Meson Structure at the EIC

Temple EIC User Meeting

March 19th, 2020

Richard Trotta and the meson structure working group

Jefferson Lab

THE CATHOLIC UNIVERSITY OF AMERICA

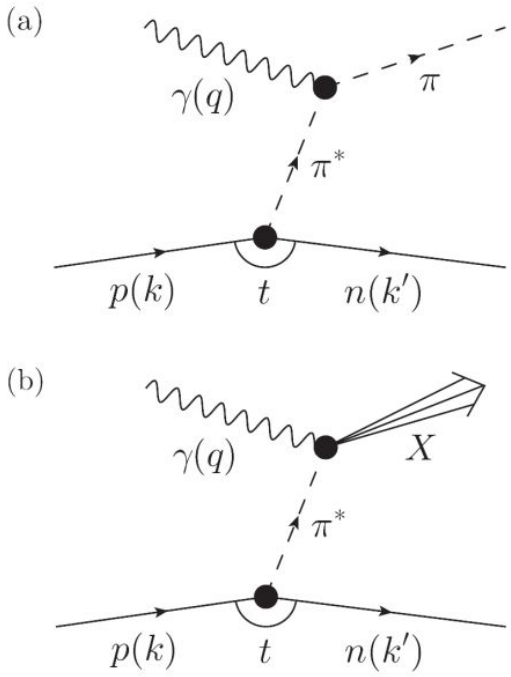
5 key EIC measurements

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^2~35 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

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
- Empirically, this can be studied through data covering a range in low -t and compare
  - Pion, $-t < 0.6\ \mathrm{GeV}^2$
  - Kaon, $-t \leq 0.9\ \mathrm{GeV}^2$

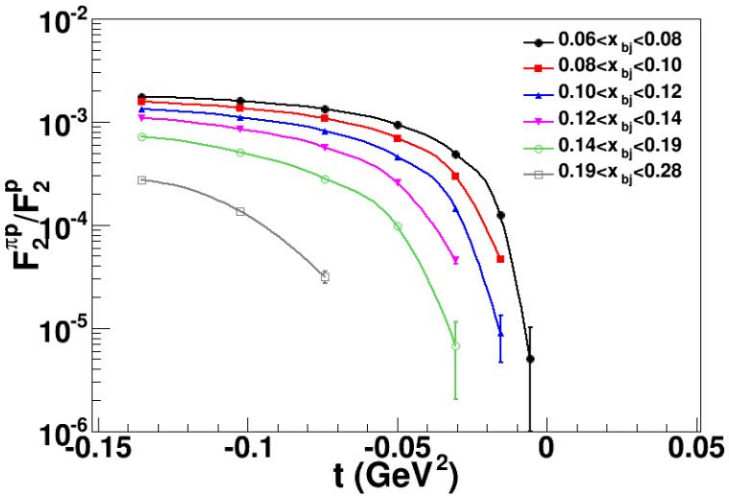


Pion cloud can access a)Elastic FF b) PDF

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

EIC Capabilities

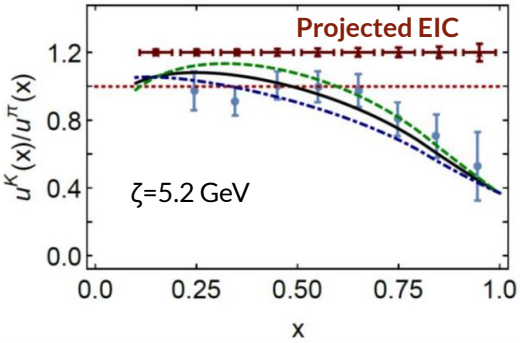
- $L_{EIC} = 10^{34}$ e-nucleons/cm^2/s = 1000 x L_{HERA}
- Fraction of proton wave function related to pion Sullivan process is roughly 10^{-3} for a small –t bin (0.02)
  - pion data at EIC should be comparable or better than the proton data at HERA, or the 3D nucleon structure data at COMPASS
- By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

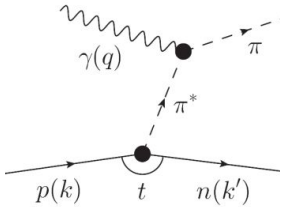


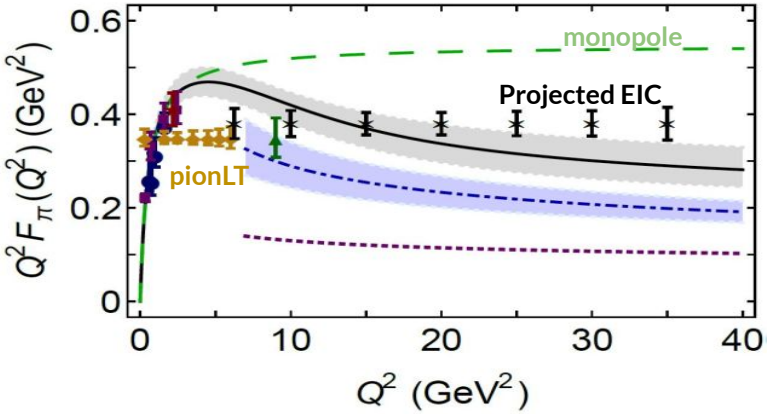
Jefferson Lab TDIS Collaboration, JLab Experiment C12-15-005 Proposal

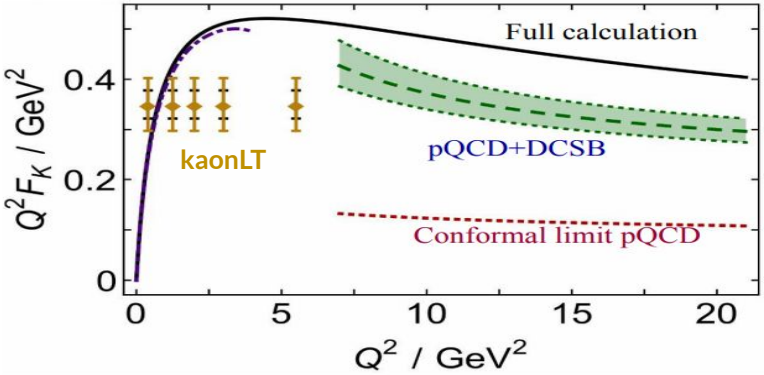
EPJA Pion and Kaon Structure Projections

- 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

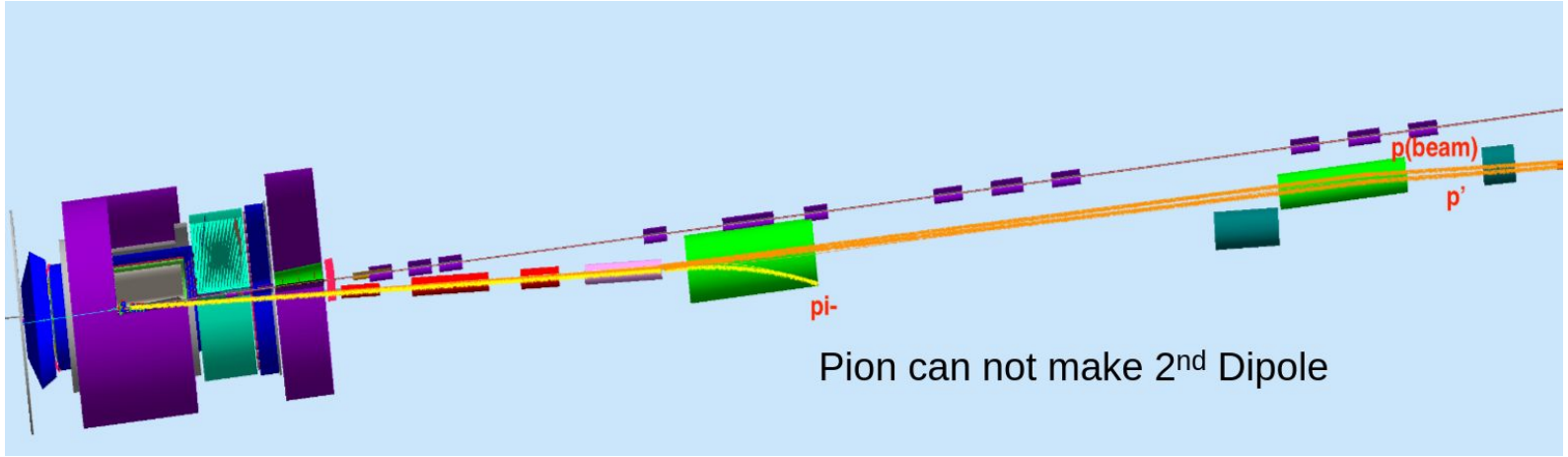
Geometric particle detection fractions

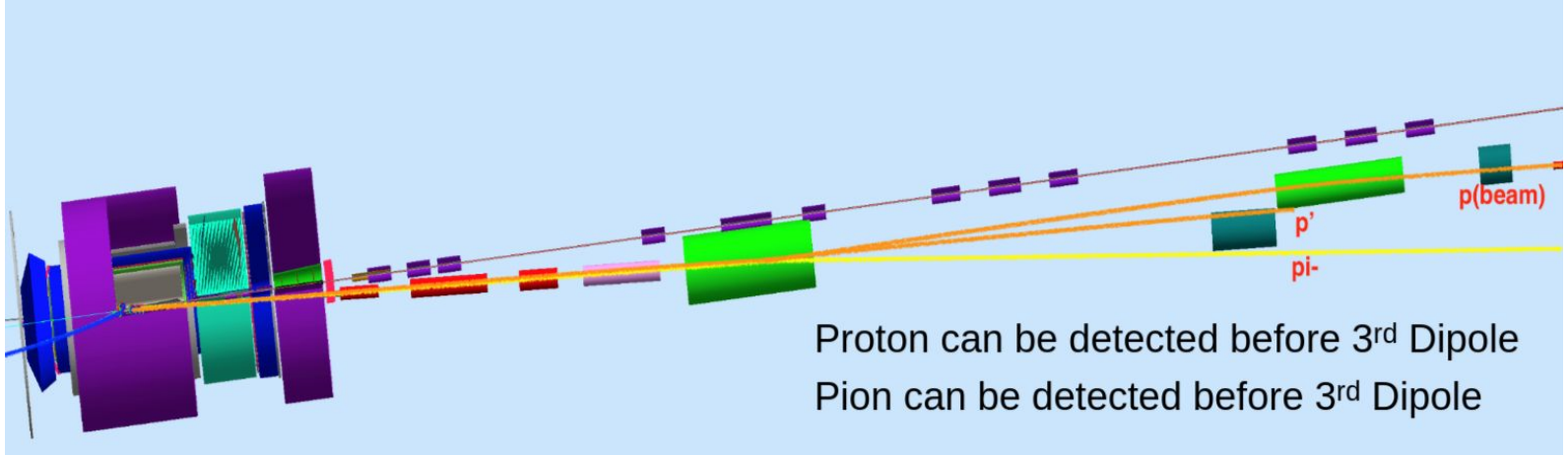
- For p(e,e'π^+n)X, the final state neutron moves with an energy near that of the initial proton beam
  - The Zero Degree Calorimeter (ZDC) must reconstruct the energy and position well enough to constrain both scattering kinematics and 4-momentum of pion
  - Constraining neutron energy around 3.5% will assure an achievable resolution in x
- For p(e,e'$K^+\Lambda^0$)X, the decay products of the Λ^0 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' π^+) n	n	>20%
^{1}H(e , e' K^+) Λ	Λ	50%
^{1}H(e , e' K^+) Σ	Σ	17%

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

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





Event	**Date**	**Notes**
EPJA Publication	July 19th, 2019	Final revisions Sep. 16th, 2019
Formation of meson WG	December 2019	First announcements of our groups formation!
First Meson structure WG meeting	Jan. 27th, 2020	● Integrate into YR ● Science Motivation - mass mechanism in pion/kaon as way to understand QCD, puzzles about gluon content, large x ● Check if can adequately do the meson structure physics with the EIC at BNL
Meson structure WG meeting	Feb. 25th, 2020	● Detection fractions ○ Can detect forward-going particles, but how to distinguish decay products, e.g. lambda ● Structure functions ○ progress with generator development since EPJA article: now can make pion SF projections
Meson structure WG meeting	March 16th, 2020	● Detection fractions checks ○ Proton and neutron done ○ for K/Λ: checking Λ decay ○ Virtual planes are ready - working on analysis chain with reconstruction for K-Lambda

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

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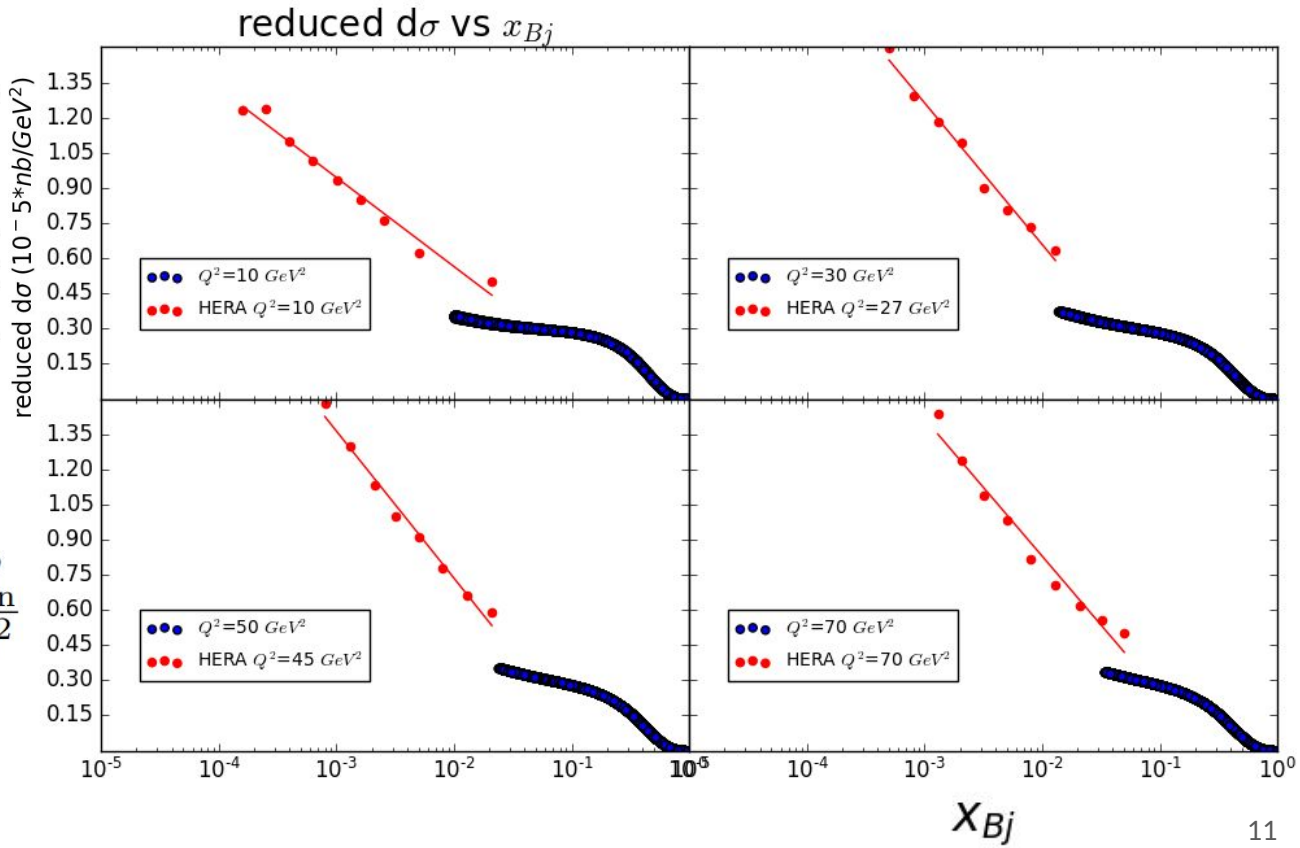
Structure functions

- For projections use a Fast Monte Carlo that includes the Sullivan process
  - PDFs, form factor, fragmentation function projections
- Progress with generator development since EPJA article:
  - fixes made in generator to remove fixed-target leftovers
  - now can make pion structure function (pion SF) projections
- Current final states: π^0/p, π^+/n, K^+/Λ^0
- Beam energies: 5 on 100, 10 on 100, 18 on 275

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)

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



Validation: F_π^2 with GRV fit/DESY-HERA-H1 data

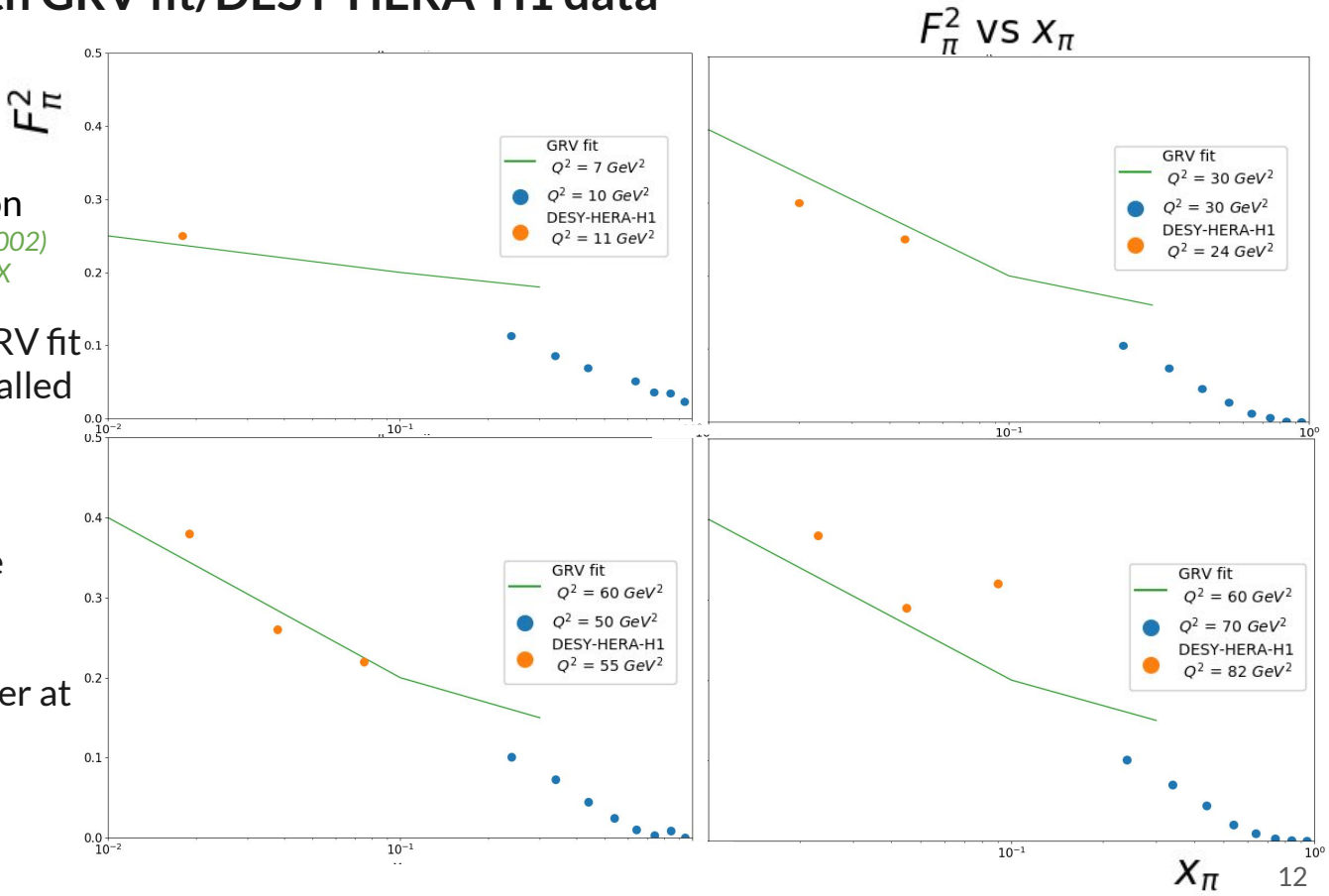
- $F^2_\pi = (0.361)*F^2_P$
  - ZEUS Parameterization

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

- DESY-HERA-H1 data and GRV fit (for three points) were eyeballed from plots

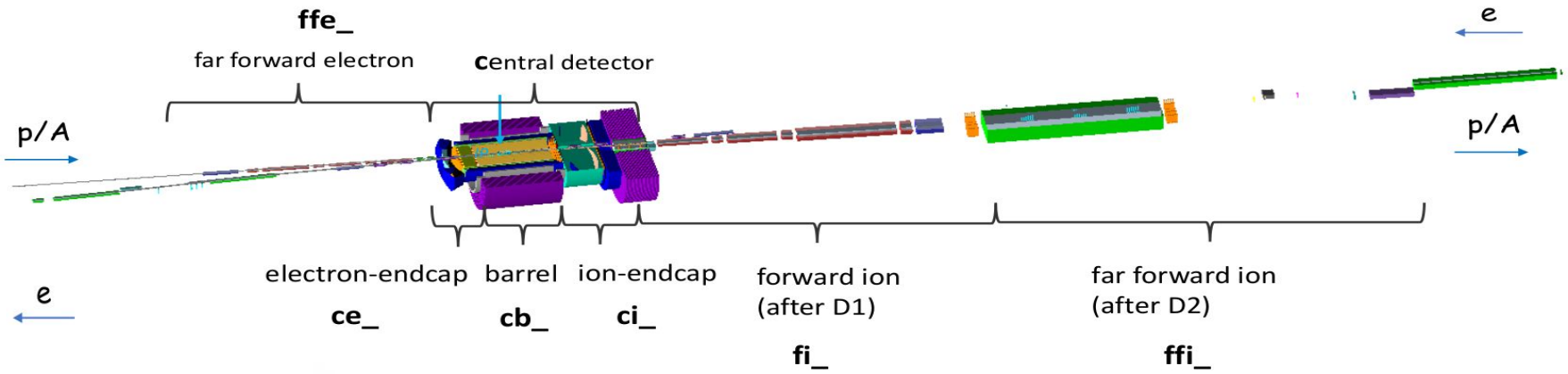
  J. Lan et. al., arXiv preprint (2019)
  arXiv:1907.01509

- HERA F_π^2 data appear to be consistent with the MC projections though the x-dependence seems stronger at higher x



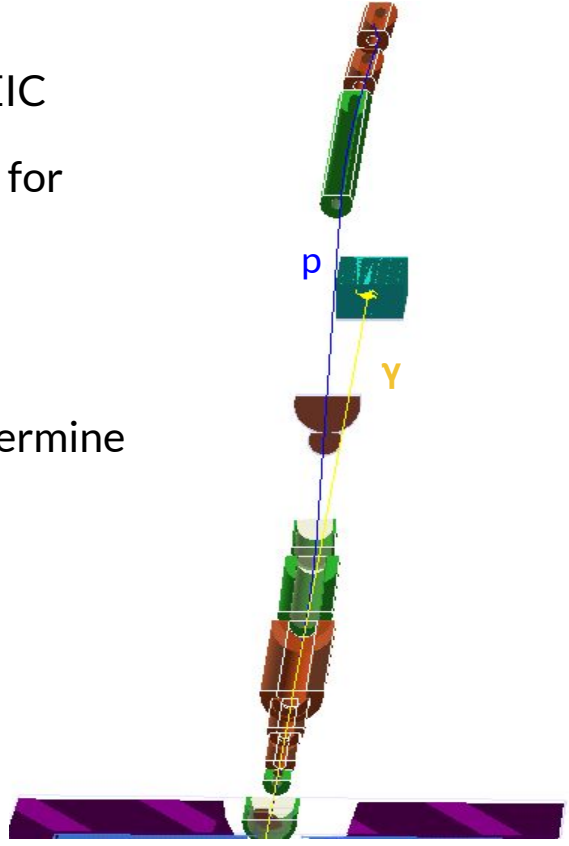
GEANT4 for EIC

- Meson structure MC outputs lund files for use in GEANT4
- Detector MC updated with eRHIC specifics (crossing angle changes primarily)
- Updating 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



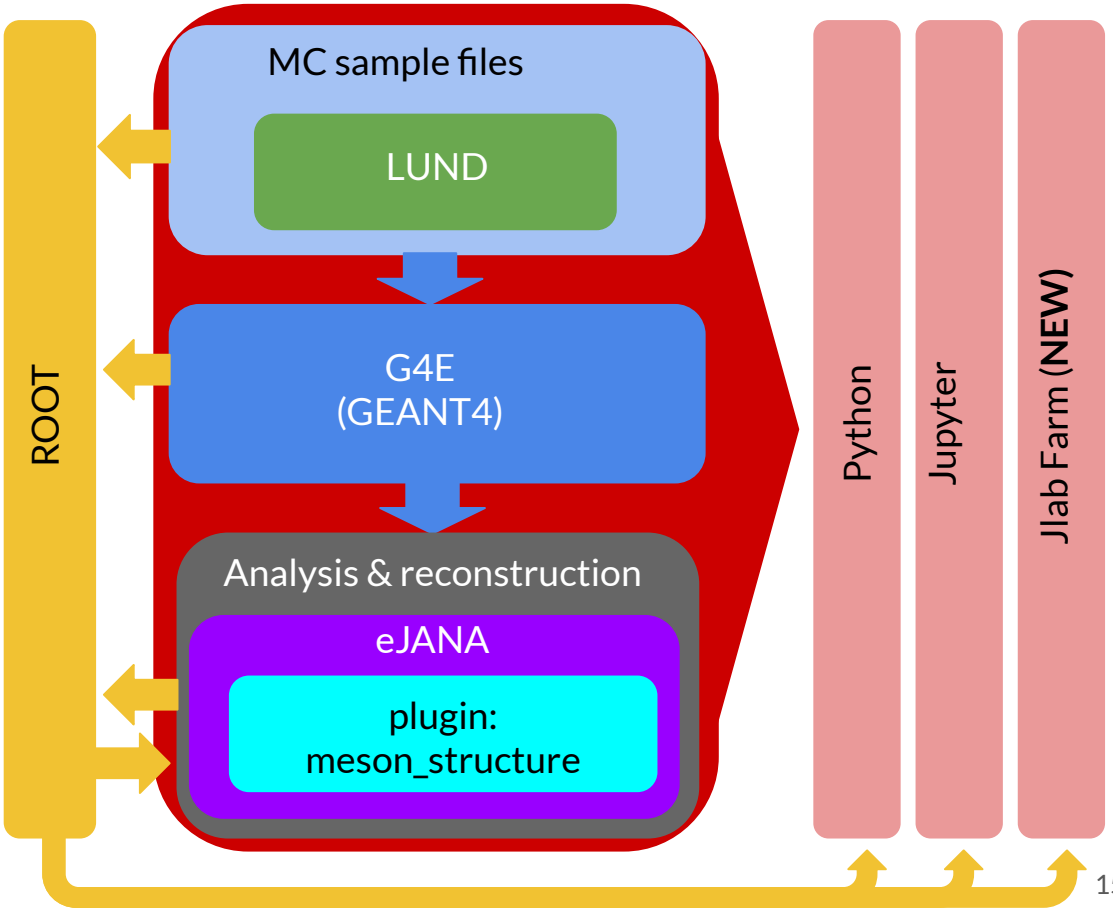
p(e,e'π^0p)X (systematic checks)

- Have the beamline CAD - generally looks similar to JLEIC
- Currently only have Roman Pots in forward region - ok for DVCS, but need more detectors for meson structure measurements
- General approach: put virtual detectors at different z-locations in between the magnets - based on this determine what space is needed for these additional detectors



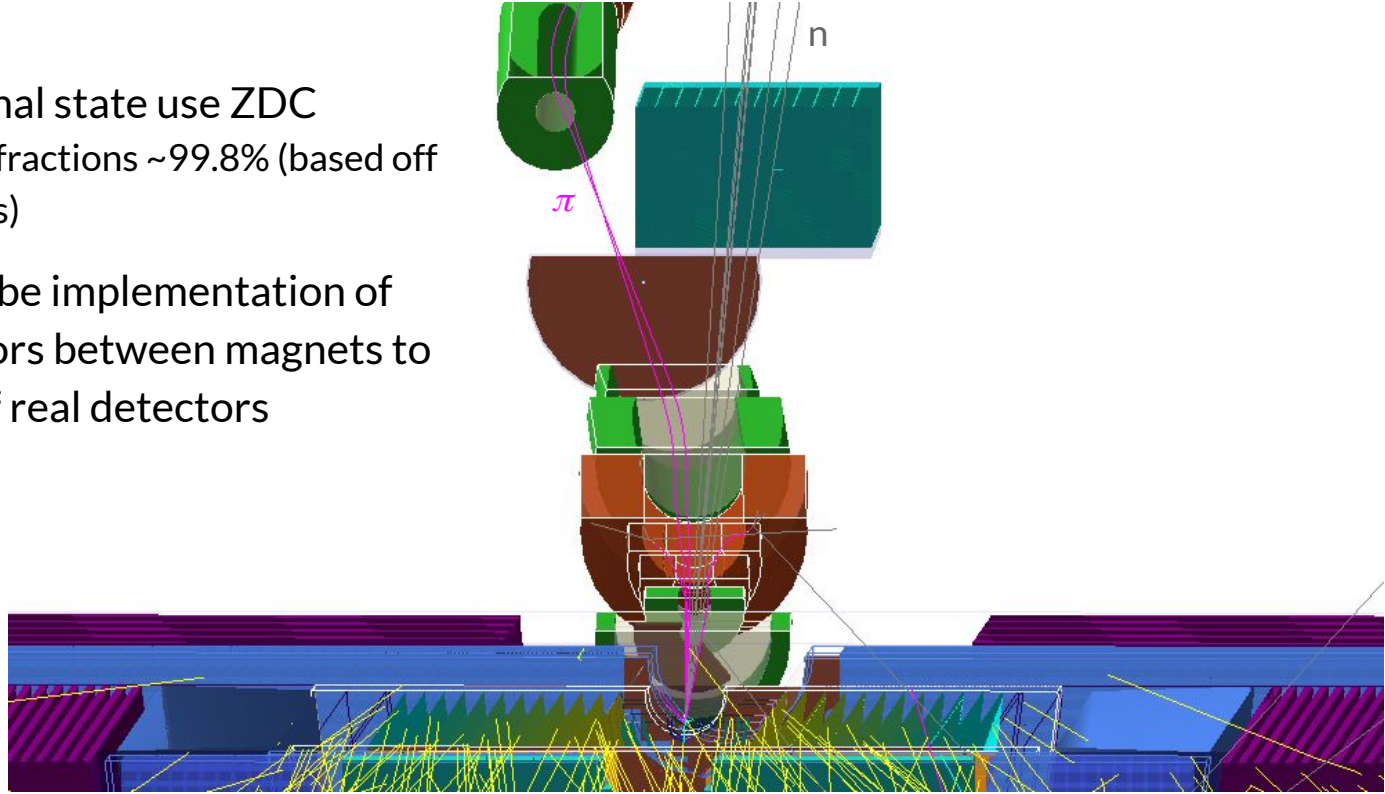
Analysis procedure

- All major phases (i.e. generator, GEANT4, and eJANA) output root files
  - Great for sanity checks
- Procedure is setup in Jupyter notebook
- See Markus Diefenthaler's talk from Thursday morning for more info on general analysis procedure



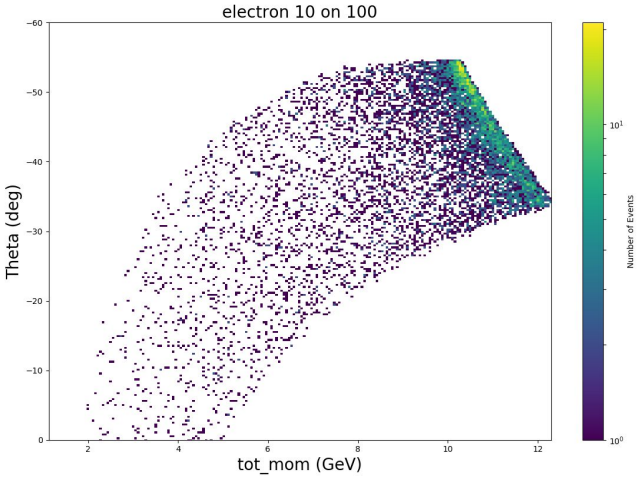
p(e,e'π^+n)X

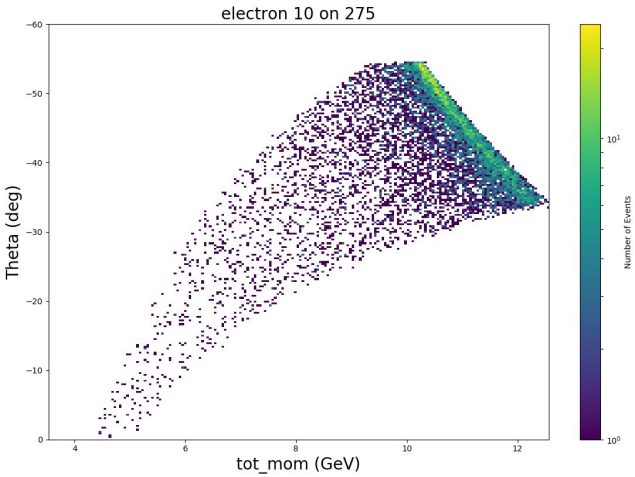
- For neutron final state use ZDC
  - detection fractions ~99.8% (based off 10k events)
- Next step will be implementation of virtual detectors between magnets to find spacing of real detectors

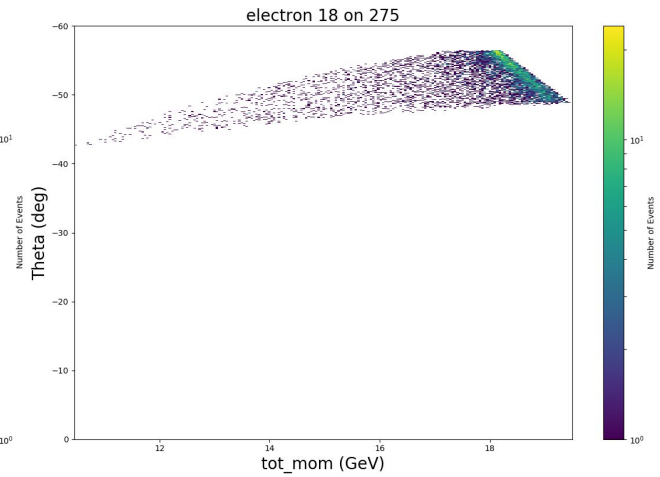


p(e,e'π^+n)X scattered electron in GEANT4

- Scattered electron angular and momentum distributions for a range of 3 kinematic settings (10 on 100, 10 on 275, 18 on 275)
- As expected: higher momentum scatter has tighter angle distributions

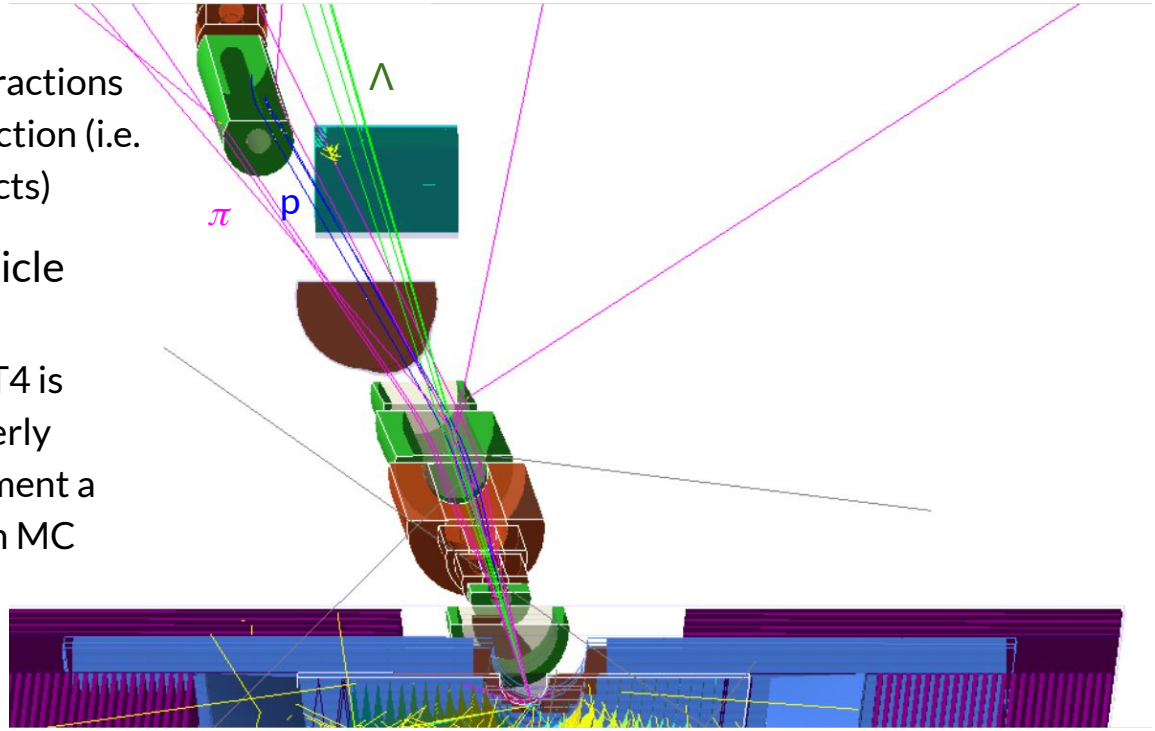






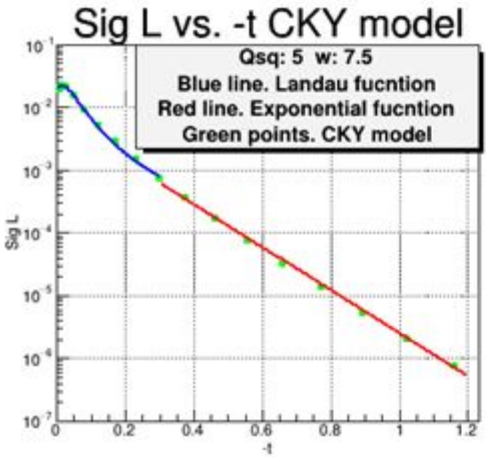
$p(e,e'K^+\Lambda^0)X$

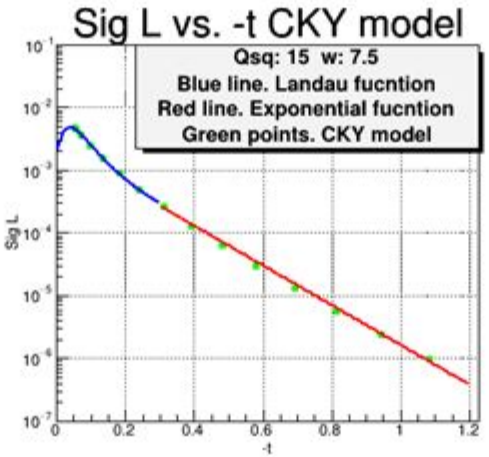
- For Lambda/Sigma
  - need to find detection fractions
  - need particle reconstruction (i.e. determine decay products)
- Next step is primarily particle reconstruction
  - Need to check if GEANT4 is decaying lambdas properly
  - If not we need to implement a decay model (possibly in MC explicitly)

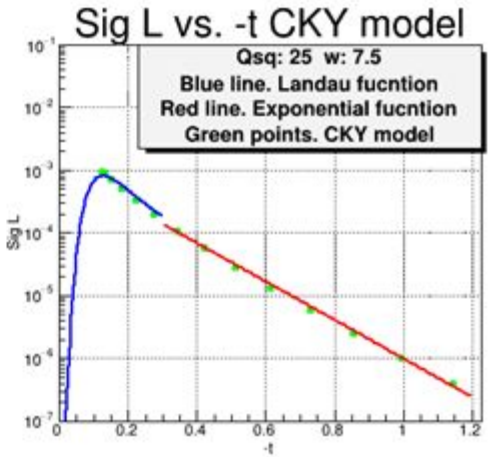


DEMP Event Generator

- 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 $5<Q^2<35$, $2<W<10$, $0<-t<1.2$

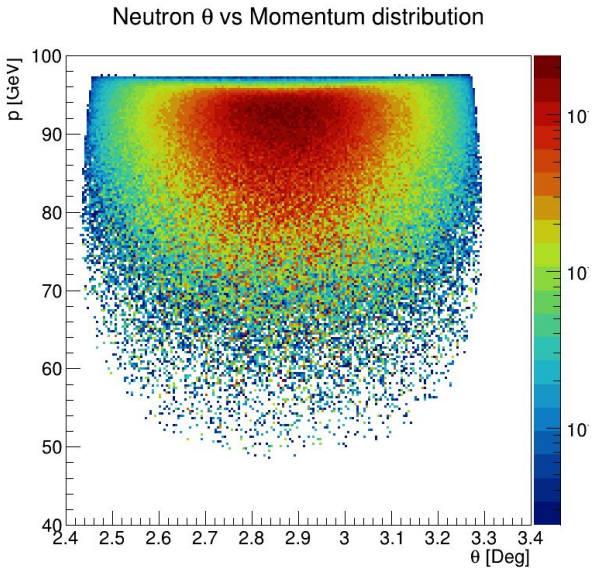


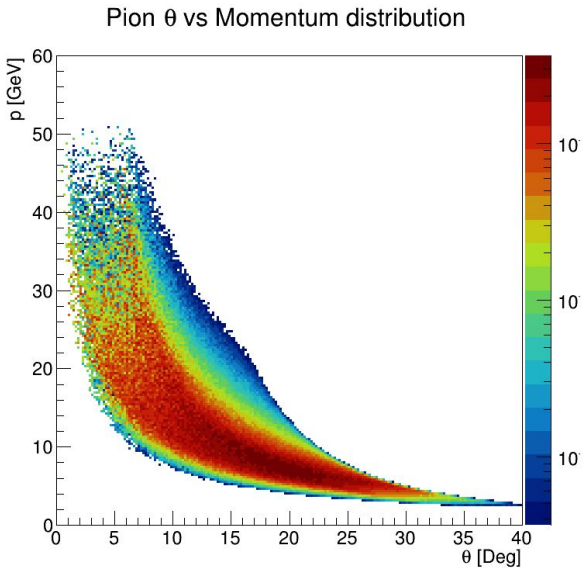


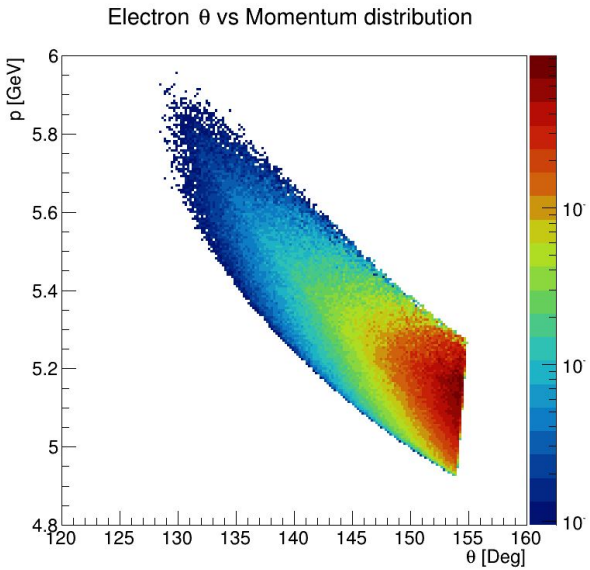


n, π^+ and e' Acceptance (-t < 0.5 GeV^2)

- 5 (e^-) on 100 (p) GeV collisions, 50 mrad crossing angle assumed
- Events weighted by cross-section





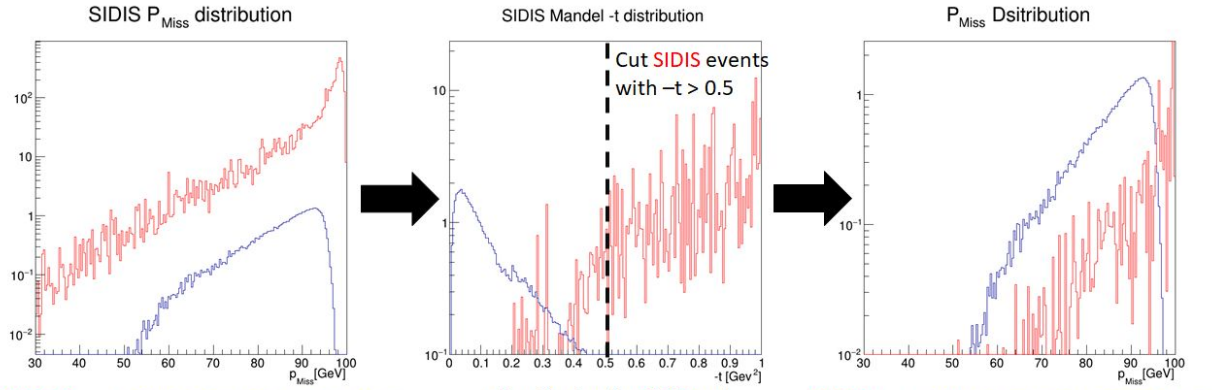


Neutrons - within 0.2° of outgoing proton beam, offset is due to crossing angle

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

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)

Timeline to come

EPJA Publication	First Meson structure WG meeting	Meson structure WG meeting	Meson structure WG meeting	Next Meson structure WG meeting	Meson Structure WG meeting	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	Feb. 25th, 2020	March 16th, 2020	March 30th, 2020	April 13th, 2020	May 22-24, 2020	June 1-5, 2020	**August 3-7, 2020**	Sep. 17-19, 2020	Oct. 5-9, 2020	Nov. 19-21, 2020

Conclusion and Outlook

- Current final states: π^0/p, π^+/n, K^+/Λ^0
  - Need to include: K^+/Σ^0
- Detection fractions completed for proton and neutron
  - Proton ~100%
  - Neutron ~99.8%
- Particle reconstruction for Λ (and Σ) and determine detector locations
- Implement virtual detectors and determine detection fractions for all final states
- Make Analyzer plugin for physics variables including smearing
- Next steps for pion SF parameterization and extension to kaon SF

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,Θex), where Θex is smearing
  - PbeamMC=Pbeam*ran3.Gaus(0, iDp/p), where iDp/p=3e-4
  - PbeamMCx=PbeamMC*ran3.Gaus(0, Θix)

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

Collider vs. fixed target

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Kinematic Variables

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

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

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

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

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

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

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

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

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