Pion and Kaon Structure Functions at the EIC

CFNS Workshop

June 2nd, 2020

Richard Trotta and the meson structure working group

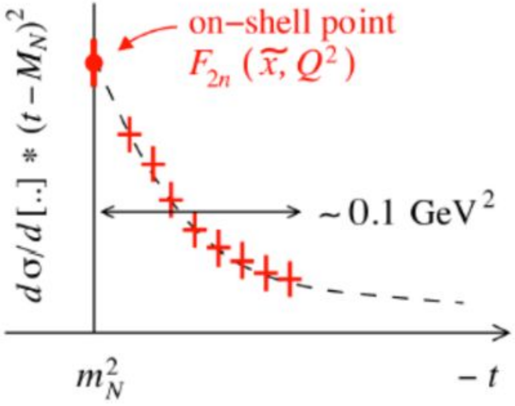
Jefferson Lab

THE CATHOLIC UNIVERSITY OF AMERICA

See Tanja Horn's talk
June, 2nd @ 8:40 EST

Pion and Kaon Sullivan Process

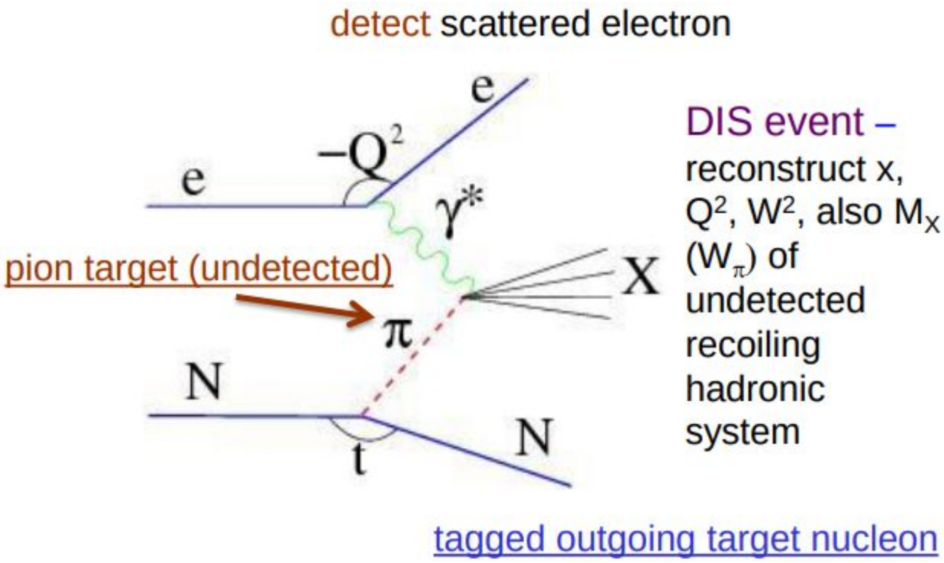
- The Sullivan process can provide reliable access to a meson target as t becomes space-like
- If the pole associated with the ground-state meson remains the dominant feature of the process
  - the structure of the related correlation evolves slowly and smoothly with virtuality
- Recent theoretical calculations 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 $-t \leq 0.9\ \mathrm{GeV}^2$

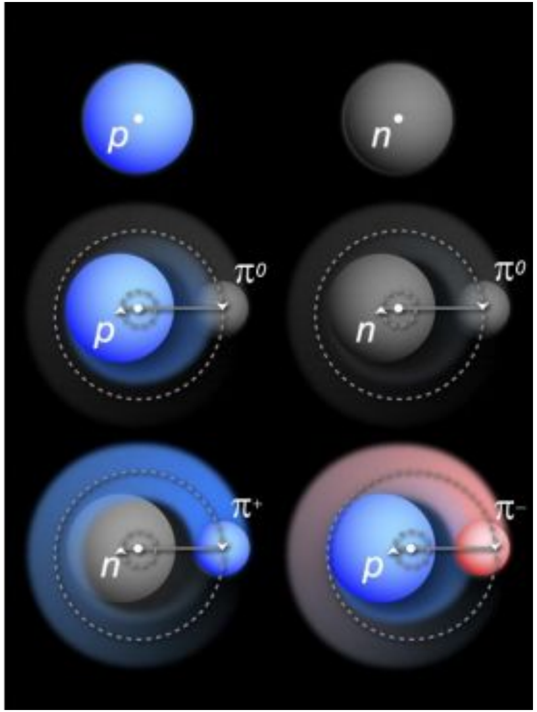


S-X Qin, C. Chen, C. Mezrag, C.D. Roberts, Phys. Rev. C 97 (2018) 015203

Tagged Deep Inelastic Scattering (TDIS)

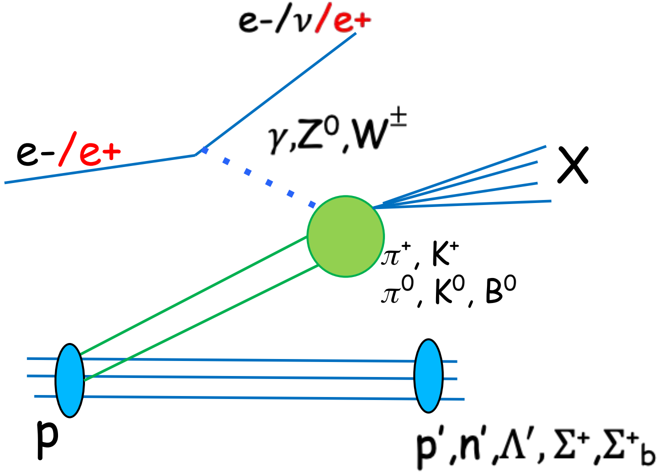
- Use Sullivan process – scattering from nucleon-meson fluctuations





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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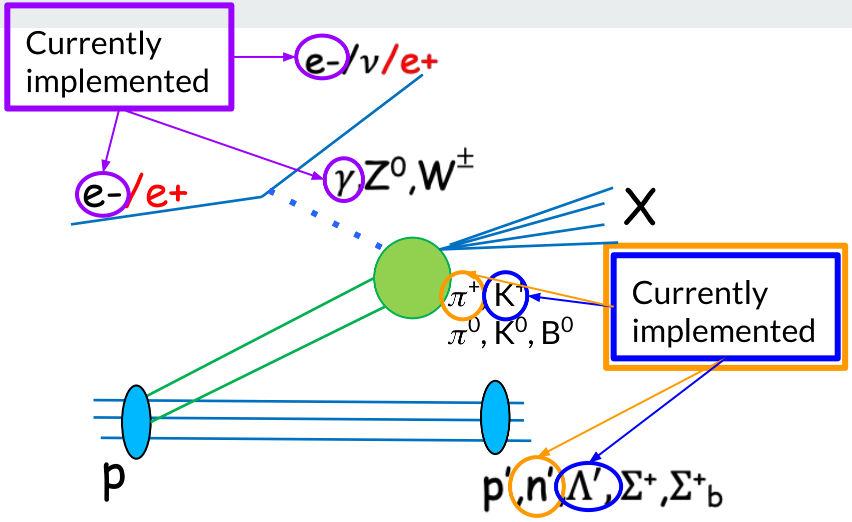


- Progress with generator development since 2019 EPJA article:
  - fixes made in generator to remove fixed-target leftovers
  - now can make pion structure function (pion SF) projections

- 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*)
$^{1}H(e, e'\,\pi^{+})\,n$	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

EIC fast Monte Carlo

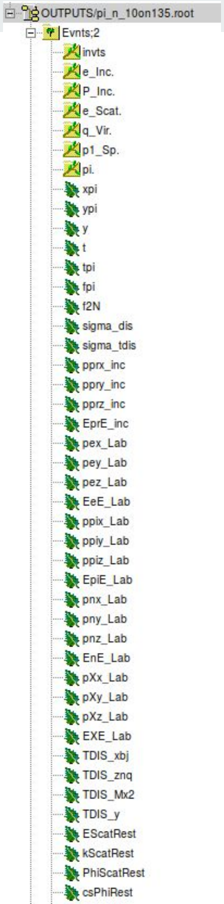
- C++ based fast MC which outputs root files and text file for GEANT4 input

Cpp Script(TDISMC_EIC.cpp)-requires as input: range of Q2 and x

Calls 4 quantities…
1. CTEQ6 PDF table
2. F_2^{π} with various parameterizations
3. F_2^{N}, nucleon structure function
4. Initial beam smearing function

```
Your kinematics: [xBj_min:xBj_max] = [ 0.001000: 1.000000]
Your kinematics: [Q2_min:Q2_max] = [ 1.000000:1100.000000]
Incident Ion Mass    0.93827 GeV
Incident Electron, Ion Momenta:  10.0000,   135.00 GeV/c | s_0 =  5400.1019 GeV^2

Warning in <TTree::Bronch>: TLorentzVector cannot be split, resetting splitlevel
to 0
Warning in <TTree::Bronch>: TLorentzVector cannot be split, resetting splitlevel
to 0
Total of 58042 events out of 500000 Trials ============================] 100 %
```



Collider vs. fixed target

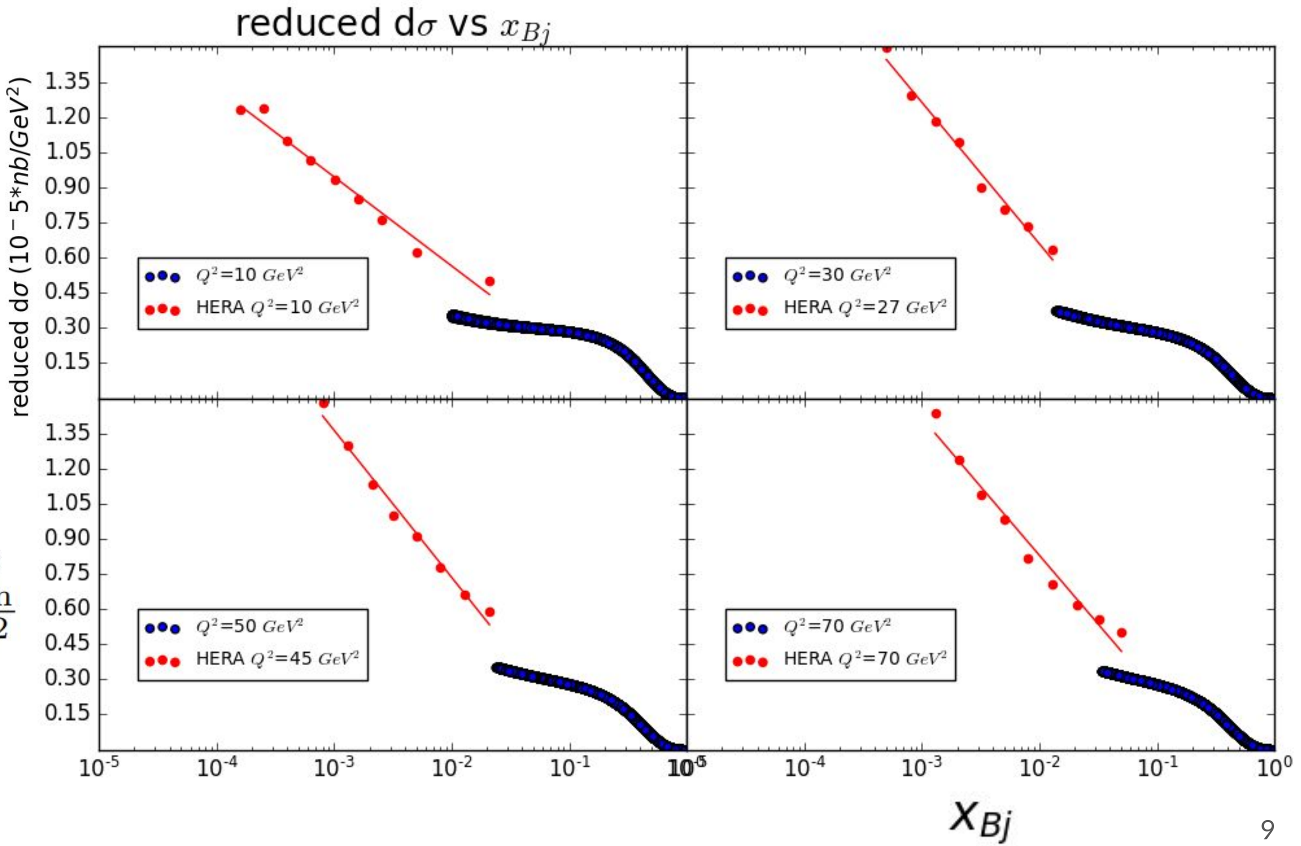
Careful with kinematic definitions

- 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

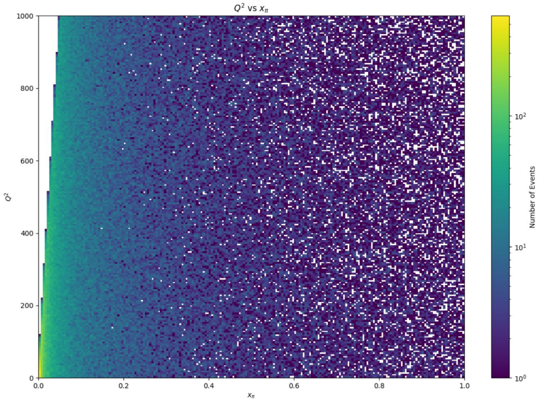
Validation: Reduced cross-section compared with HERA

- 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)

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

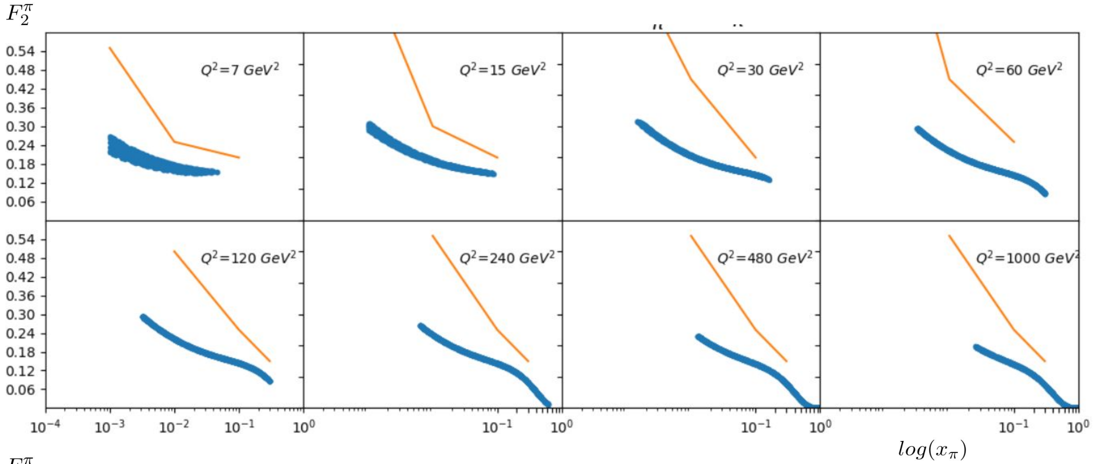


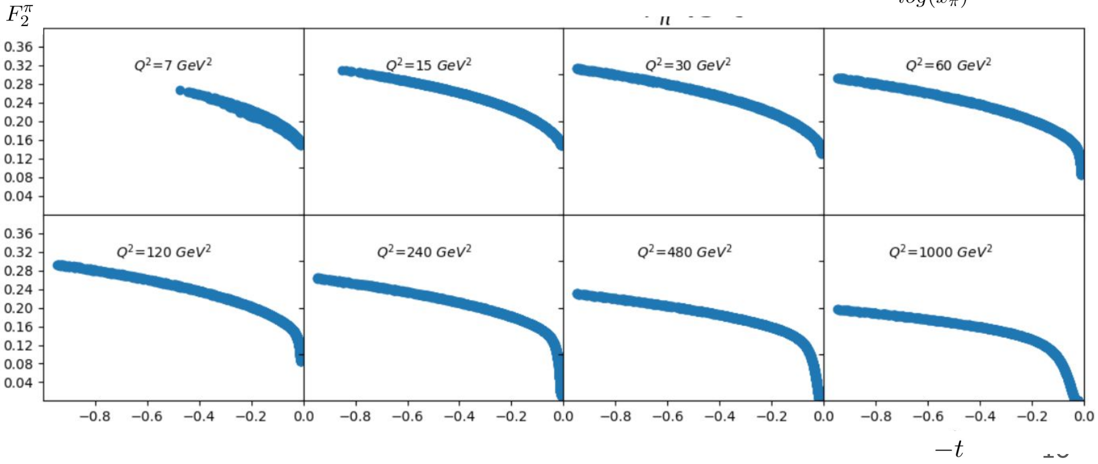
Pion Structure Function Projections



- e-P collision
- 18 on 275 [(0.01 < y < 0.95)]
- MC:[x(0.001-1.0),Q2(1,1000)]
- $F^2_\pi = (0.361)^*F^2_P$
    - ZEUS Parameterization
    - GRV fit
    - L=10 fb^{-1}

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

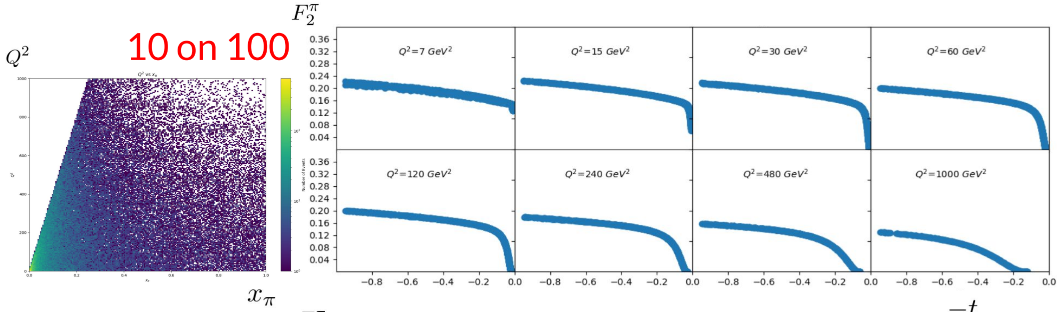




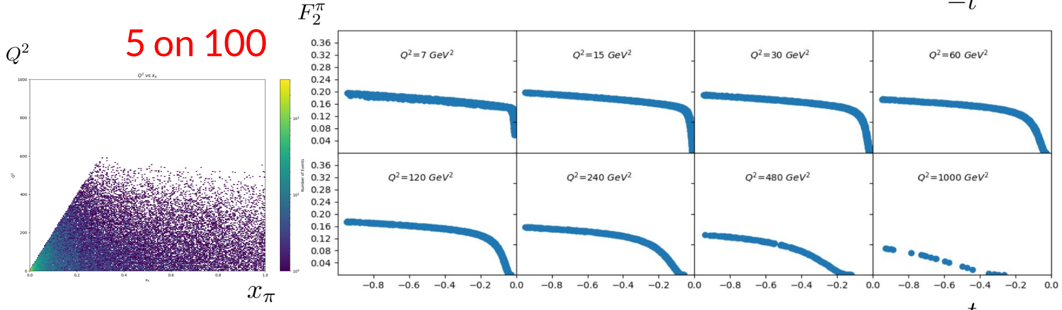
Pion Structure Function Projections

- MC:[x(0.001-1.0),Q2(1,1000)]
    - Cuts:[(0.01 < y < 0.95)]
- Determined that the high energy 18 on 275 was not useful for high x studies
- -t coverage is similar for the various beam energies, as expected

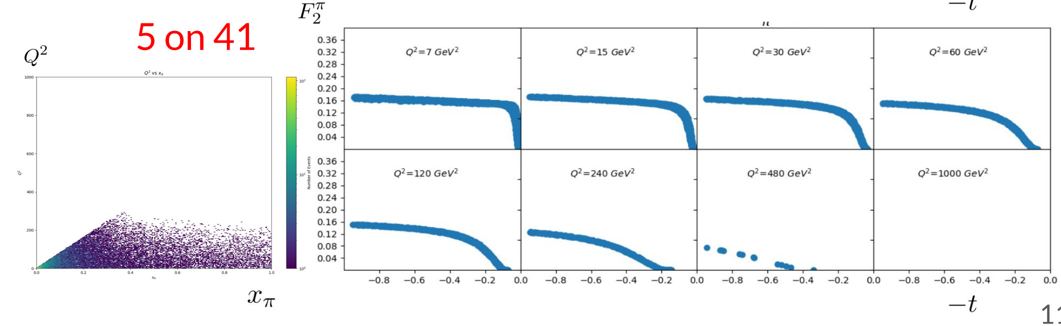
10 on 100



5 on 100

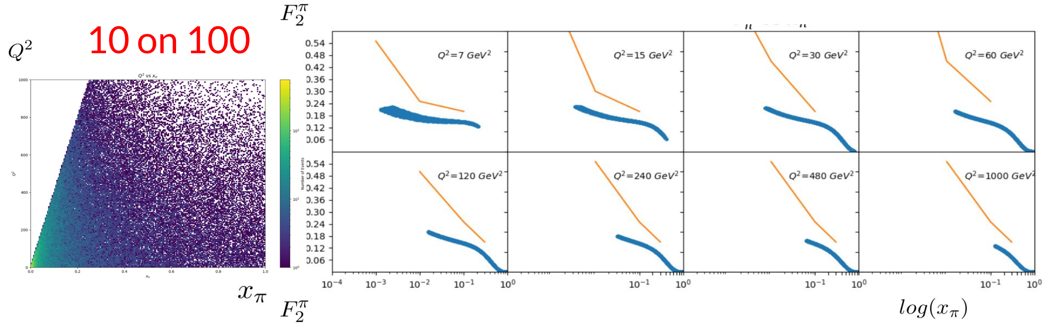


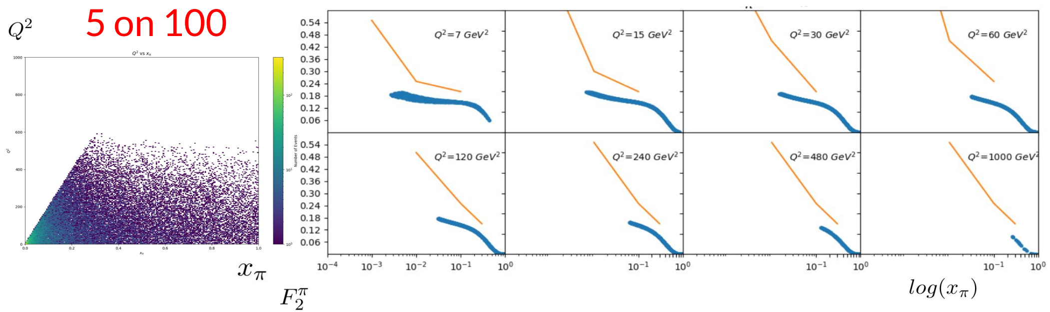
5 on 41

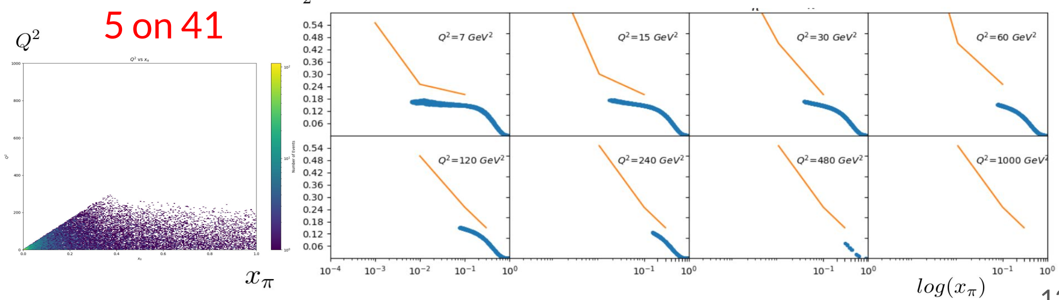


Pion Structure Function Projections

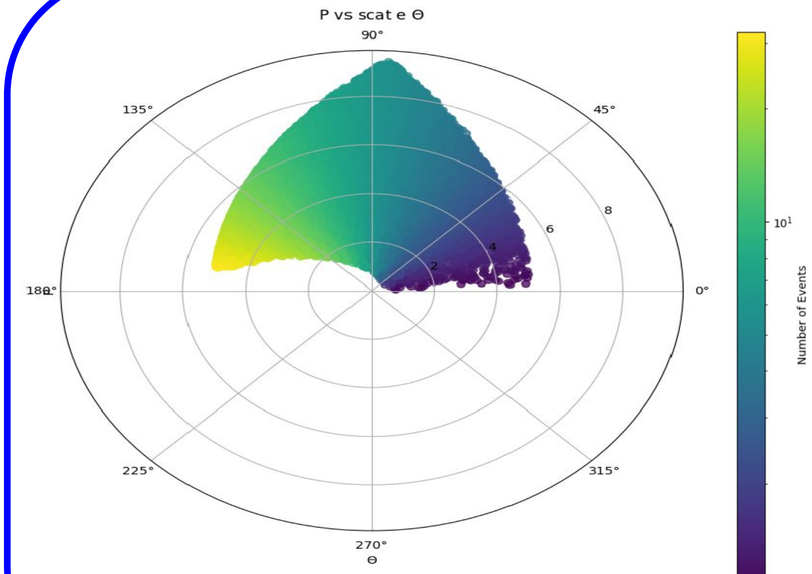
- To reach the large x region at a certain intermediate Q^2, the lowest possible energy is normally best
- For high beam energies this area requires y to be low
- 5 on 100 can access more acceptance at high-x, but lose acceptance to the low-x region
- Even more for 5 on 41
  - There are some advantages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



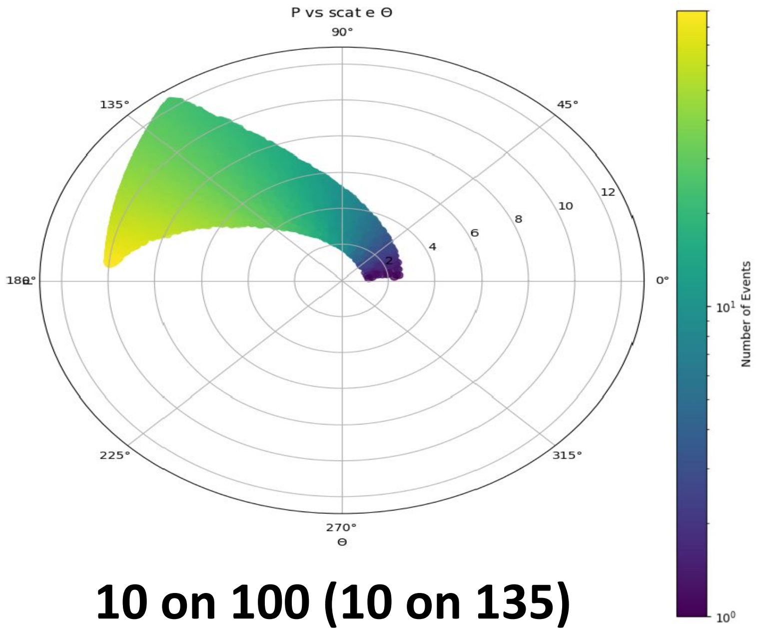




Meson Structure Functions – Scattered Electron



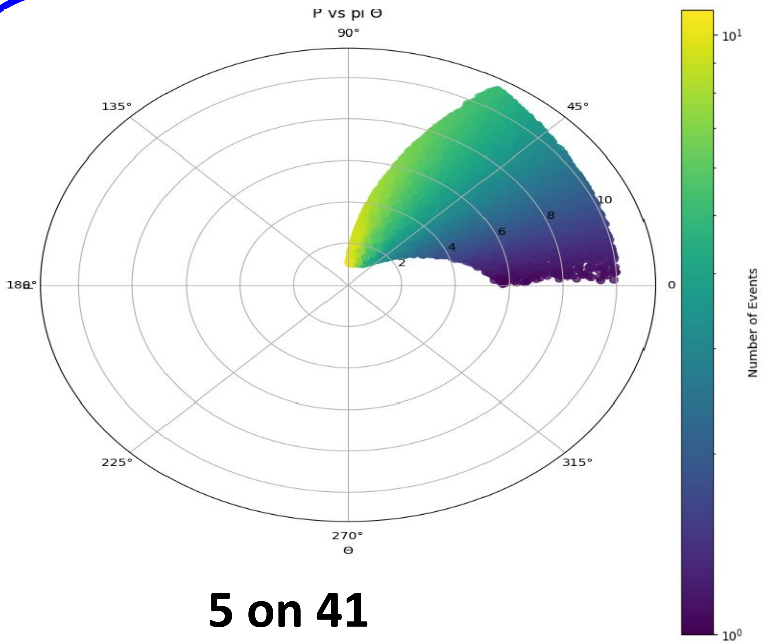
5 on 41



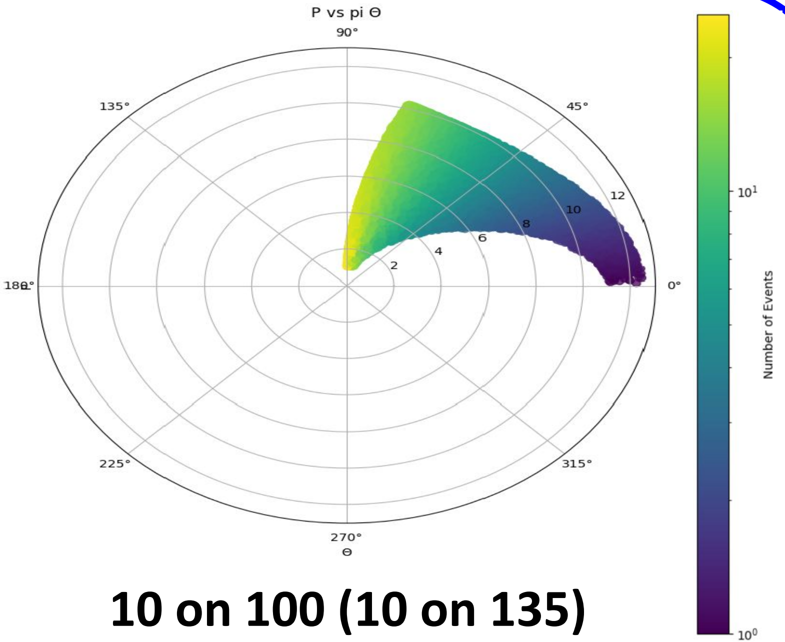
10 on 100 (10 on 135)

- Scattered electrons can be detected in the central detector

Meson Structure Functions – Scattered Meson

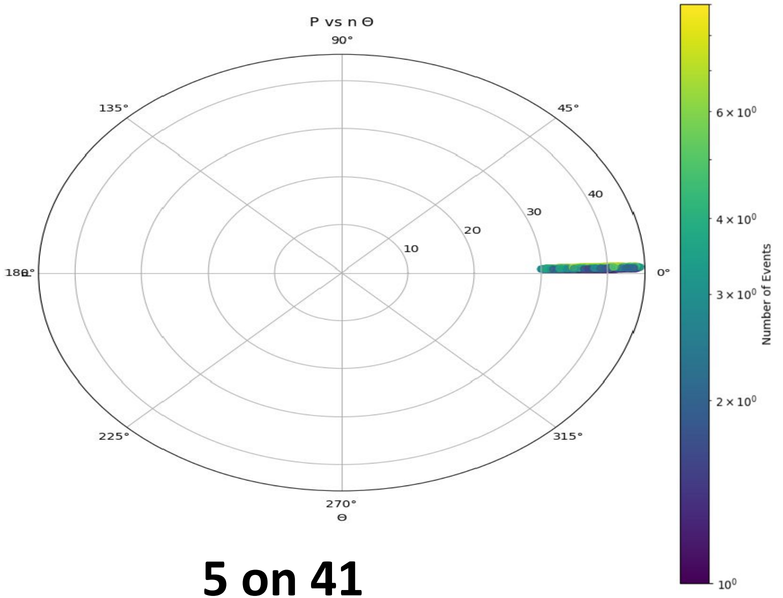


5 on 41

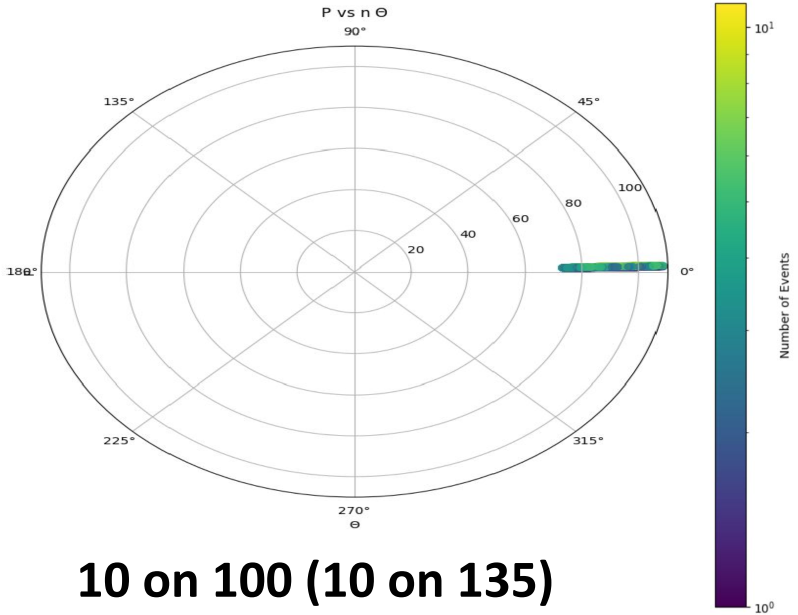


10 on 100 (10 on 135)

Meson Structure Functions – Forward Baryon



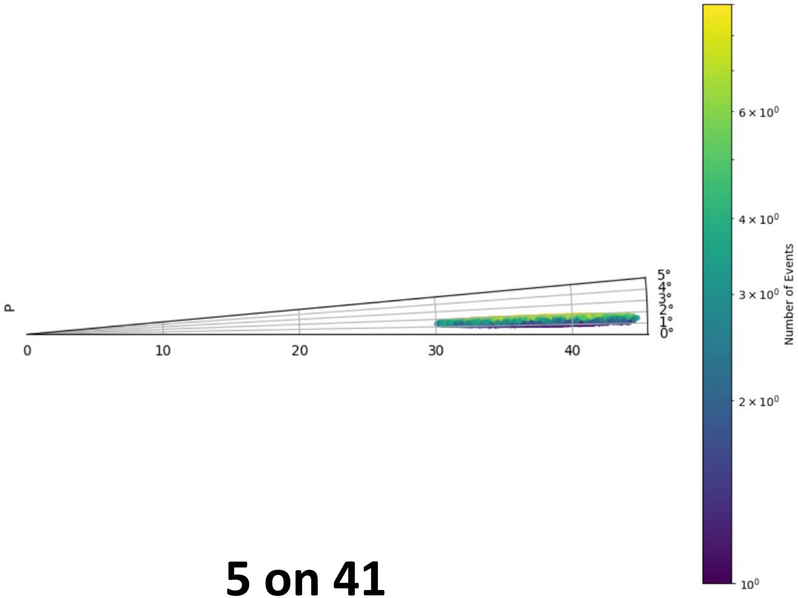
5 on 41



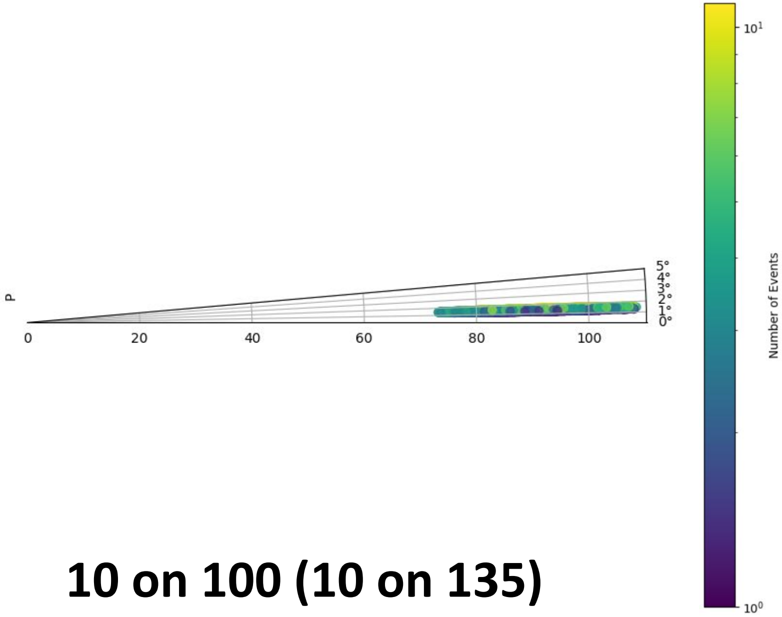
10 on 100 (10 on 135)

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

Meson Structure Functions – Forward Baryon



5 on 41



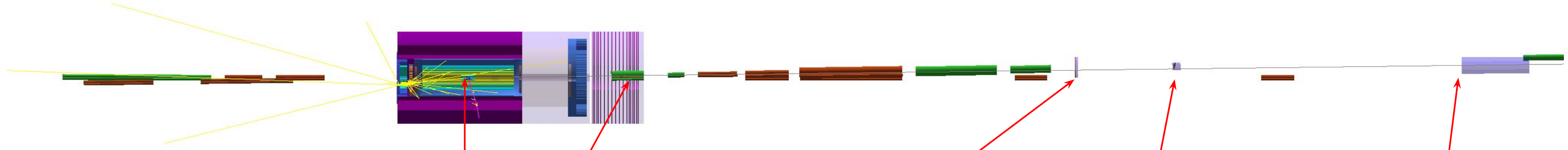
10 on 100 (10 on 135)

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

See Yulia Furletova's talk
June, 2nd @ 10:15 EST

GEANT4 for EIC

- Meson structure MC outputs lund files for use in GEANT4



IP

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

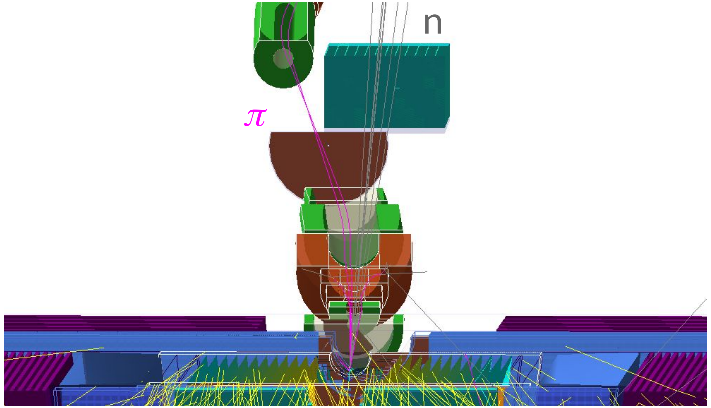
RP2 (not seen):
Zpos = 28.2 m
Xpos = 91 cm

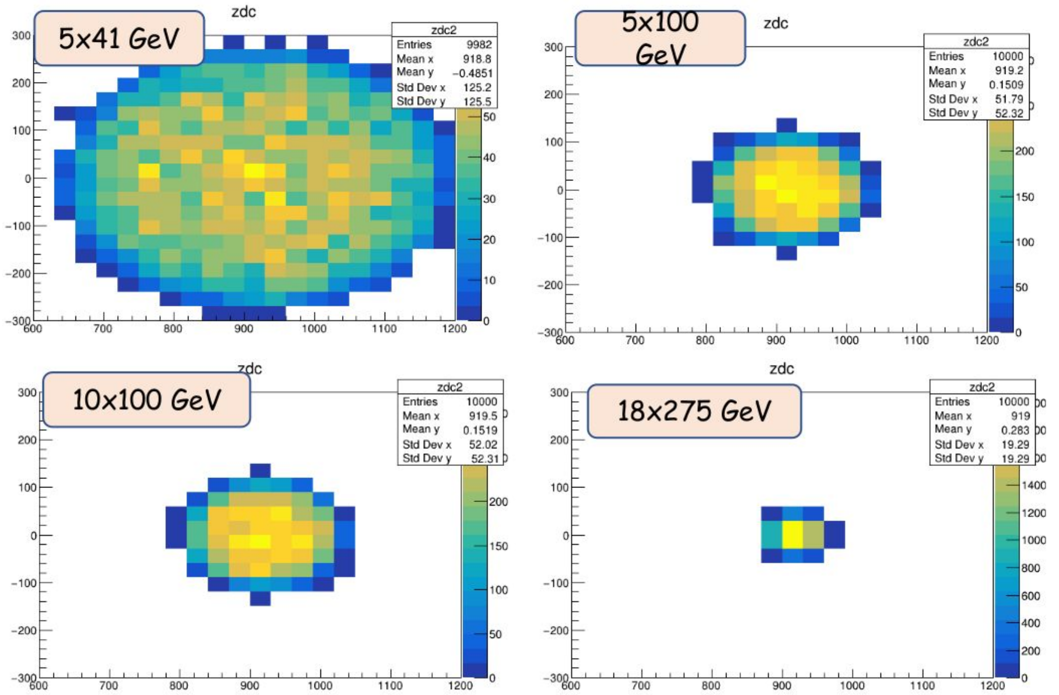
ZDC:
60x60cm EMCAL
LG: 1x1cm^2
HG: 100x100um^2
HCAL: 10x10 cm

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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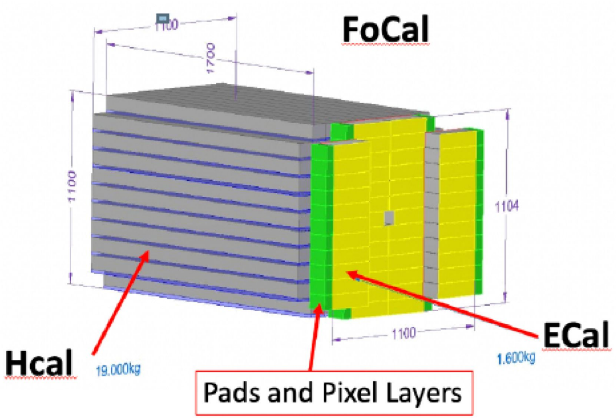
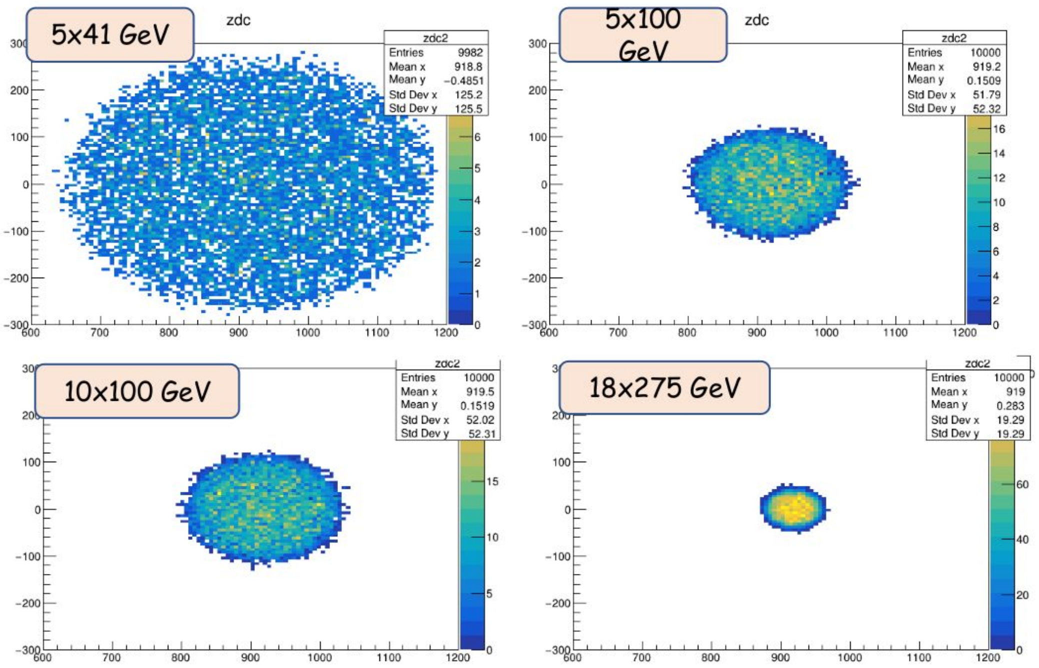




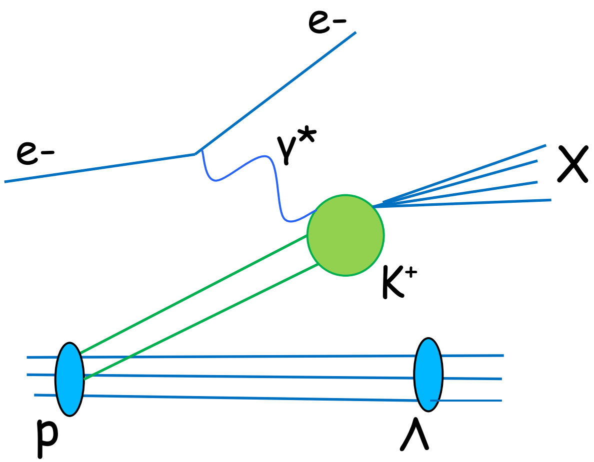
- ZDC: [60x60 cm, 100 bins → 0.6 cm towers]
- If we want energies over 100 GeV, we will need resolution of ~1 cm or better

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

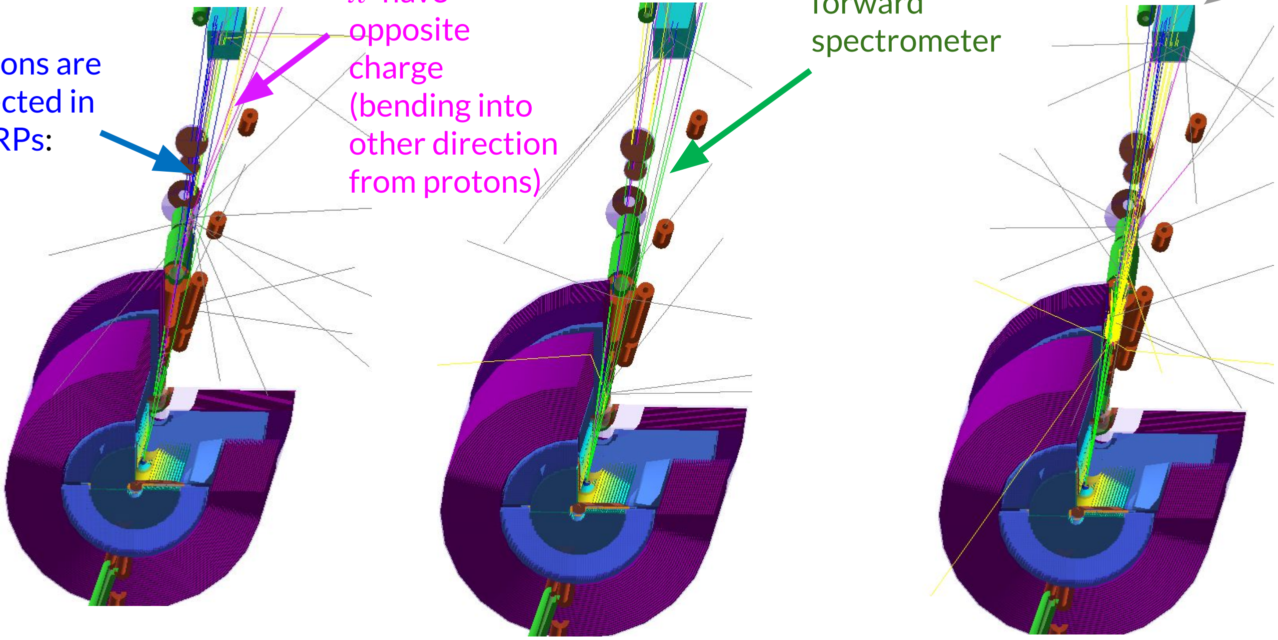
$$\Lambda \to p + \pi^-$$
$$\Lambda \to n + \pi^0$$

Protons are detected in the RPs:

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

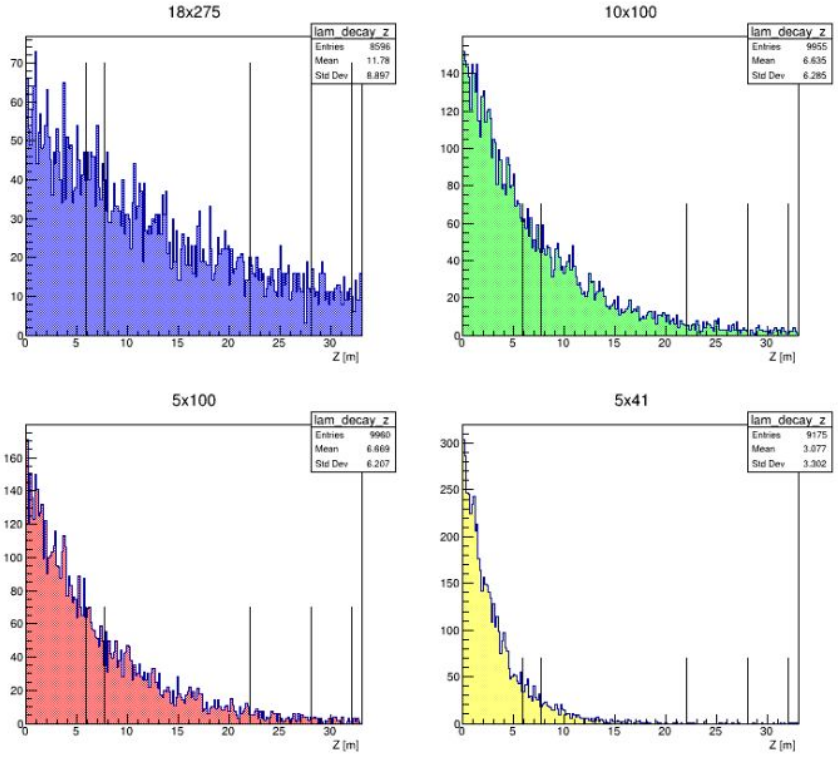
30% of Λ at high energy does not decay before forward spectrometer

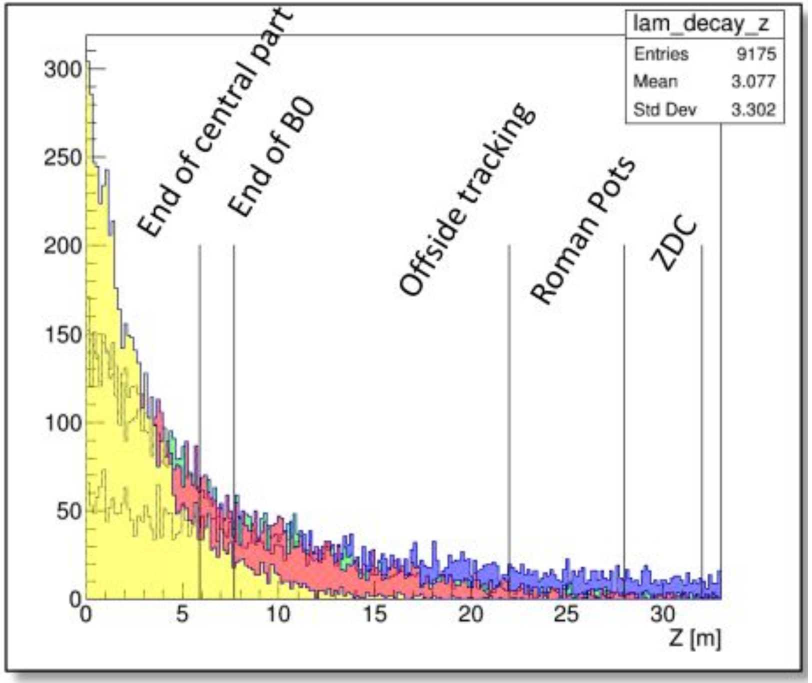
Neutrons and a fraction of π^0 goes into ZDC



18 x 275

Decay Length





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

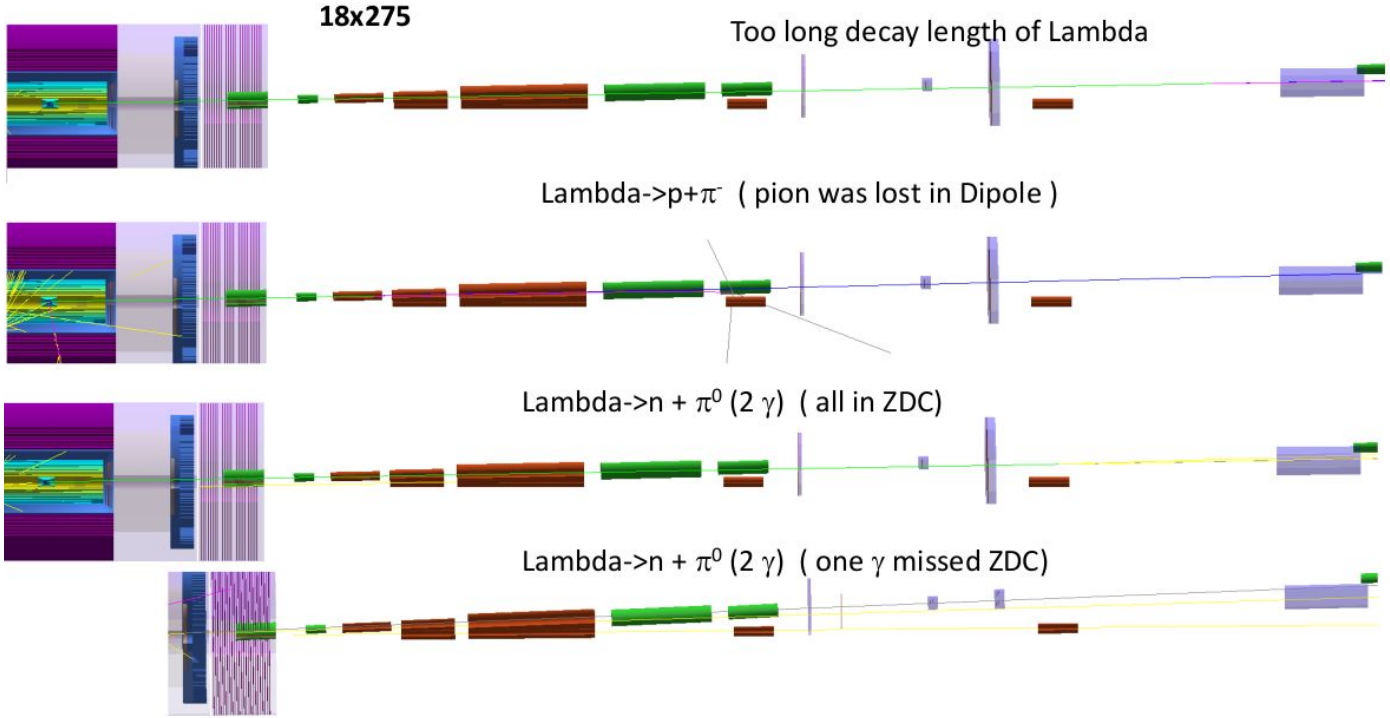
Lambda Final State

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

- ➢ need additional particle tracking between dipoles and ZDC

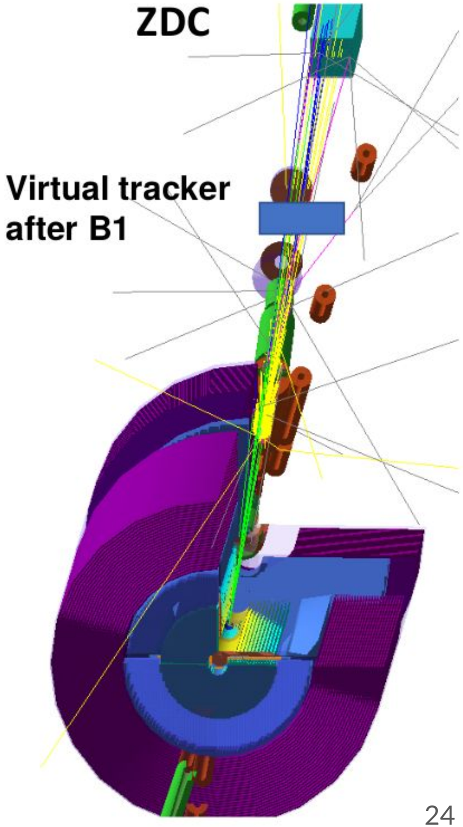
$\Lambda \rightarrow n + \pi^0$: looks promising

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



Summary of Detector Requirements

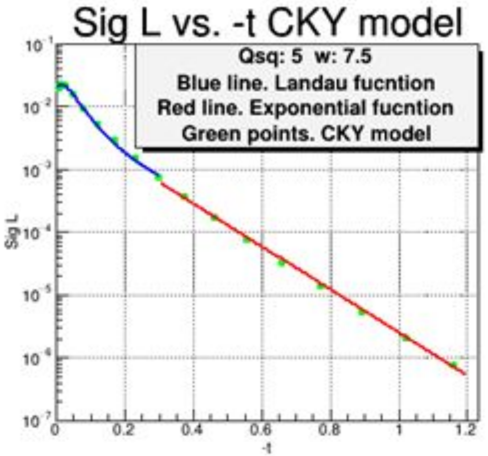
- For π^+/n...
  - For all energies, the neutron detection efficiency is ~100% with planned ZDC
  - Lower energies [5 on 41, 5 on 100], **require at least 60cmx60cm size** to access wider range of energies
- For π^+/n and K^+/Λ...
  - All energies need good ZDC angular resolution for the required t resolution
  - 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

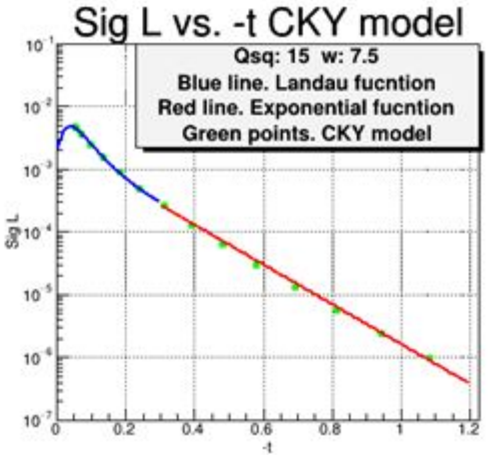


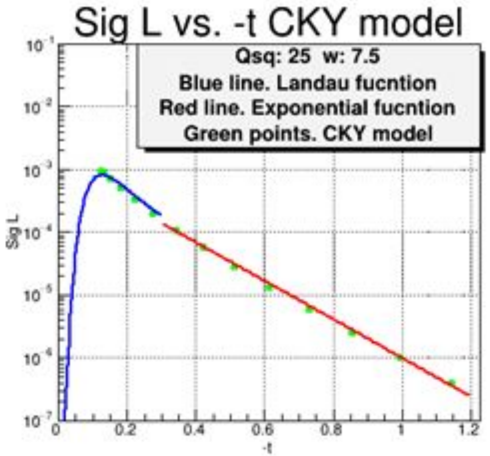
See Stephen Kay's talk
June, 5th @ 10:25 EST

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







See Timothy Hobbs' talk
June, 3rd @ 11:15 EST

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

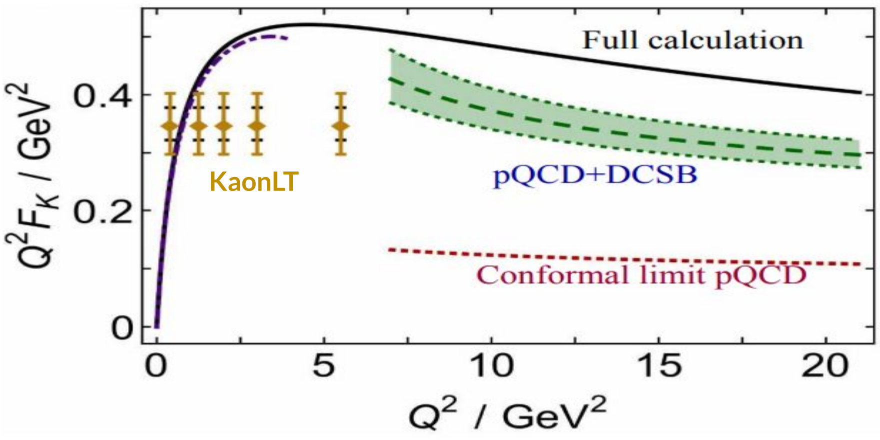
*S. Goloskokov and P. Kroll, Eur.Phys.J. **A47** (2011) 112:*

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

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

Kaon Form Factor Projections

- To measure the kaon form factor one has to isolate the pole process and show its dominance
- Done in the same way as the pion
  - careful analysis of the t-dependence at low -t
  - 12 GeV JLab data (E12-09-011, KaonLT experiment) will provide important insight



Summary

- Meson Monte Carlos event generator...
  - Produce π structure function projections with ZEUS parameterization
    - need to achieve more comprehensive control/quantification of theory/model uncertainties
  - Measure “X” and tagged Λ/Σ (K structure function)
    - kaon projected structure function data will be roughly of similar quality as the projected pion structure function
  - Measure π and tagged neutron (π form factor) and Measure K and tagged Λ/Σ (K form factor)
    - one has to isolate the pole process and show its dominance
- 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)
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  - [In progress] Good hadronic calorimetry to obtain good x resolution at large x

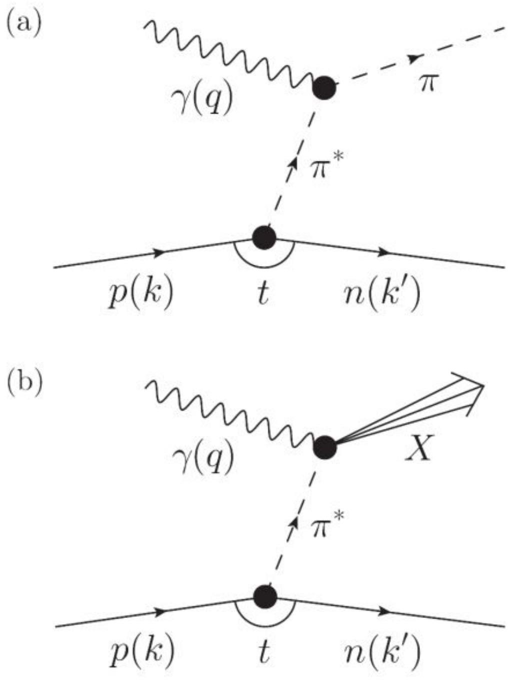
Meson structure working group members!

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

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

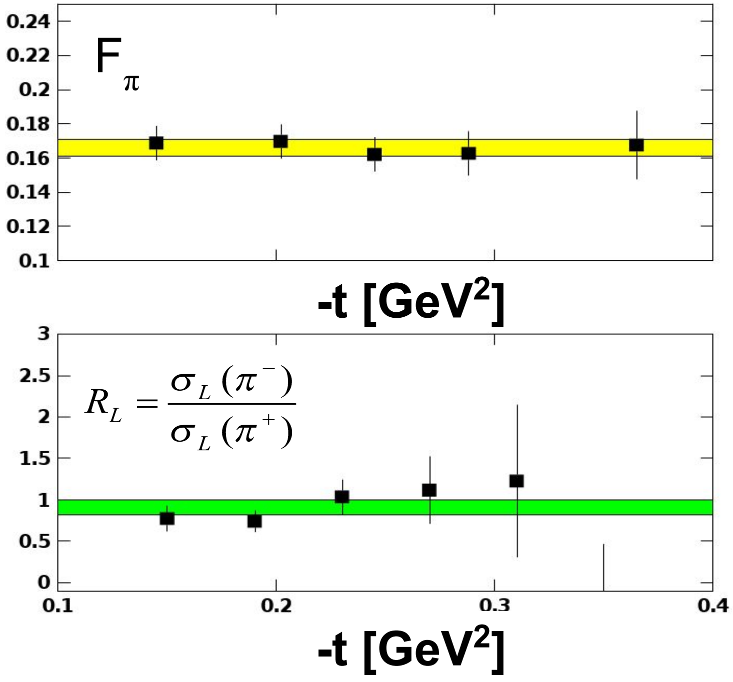


Pion cloud can access a) Elastic FF b) DIS

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

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)

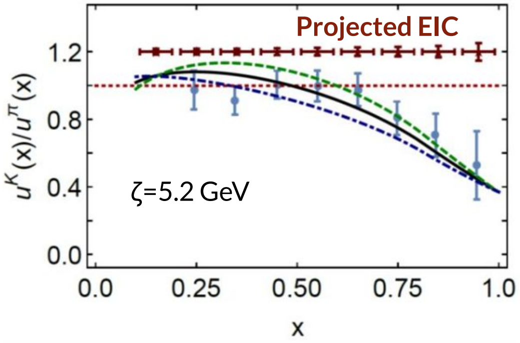
5 key EIC measurements

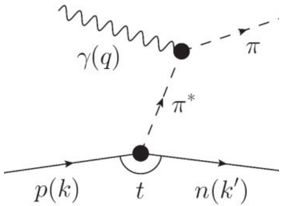
Arlene C. Aguilar, et al., Eur. Phy. J. A (2019) DOI:10.1140/epja/i2019-12885-0

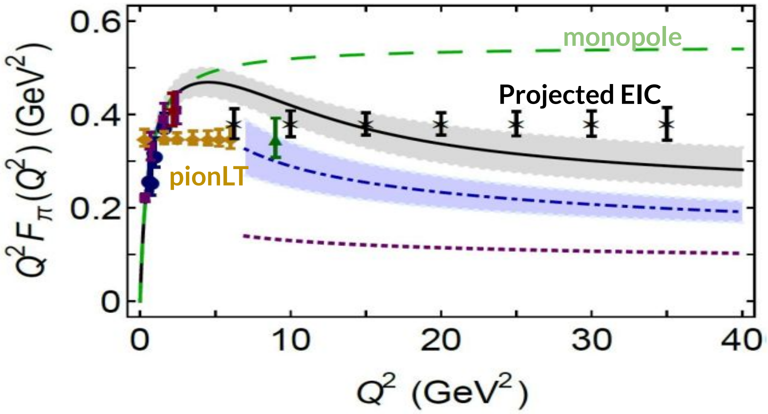
1. Measurement of pion and kaon structure functions and their GPDs
   - insights into quark and gluon energy contributions to hadron masses
2. Measurement of open-charm production
   - settle question of whether gluons persist or disappear within pions in the chiral limit
3. Measurement of the charged-pion 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

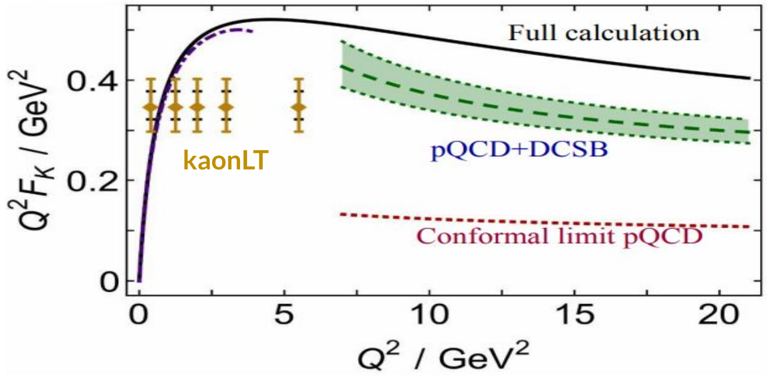
2019 EPJA Pion and Kaon Structure Projections

- 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





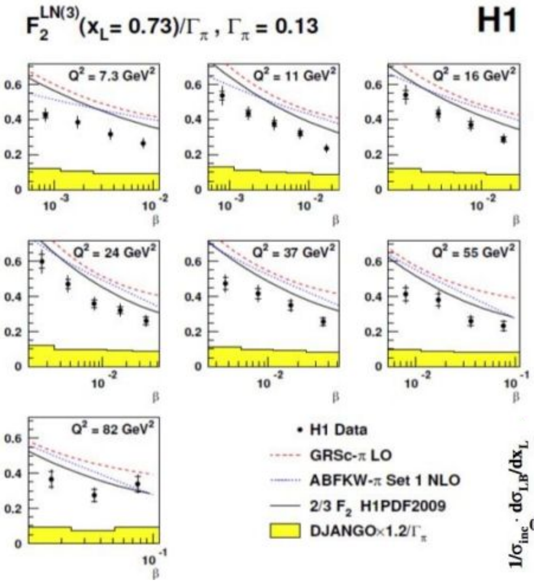




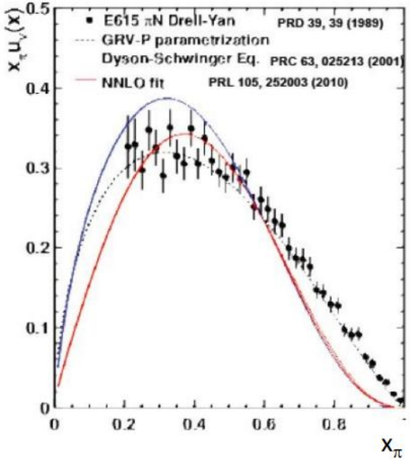
Arlene C. Aguilar, et al., Eur. Phy. J. A (2019) DOI:10.1140/epja/i2019-12885-0

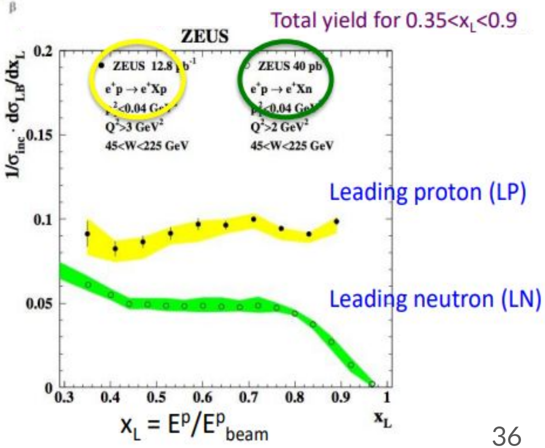
Pion Structure Function Measurements

- 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…



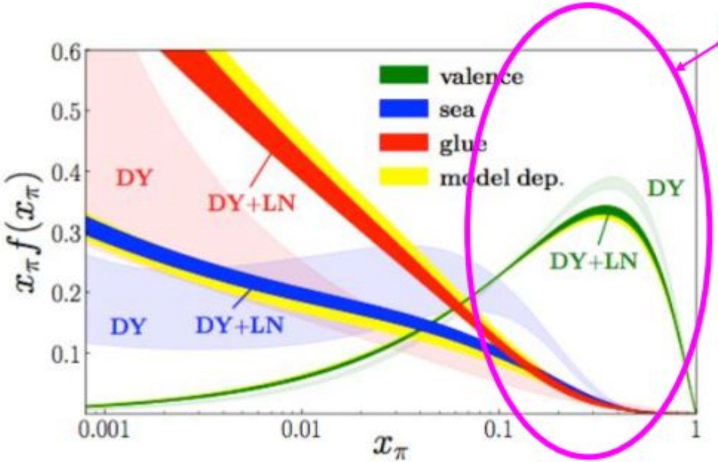
DESY 08-176 JHEP06 (2009) 74





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

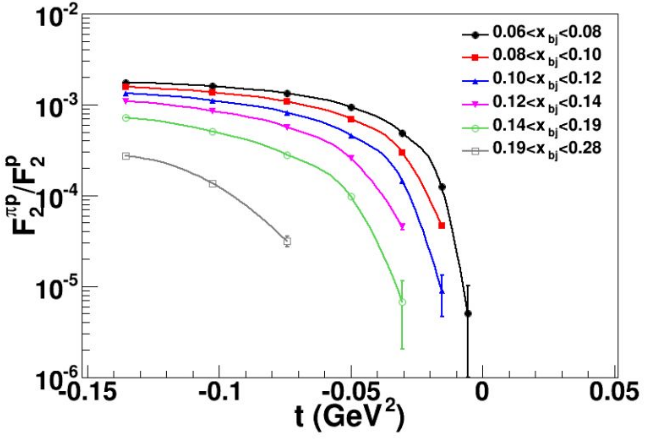
DY = πN Drell-Yan

LN = Leading Neutron

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

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

Kinematic Variables

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

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

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

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

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

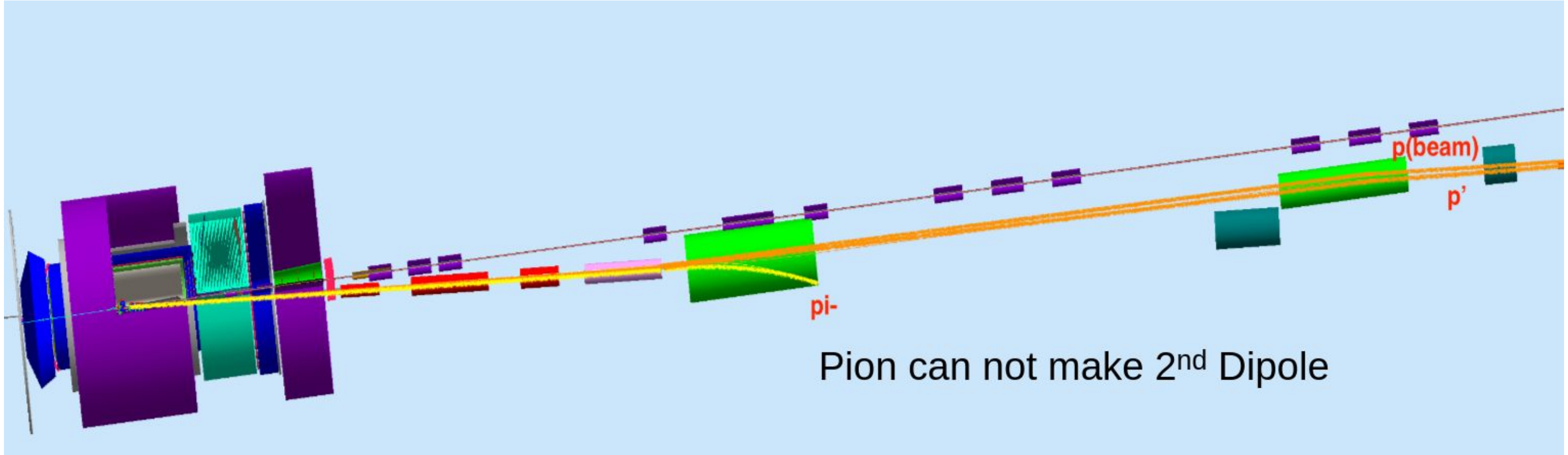
$$y_\pi = \frac{(pScatPion)_{rest}(qVirt)_{rest}}{(pScatPion)_{rest}(kIncident)_{rest}}$$

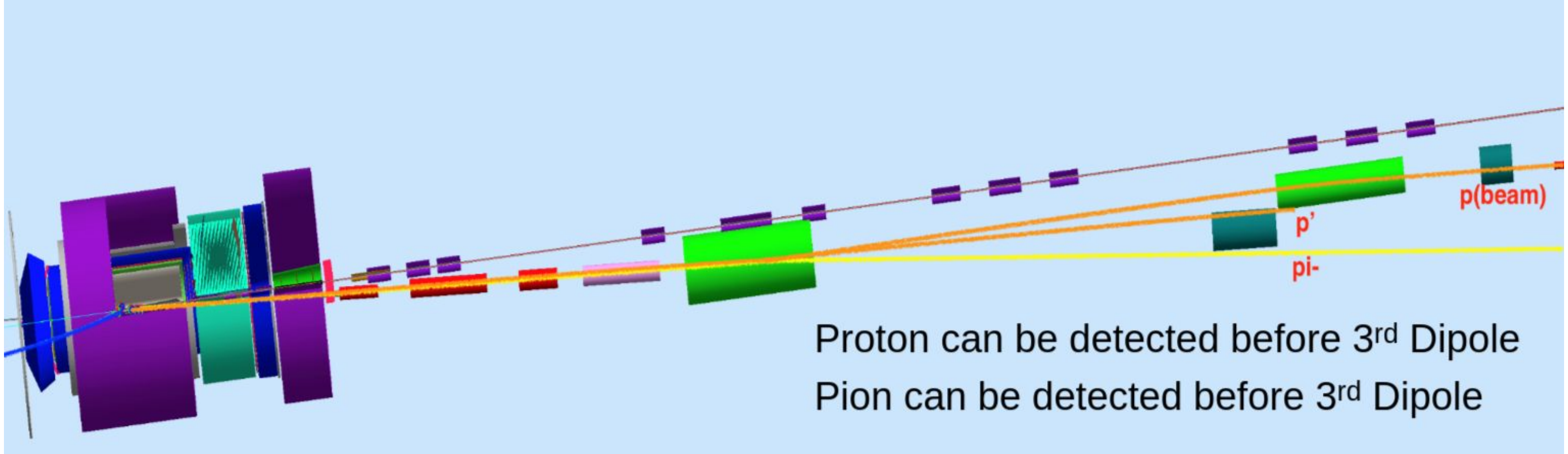
$$t_\pi = E_\pi^2 - |pScatPion.v3|^2$$

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

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

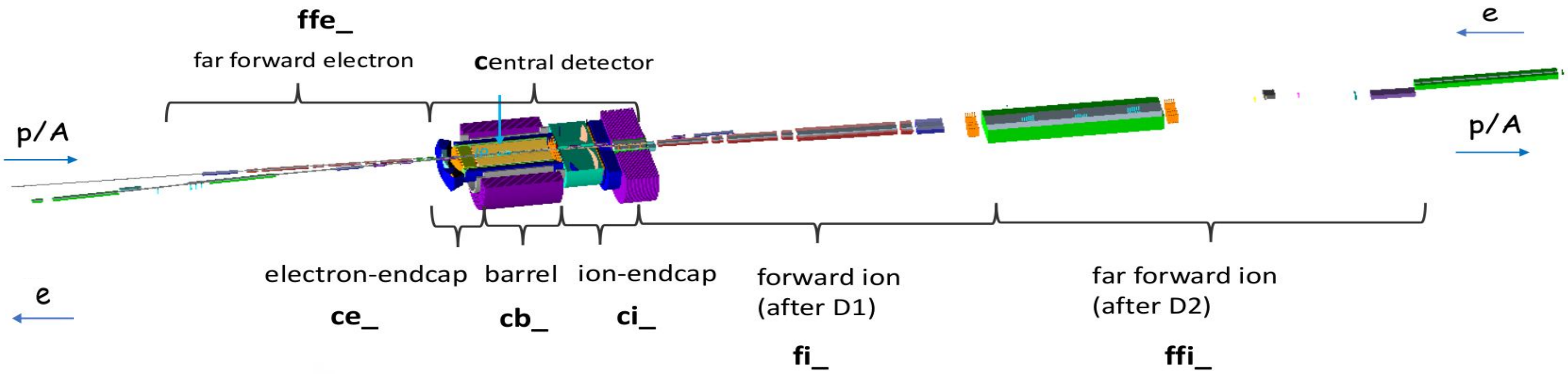
Detection of $^{1}H(e,e'K^{+})\Lambda$, Λ decay to $p + \pi^{-}$



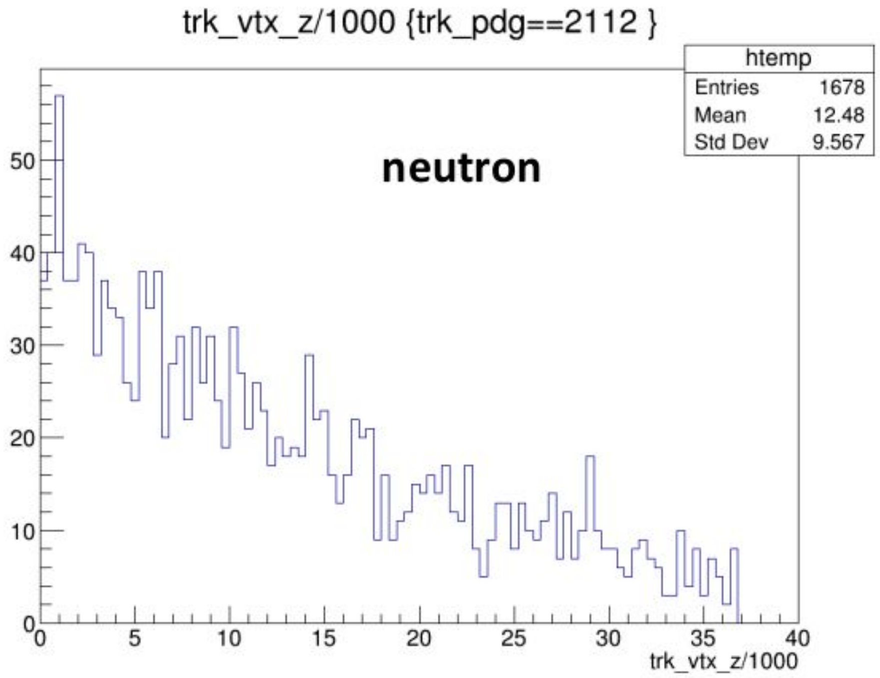


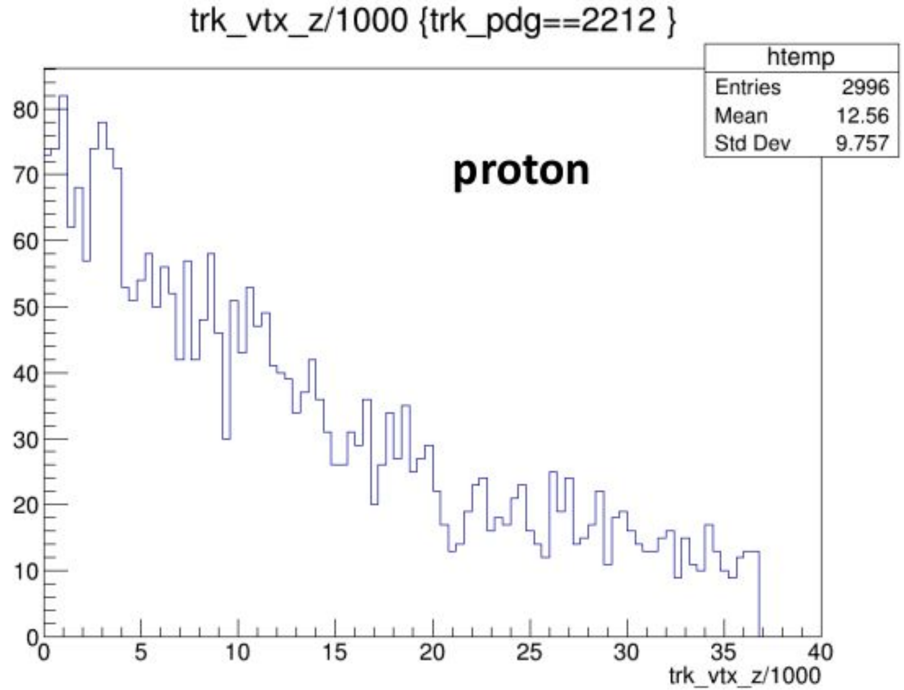
GEANT4 for EIC

- 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$^+$Λ^0)X]

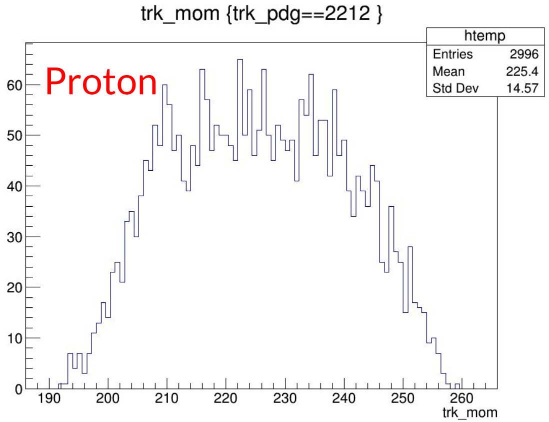


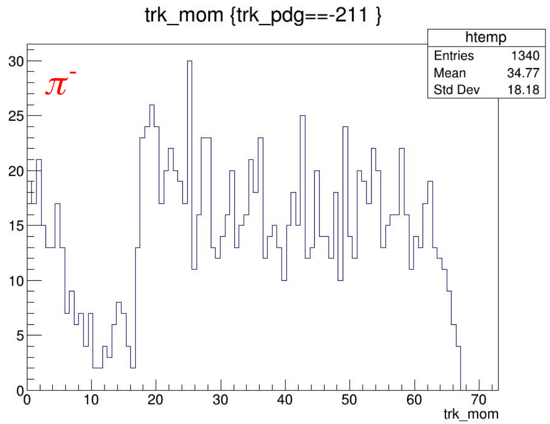


- 10k events → 3580 neutrons → ~47%
  - Need to add π^0 efficiency
- 10k events → 6390 protons → ~47%
  - Need to add π^- efficiency

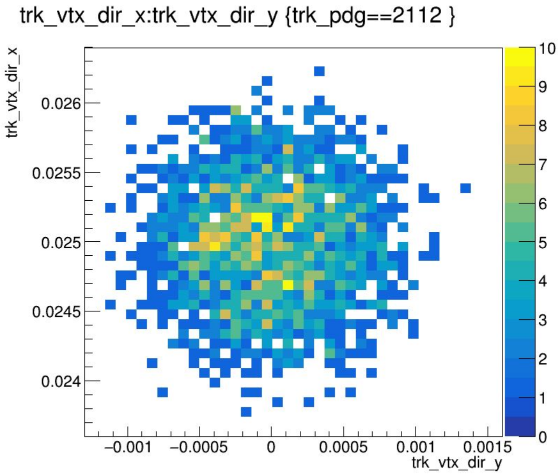
Virtual planes [p(e,e'$K^+\Lambda^0$)X]

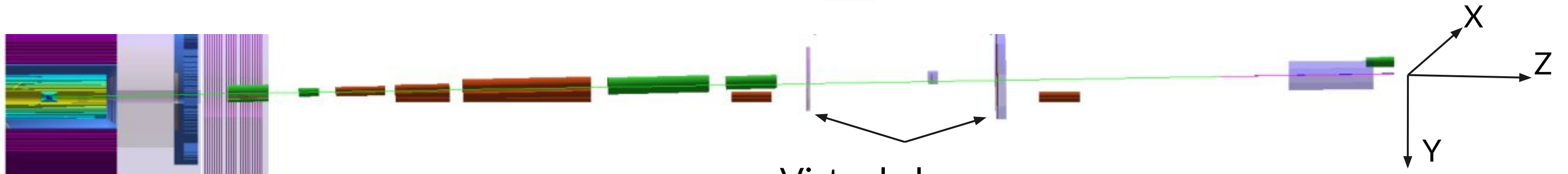
- Next step: Switch from virtual planes to the real size detector and check detector efficiency





Angular distribution for Proton





Virtual planes