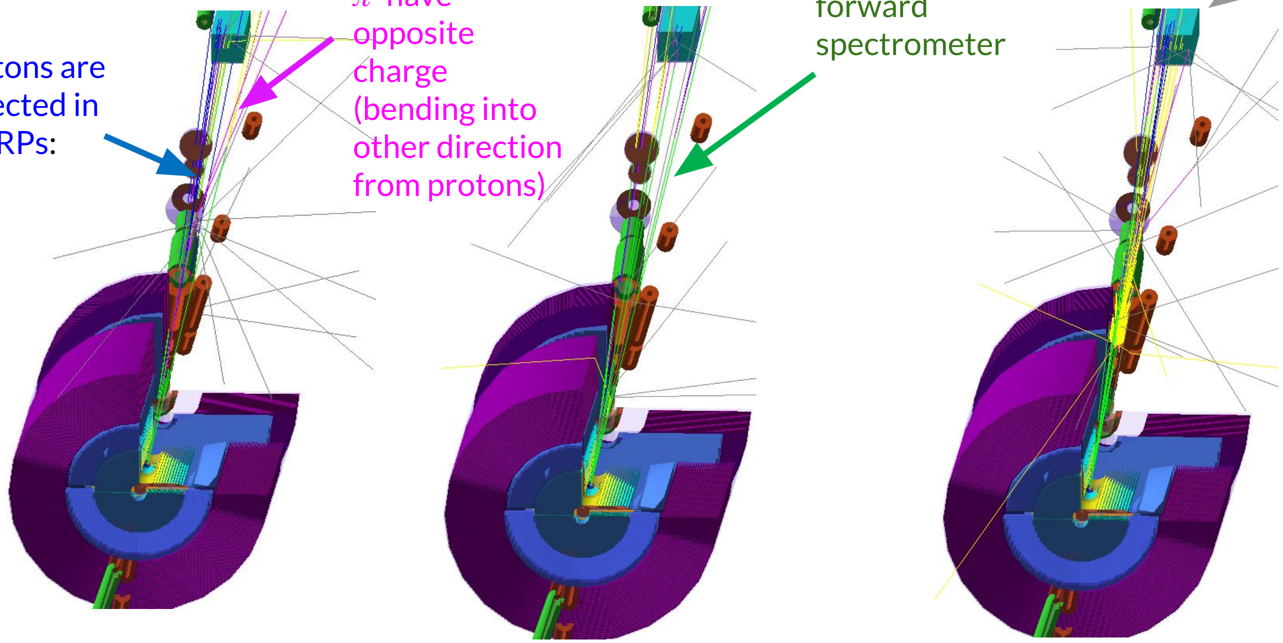
$$\Lambda \rightarrow p + \pi^{-}$$
$$\Lambda \rightarrow n + \pi^{0}$$

Protons are detected in the RPs:

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

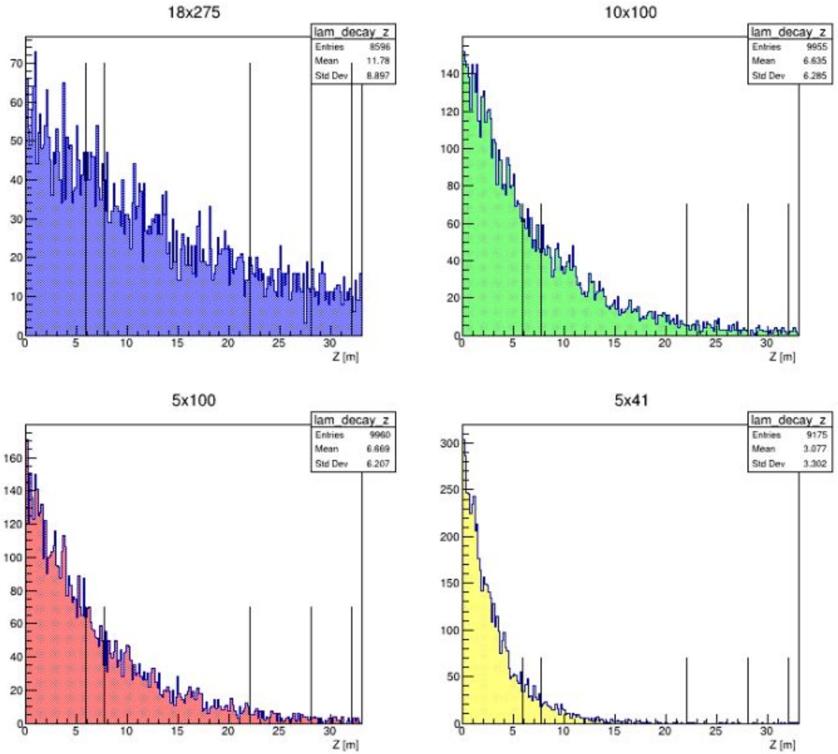
30% of Λ at high energy does not decay before forward spectrometer

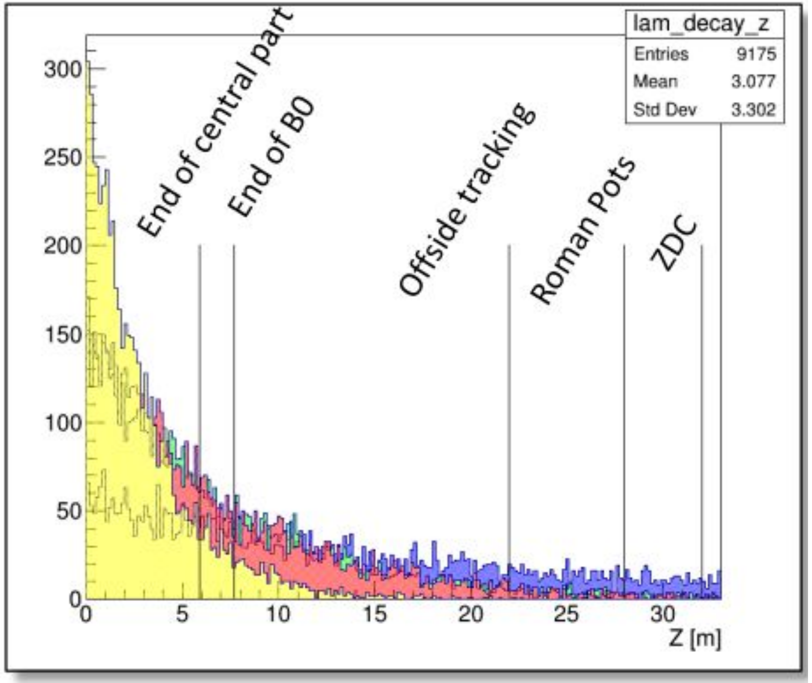
Neutrons and a fraction of π^{0} goes into ZDC



18 x 275

Decay Length





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

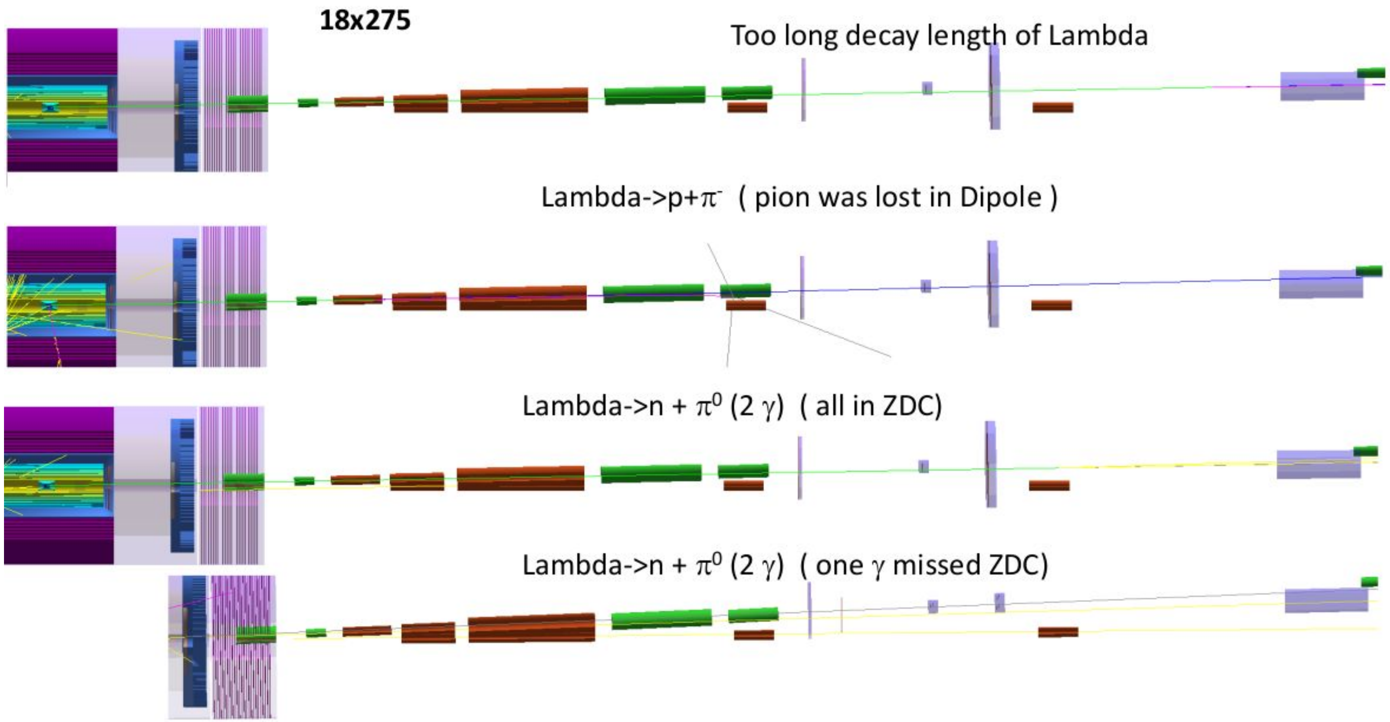
Lambda Final State

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

- need additional particle tracking between dipoles and ZDC

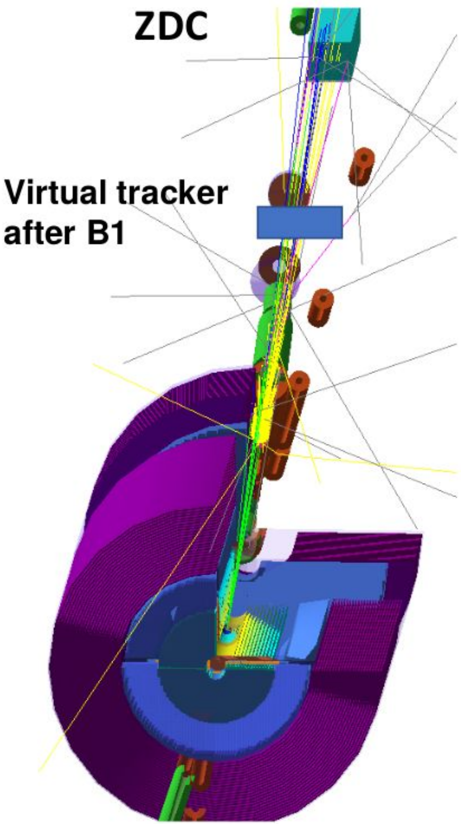
$\Lambda \rightarrow n + \pi^0$: looks promising

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



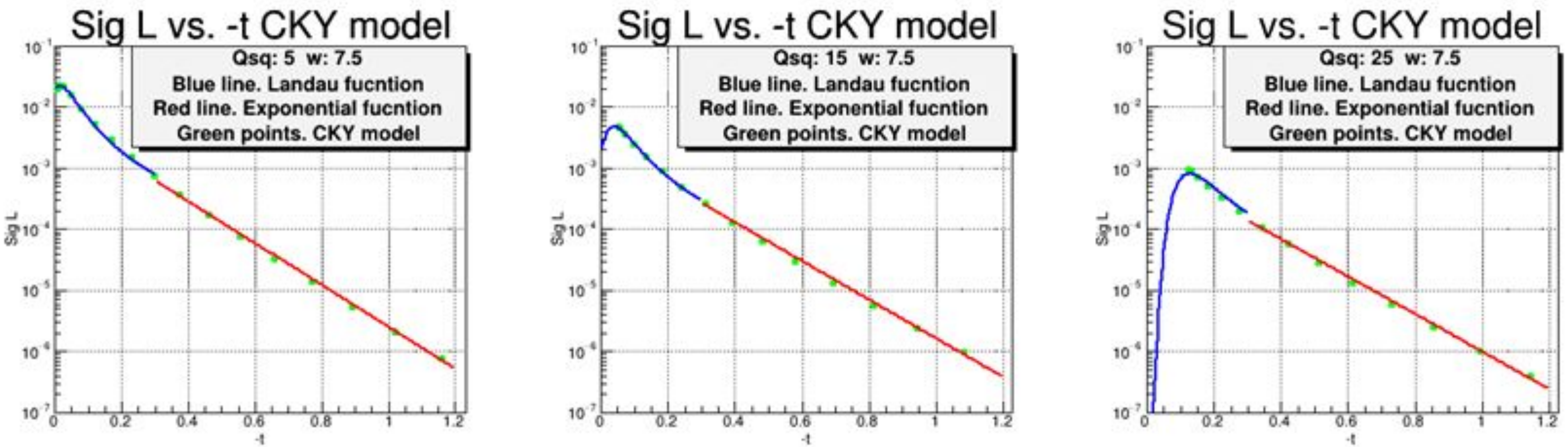
Summary of Detector Requirements

- 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)
- Standard detection requirements
- [In progress] Good hadronic calorimetry to obtain good x resolution at large x



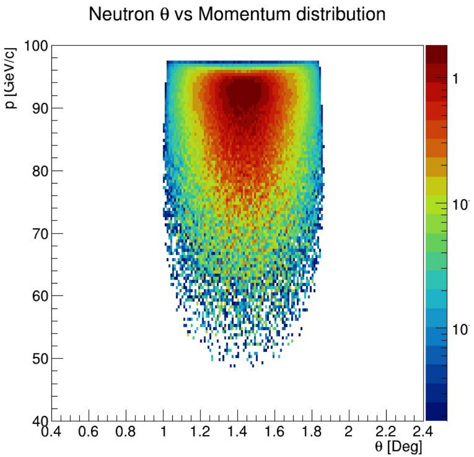
DEMP Event Generator

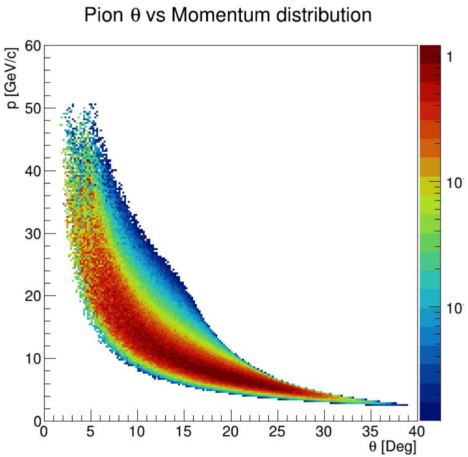
- Want to examine **exclusive** reactions too for π^+ form factor studies
  - p(e,e'π^+n) exclusive reaction is reaction of interest, treat p(e,e'π^+)X SIDIS events as background
- Regge-based p(e,e'π^+ n) model of T.K. Choi, K.J. Kong, B.G. Yu (CKY) arXiv: 1508.00969
  - MC event generator has been created by parameterizing the CKY σ_L,σ_T for 5<Q^2<35, 2<W<10, 0<-t<1.2

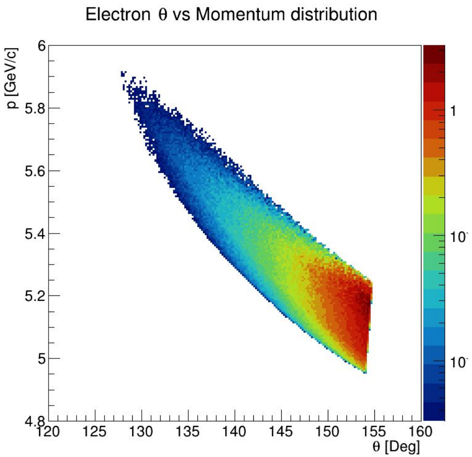


n, π^+ and e' Acceptance ($-t < 0.5$ GeV^2)

- 5 (e^-) on 100 (p) GeV collisions, 25 mrad crossing angle assumed
- Events weighted by cross-section
- Will need good angular resolution for neutron detection





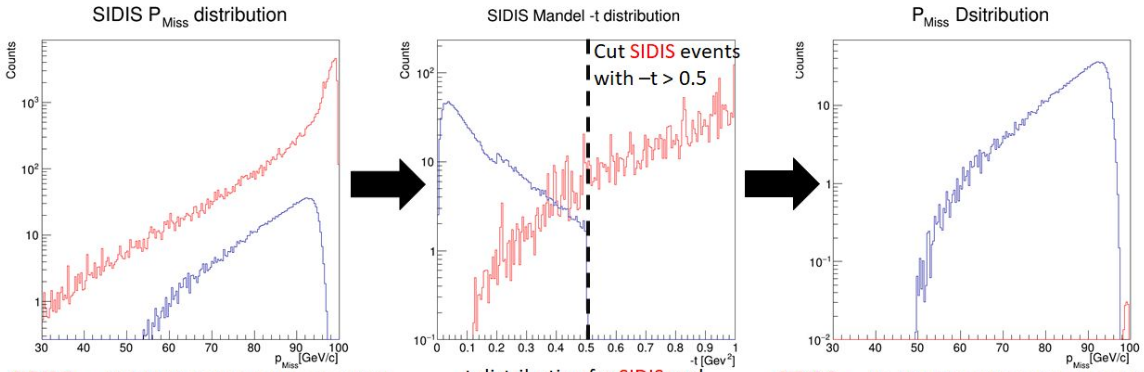


Neutrons - within 0.2° of outgoing proton beam (offset is due to crossing angle)

Plots and analysis by Stephen Kay, University of Regina

Dealing with p(e,e'π^+)X Events

- Used Duke event generator to generate p(e,e'π^+)X SIDIS events as background
    - /work/eic/evgen/SIDIS_Duke on JLab ifarm
- SIDIS events dominate over exclusive events
    - However, distributed over a wider momentum range and are primarily at large -t
- Compare neutron from DEMP events with missing 4-momentum from SIDIS events



SIDIS P_{Miss} vs DEMP neutron 4 momentum, **no cuts**

-t distribution for SIDIS and DEMP events. SIDIS primarily at high -t

SIDIS P_{Miss} vs DEMP neutron 4 momentum -t and θ cuts remove large number of SIDIS events

Plots and analysis by Stephen Kay, University of Regina

Summary

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 <u>all energies</u>: ~100% detection efficiency
     - <u>Low energies</u> [5 on 41, 5 on 100] **require at least 60cmx60cm size** to access wider range of energies
     - <u>High energies [10 on 100, 10 on 135, 18 on 275]</u> **requires resolution of 1 cm or less**
   - For measuring the tagged Λ benefits from <u>low energies</u> [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)
   - [In progress] Good hadronic calorimetry to obtain good x resolution at large x

Timeline to come

EPJA Publication	First Meson structure WG meeting	Meson structure WG meetings	First workshop at Temple	Meson Structure WG meetings	Second workshop at U of Pavia	Workshop on meson structure at EIC at CFNS/ SBU	**Status reports at EICUGM**	Third workshop at CUA	Week with pion and kaon structure focus	Fourth workshop at UCB/ LBL
July 19th, 2019	Jan. 27th, 2020	3 meetings	March 19th, 2020	5 meetings	May 22-24, 2020	June 1-5, 2020	**August 3-7, 2020**	Sep. 17-19, 2020	Oct. 5-9, 2020	Nov. 19-21, 2020

Workshop on Pion and Kaon Structure Functions at the EIC

Center for Frontiers in Nuclear Science
Workshop series

2-5 June 2020
Online
US/Eastern timezone

Remote Workshop in June

- Overview
- Call for Abstracts
- Timetable
- Contribution List
- Registration
- Participant List

Contact
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The Lagrangian masses of the quarks deliver only ≈ 1% of the proton mass, *mp*; and it is the emergence of the bulk of *mp* and the (very probably) related mechanism of confinement that are the key unresolved issues in hadron physics. In addressing these issues, the potential of the EIC is enormous. It promises to enable a quantitative understanding of the structure of hadrons, such as the nucleon, pion and kaon, in terms of quarks and gluons, thereby achieving key goals of modern physics. Recent synergistic advances in computation, experiment and theory reveal the prospects for a precise description of the one-dimensional structure of hadrons, exemplified by parton distribution functions (PDFs) and electromagnetic form factors, and of constructing three-dimensional images of hadrons, as expressed in Generalized Parton Distributions (GPDs) and Transverse-Momentum-Dependent Distributions (TMDs). Hence, today, there is an unprecedented opportunity to chart the in-hadron distributions of, *inter alia*, mass, charge, magnetization and angular momentum.

This workshop will canvass recent progress toward a coherent program of pion and kaon structure studies at the Electron-Ion Collider (EIC) that will deliver these maps. Their drawing demands an interplay between experiment and theory. Here, recent experimental developments have been matched by new theoretical insights and rapid computational advances. The progress triad is completed by high-level phenomenology in the form of global structure function fitting frameworks. Machine learning and exascale computing are both expected to play a material role in this march of progress.

This workshop aims to capitalize on the success of two prior meetings (PIEIC2017, PIEIC2018), which led to a White Paper, published in Eur.Phys.J.A 55 (2019) 10, 190. Its near-term goals are to expand this documentation, driving toward a significant new element in the EIC User Group Physics and Detector Handbook, and develop contributions as part of the ongoing Yellow Report Initiative.

Large (remote) interest:

- All invited speakers accept
- 66 participants already

Starts Jun 2, 2020, 8:00 AM
Ends Jun 5, 2020, 7:00 PM
US/Eastern

Online

Craig Roberts
Tanja Horn

https://indico.bnl.gov/e/PIEIC2020

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 Lee, Yulia Furletova, Dmitry Romanov, Markus Diefenthaler, Richard Trotta, Tanja Horn, Rolf Ent, Tobias Frederico

ECT* EUROPEAN CENTRE FOR THEORETICAL STUDIES IN NUCLEAR PHYSICS AND RELATED AREAS

Argonne NATIONAL LABORATORY

University of Glasgow

ITA 1950

University of Regina

MICHIGAN STATE UNIVERSITY

NIP 南京大学

UNIVERSIDAD PABLO DE OLAVIDE SEVILLA AÑO 1997

SMU

Jefferson Lab

南开大学 Nankai University

Vitreous State Laboratory of The Catholic University of America

THE CATHOLIC UNIVERSITY OF AMERICA

EXTRA

EIC fast Monte Carlo

- C++ based fast MC which outputs root files and text file for GEANT4 input

Cpp Script(TDISMC_EIC.cpp)-requires as input: range of Q2 and x and uses a header file for beam energy, beam polarization, structure function parameterization, physical constants, etc.
Calls 4 quantities...
1. CTEQ6 PDF table
2. f2π with various parameterization (the header file defines the structure function)
3. F2N, nucleon structure function (the header file defines the structure function)
4. Beam smearing function

Event generation
Random number generation uses TRandom3 (run3.SetSeed(#))
- Defining electron and proton/deuterium beam...
  - kbeamMC=kbeam*ran3.Gaus(1,eD/k), where eD/k=7.1e-4 is the fractional energy spread normalized emittance value
  - kbeamMCx=kbeamMC*ran3.Gaus(0,Ɵex), where Ɵex is smearing
  - PbeamMC=Pbeam*ran3.Gaus(0, iDp/p), where iDp/p=3e-4
  - PbeamMCx=PbeamMC*ran3.Gaus(0, Ɵix)

Collider vs. fixed target

Careful with kinematic definitions

- Original code was written for fixed target – found and fixed several instances with restrictions that apply to fixed target, but not to collider
- Examples:
  - Measurable proton range (for fixed target given by TPC – imposes limits on k, z)
  - Removed fixed target restrictions on x for structure function calculations

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Kinematic Variables

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

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

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

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

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

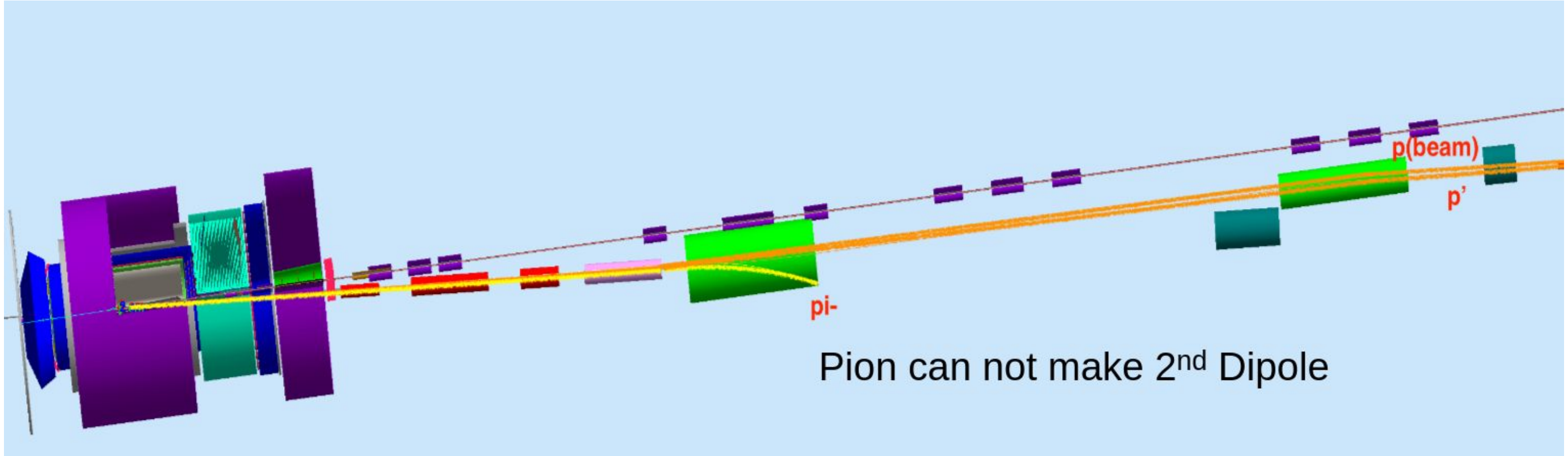
$$y_\pi = \frac{(pScatPion)_{rest}(qVirt)_{rest}}{(pScatPion)_{rest}(kIncident)_{rest}}$$

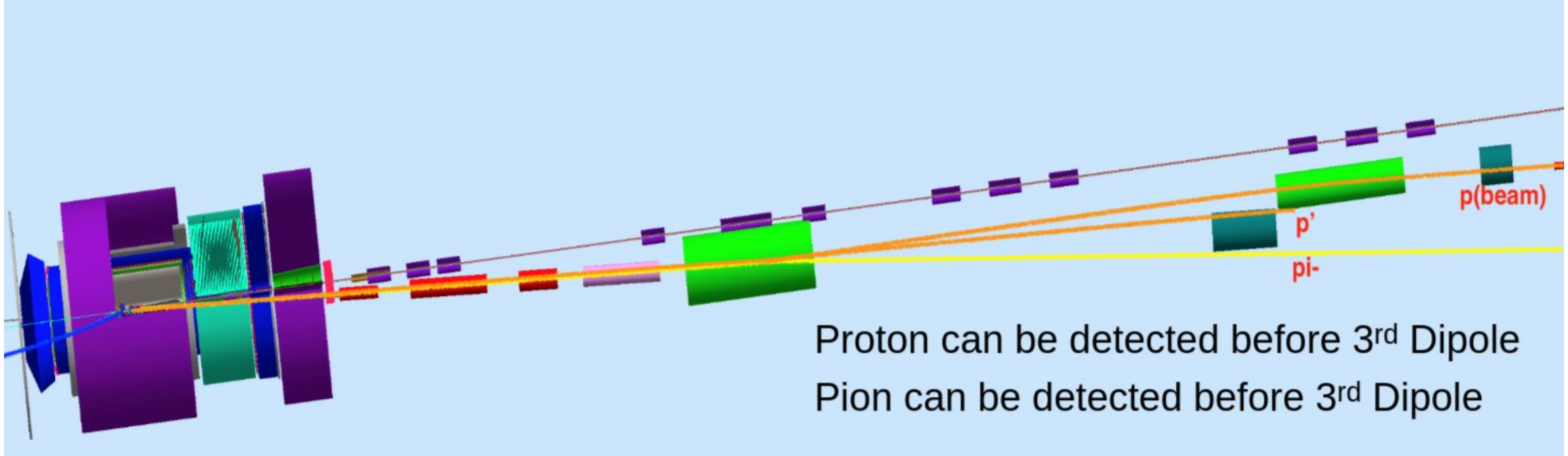
$$t_\pi = E_\pi^2 - |pScatPion.v3|^2$$

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

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

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

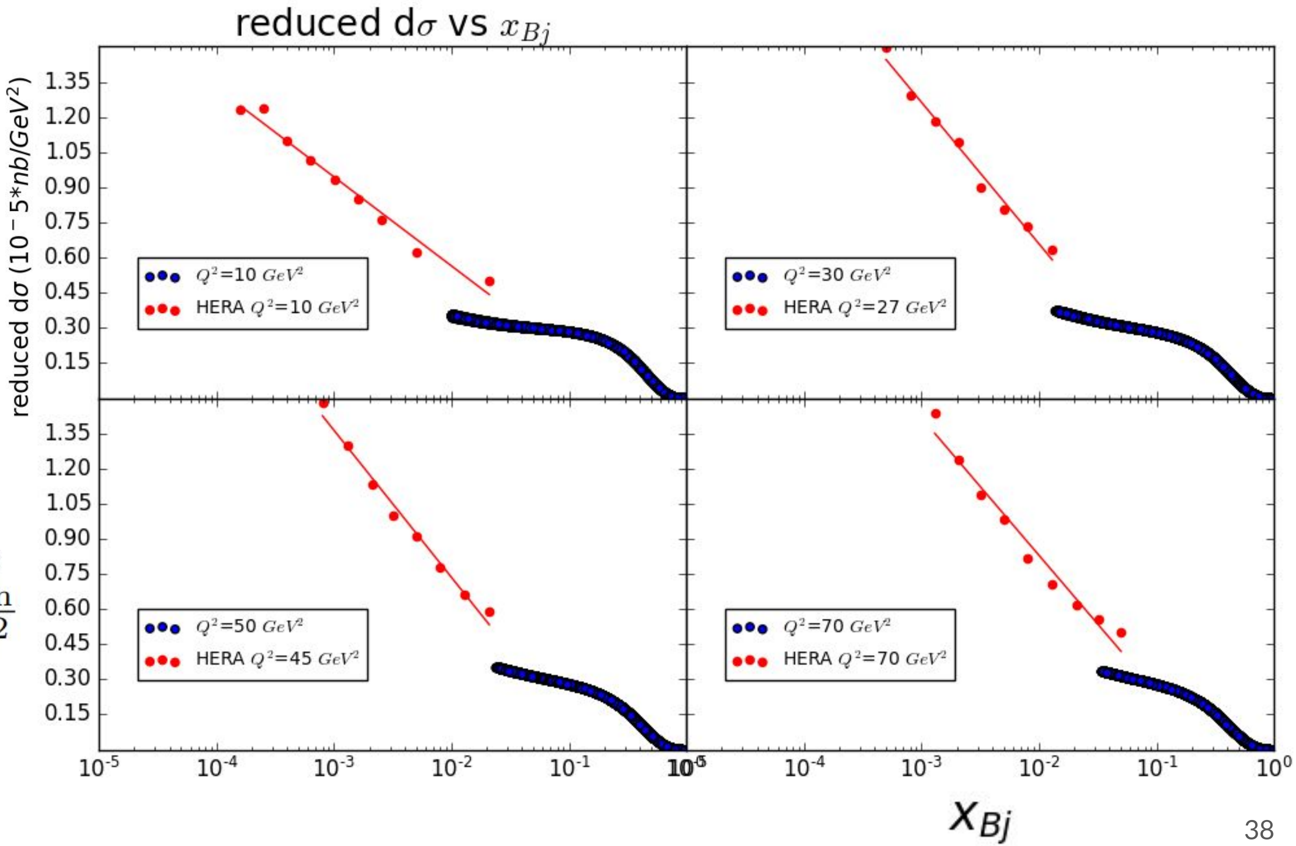




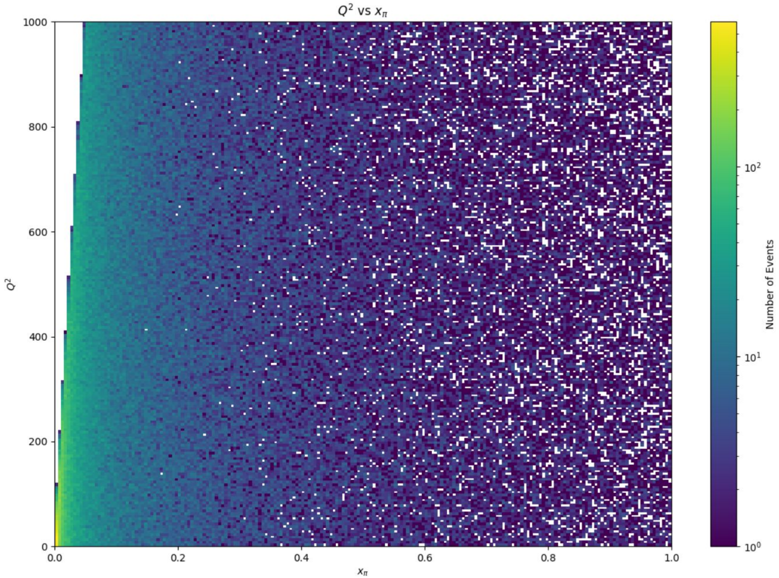
Validation: Reduced cross-section compared with HERA

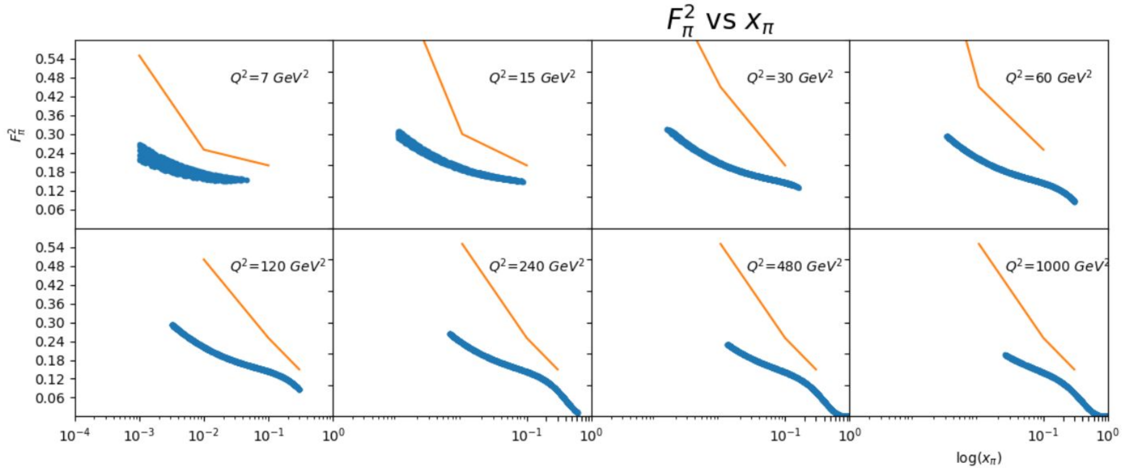
- HERA data from *ZEUS collab, Eur. Phys. J. C 21 (2001) DOI:10.1007/s100520100749*
- Proton beam = 100 GeV/c
- Electron beam = 5 GeV/c
- x_{Bj}=(0.01-1.0)
- Q^2=(10-100)

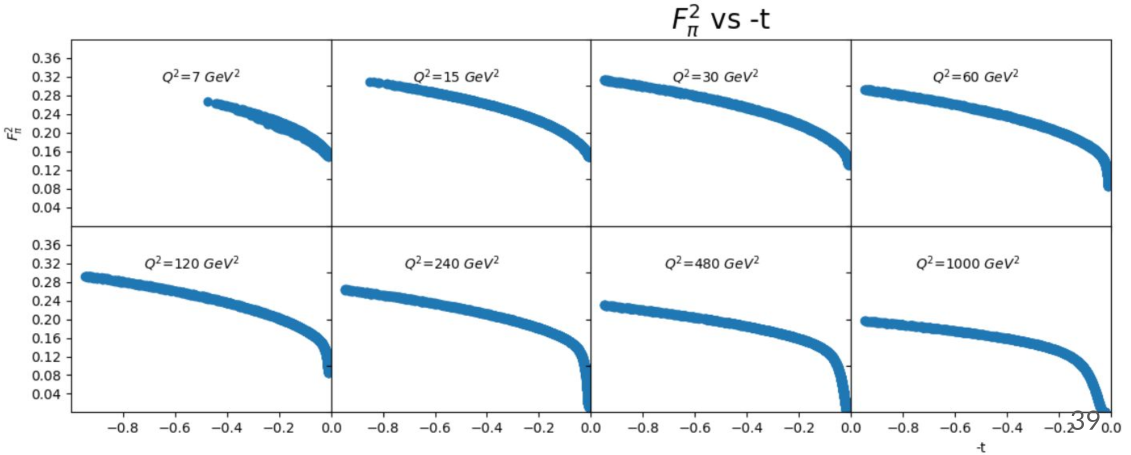
$$\tilde{\sigma}^{e^+p} = \left[\frac{2\pi\alpha^2}{xQ^4}Y_+\right]^{-1}\frac{d^2\sigma^{e^+p}_{\mathrm{Born}}}{dx\,dQ^2}$$



18 on 275 [(0.01 < y < 0.95)]
MC:[x(0.001-1.0),Q^2(1,1000)]





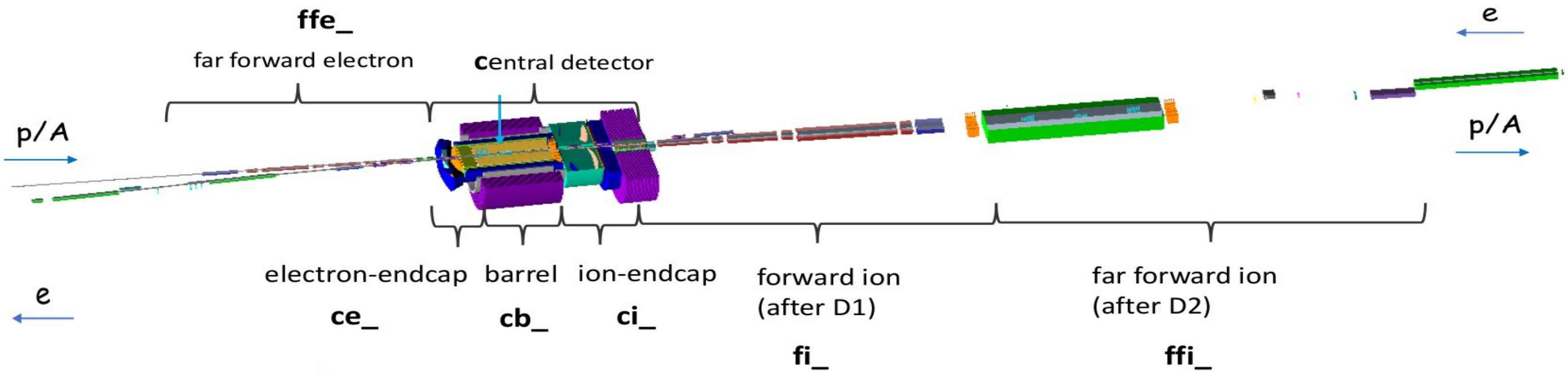


- $F^2_\pi = (0.361)*F^2_P$
  - ZEUS Parameterization
  - GRV fit

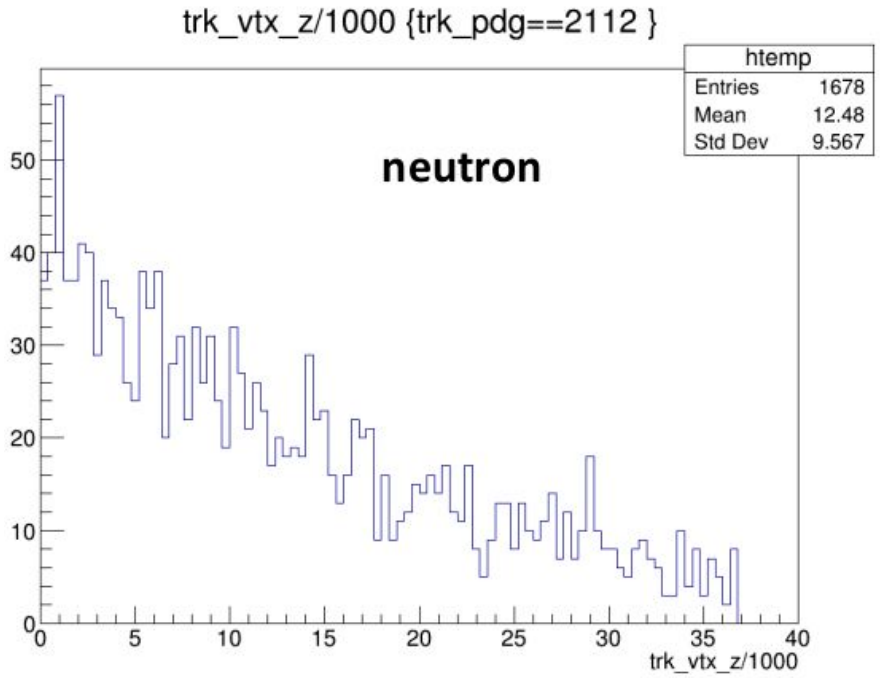
ZEUS Collaboration, Nucl.Phys. B637 (2002)
DOI:10.1016/S0550-3213(02)00439-X

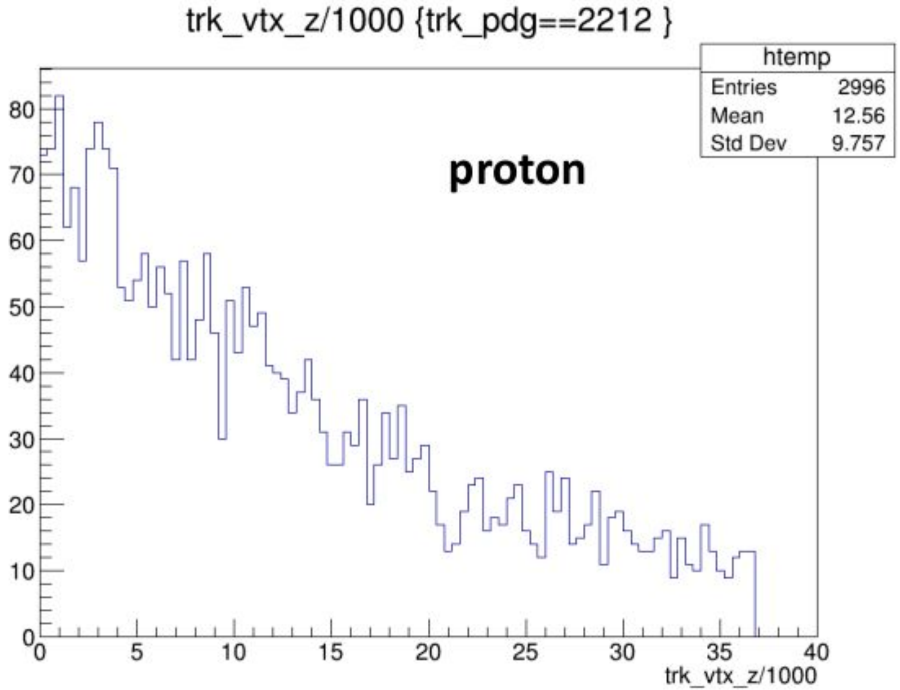
GEANT4 for EIC

- 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]

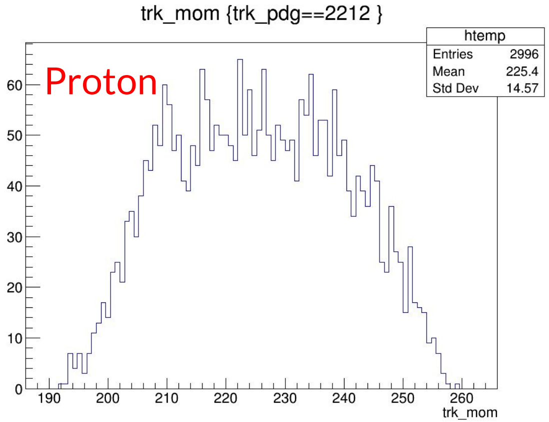


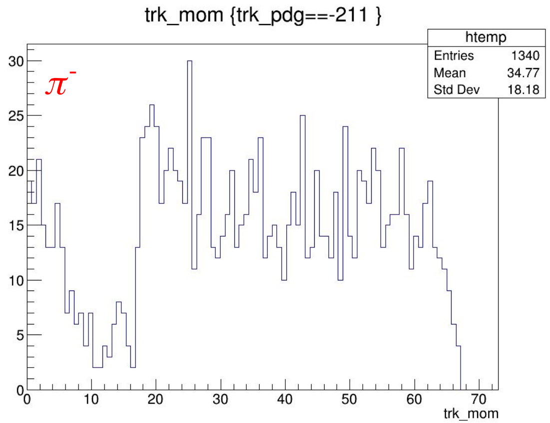


- 10k events → 3580 neutrons → ~47%
  - Need to add π^0 efficiency
- 10k events → 6390 protons → ~47%
  - Need to add π^- efficiency

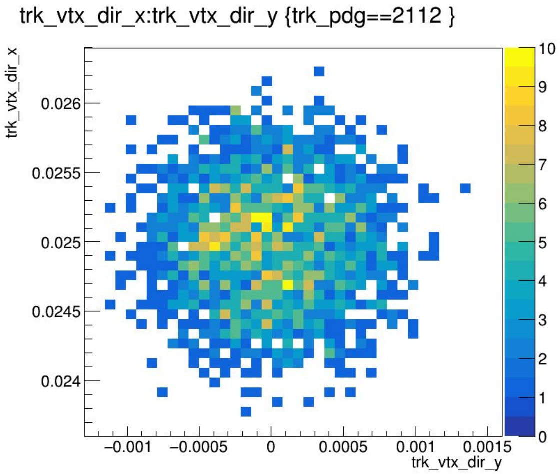
Virtual planes [p(e,e'K$^+$Λ^0)X]

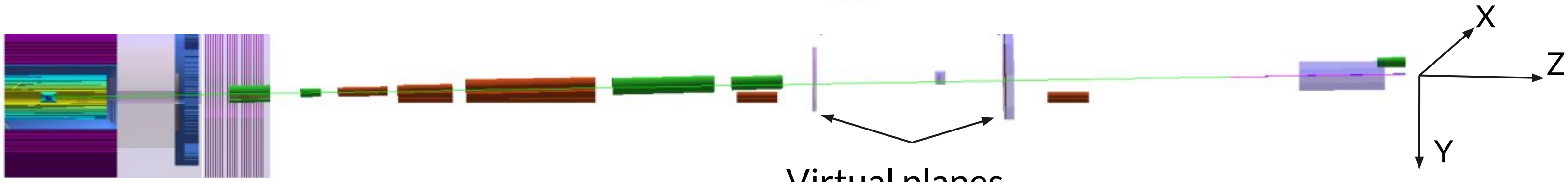
- Next step: Switch from virtual planes to the real size detector and check detector efficiency





Angular distribution for Proton





Virtual planes

Future F_π^2 projections

- Only ZEUS parameterization for F_π^2 is currently implemented
    - next step would be checking with other pion SF parameterizations
- 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
- Extend to tagged kaon structure function
- Eventually explore more elaborate final states? (e.g., to unravel contributions from Delta-exchange)