Pion and Kaon Structure Functions at JLEIC

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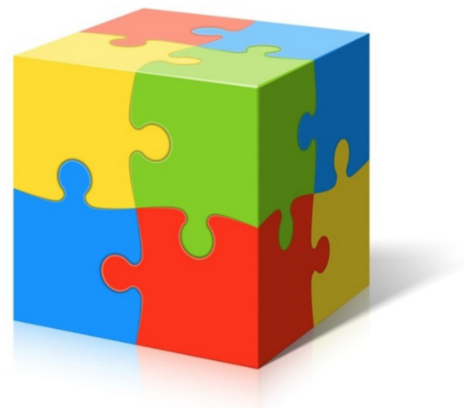
Thanks to Yulia Furletova, Elke Aschenauer and Steve Wood

Motivation: general – why pions and kaons are interesting ?

Protons, neutrons, pions and kaons
are the main building blocks of nuclear matter



- **The pion, or a meson cloud, explains light-quark asymmetry in the nucleon sea**
- **Pions are the Yukawa particles of the nuclear force – but no evidence for excess of nuclear pions or anti-quarks**
- **Kaon exchange is similarly related to the ΛN interaction – correlated with the Equation of State and astrophysical observations**
- **Mass is enigma – cannibalistic gluons vs massless Goldstone bosons**

Motivation: quark and gluon PDFs in pions and kaons

- At low x to moderate x, both the quark sea and the gluons are very interesting.
  - ❖ Are the sea in pions and kaons the same in magnitude and shape?
  - ❖ Is the origin of mass encoded in differences of gluons in pions, kaons and protons, or do they in the end all become universal?

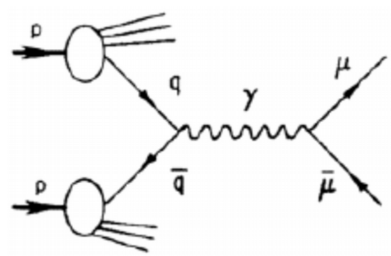
- At moderate x, compare pionic Drell-Yan to DIS from the pion cloud,
  - ❖ test of the assumptions used in the extraction of the structure function (and similar assumptions in the pion and kaon form factors).

- At high x, the shapes of valence u quark distributions in pion, kaon and proton are different, and so are their asymptotic x ➡ 1 limits.
  - ❖ Some of these effects are due to the comparison of a two- versus three-quark system, and a meson with a heavier s quark embedded versus a lighter quark.
  - ❖ However, also effects of gluons come in. To measure this would be fantastic.
  - ❖ At high x, a long-standing issue has been the shape of the pion structure function as given by Drell-Yan data versus QCD expectations. However, this may be a solved case based on gluon resummation, and this may be confirmed with 12-GeV Jefferson Lab data. Nonetheless, soft gluon resummation is a sizable effect for Drell Yan, but expected to be a small effect for DIS, so additional data are welcome.

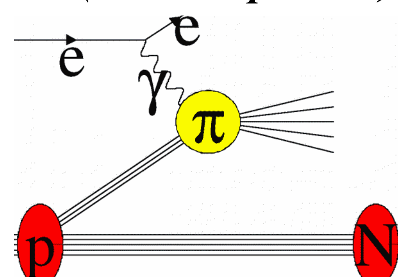
Current Experimental Status: very limited experimental data

- Experimental knowledge of the partonic structure of pions is very limited due to the lack of a stable pion target
- Most of current knowledge of the pion structure function in the valence region is obtained primarily from pionic Drell-Yan scattering
- In the pion sea region at low Bjorken-x from hard diffractive processes measured on e-p collisions at HERA

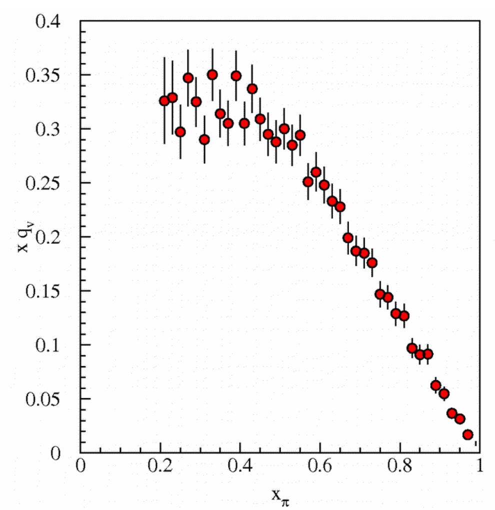
Drell-Yan scattering



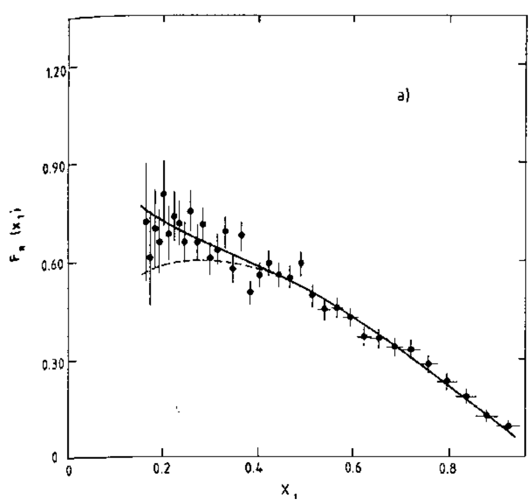
DIS (Sullivan process)

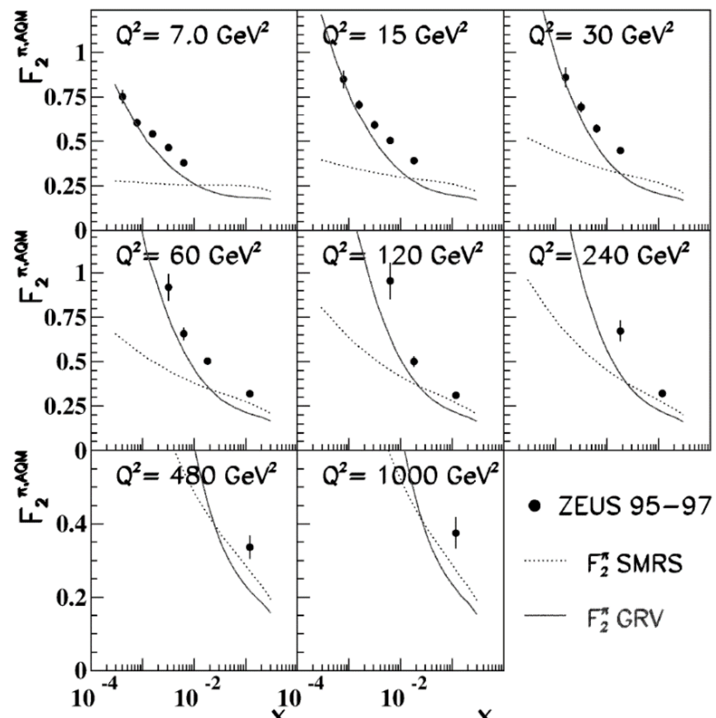


FNAL E615



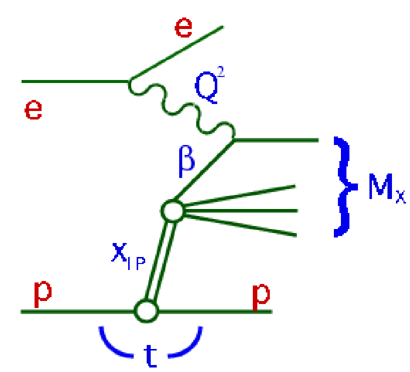
CERN NA3





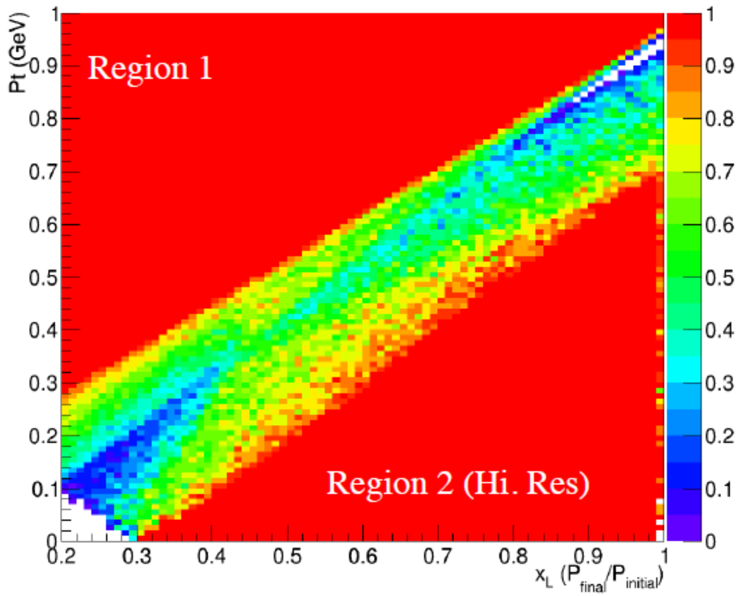
What can we do with EIC? – ongoing MC studies

Diffraction



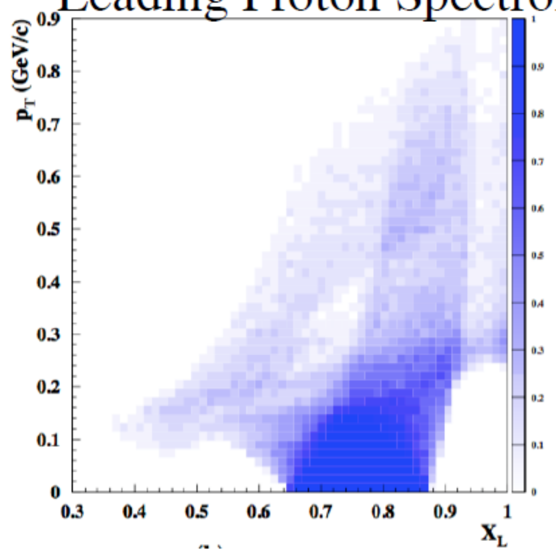
- Obtain F_2^n by tagging spectator proton from e-d, and extrapolate to on-shell neutron to correct for binding and motion effects
- Obtain F_2^p and F_2^K by Sullivan process and extrapolate the measured t-dependence as compared to DSE-based models
- Need excellent detection capabilities and good resolution in **–t**
- EIC acceptance ideal for such measurements

JLEIC acceptance



Zhiwen Zhao (Duke)

ZEUS
Leading Proton Spectrometer



Acceptance in diffractive peak (X_L>~.98)

ZEUS: ~2%

JLEIC: ~100% (also covers much higher X_L than ZEUS)

EIC Monte Carlo event generator: brief introduction

```
*  TDISMC.cpp
*
*  Created by K.Park on 08/10/2016
*  Copyright 2016. All rights reserved.
```

- TDISMC_EIC is standalone Fast Monte Carlo event generator
  Generator output files:
  - TDIS_MC_pion/kaon_10x100.root (Ntuple/Histograms)
    used for making quick uncertainty projections
  - TDIS_lund.txt (ASCII/GEMC input)
    can be used with a detector simulation like GEMC

- Code built with C++(phase-space) and ROOT v5.34.34

- Some artifacts needed to be understood and fixed
  - -Memory leak
  - -Hardcoded xBj cut into F2Pi subroutine

- User inputs: cross-section model / nucleon structure function
  - -Working on kaon parameterization model

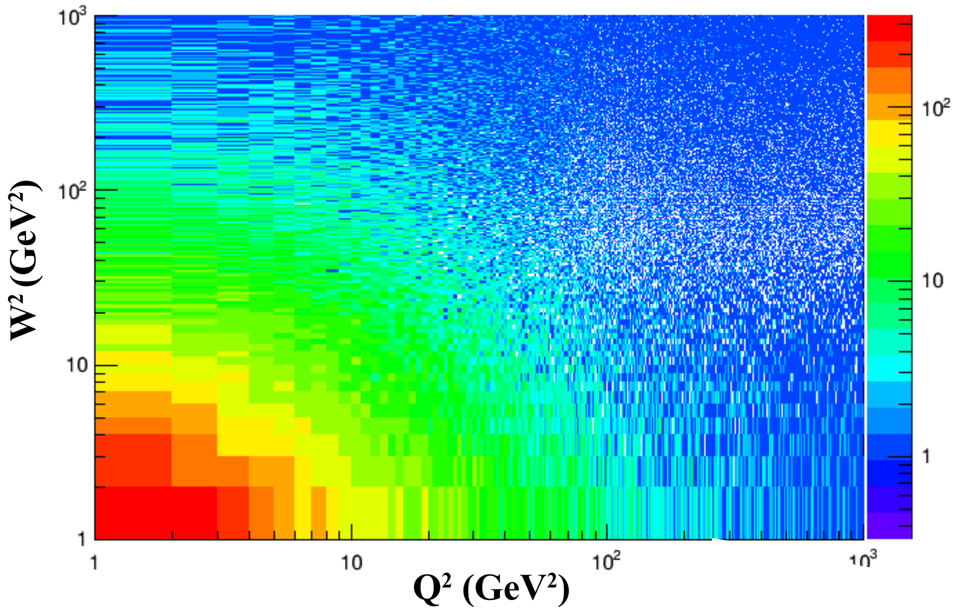
- Implemented EIC accelerator information :
  - -Beam emittances Interaction Point (IP)
  - -Cross-angle: 50 mrad
  - -Longitudinal p and angular spread of the beam: dp/p=$3\text{x}10^{4}$; dΘ=$2\text{x}10^{-4}$

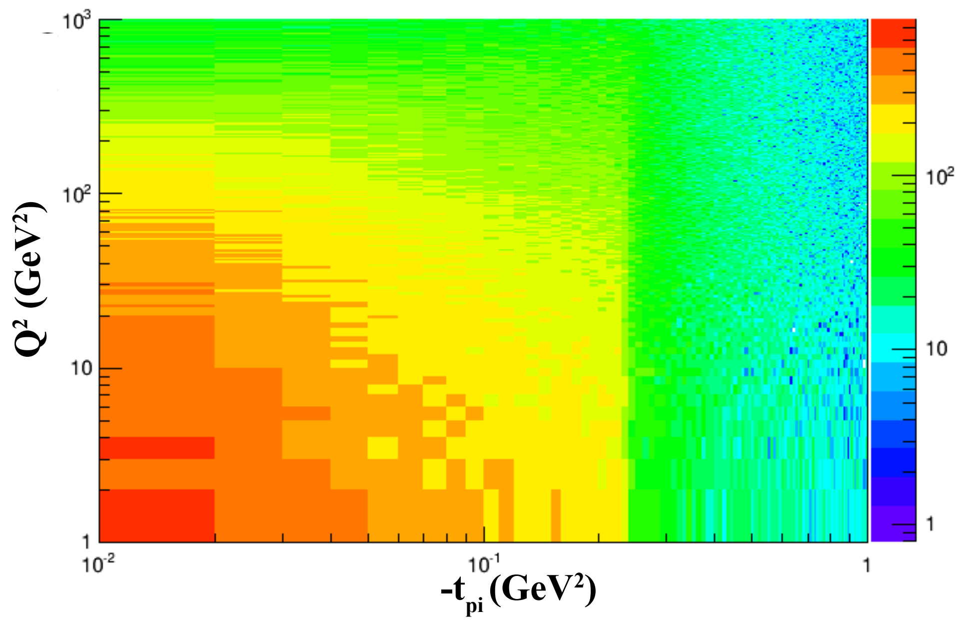
- General kinematic variables currently implemented in ROOT trees:
  - ***-Q2*** : virtuality of exchanged photon
  - ***-W2***: squared invariant mass of produced hadronic system
  - ***-x*** or ***Xbj*** : scaling variable, Bjorken X
  - ***-y*** or ***TDIS_y*** : light cone momentum fraction of the initial nucleon
    carried by the interacting pion or kaon
  - ***-tpi*** is the pion or kaon virtuality

EIC – accessible phase space

- EIC will add large (x,Q^2) landscape for both pion and kaons
- Phase space available for 10 GeV electrons and 100 GeV protons

Phase space for π



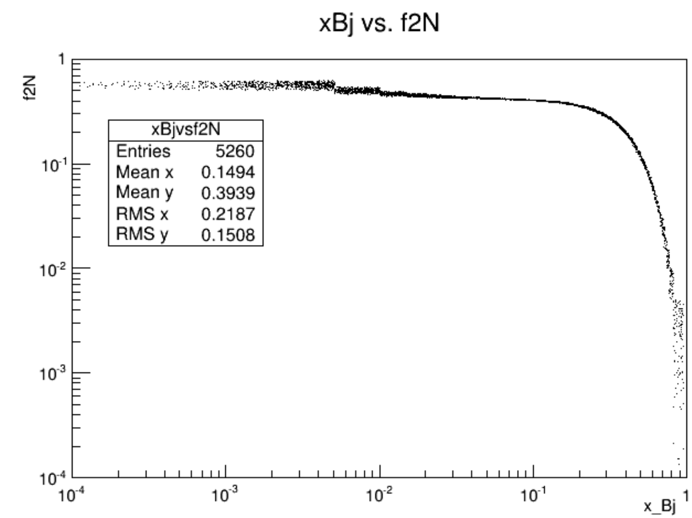


EIC Monte Carlo event genarator: cross section assignment

- *DIS cross-section defined from CTEQ parameters as function of*
  -double cdissigma(x, y, Q2, nu, eprime_rest, nucl)

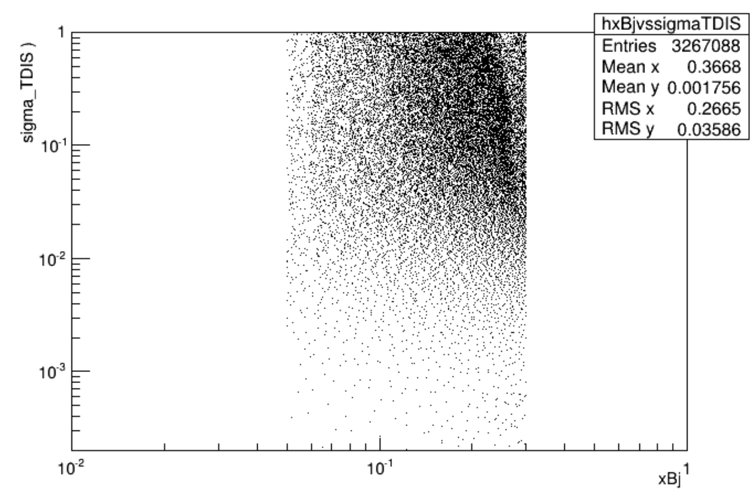
- *The TDIS cross section in MC generator is defined by formula*

$$\sigma_{TDIS}=\sigma_{DIS} * (F2pi/F2N)$$
$$\sigma_{TDIS}=\sigma_{DIS} * (F2kp/F2N)$$



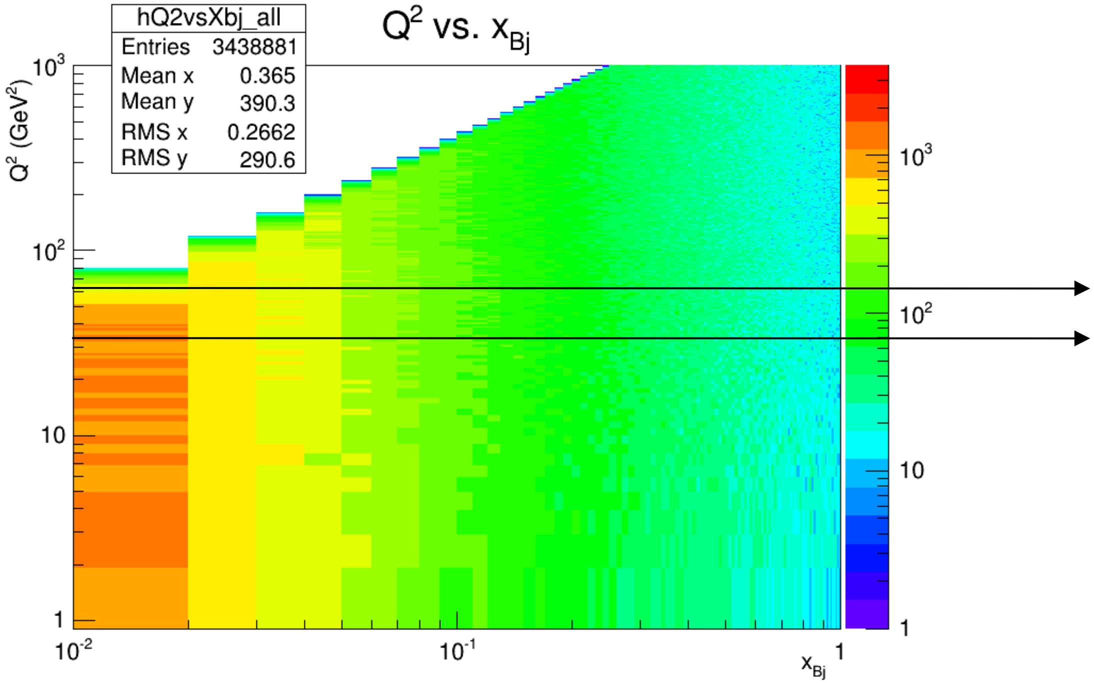
- Subroutine calculating **F2N** *is define at G4SBSDIS.hh*
  -double F2N(double x, double Q2,int nucl)
  - nucl =2; // for neutron;
  -Define the DIS PDF from CTEQ

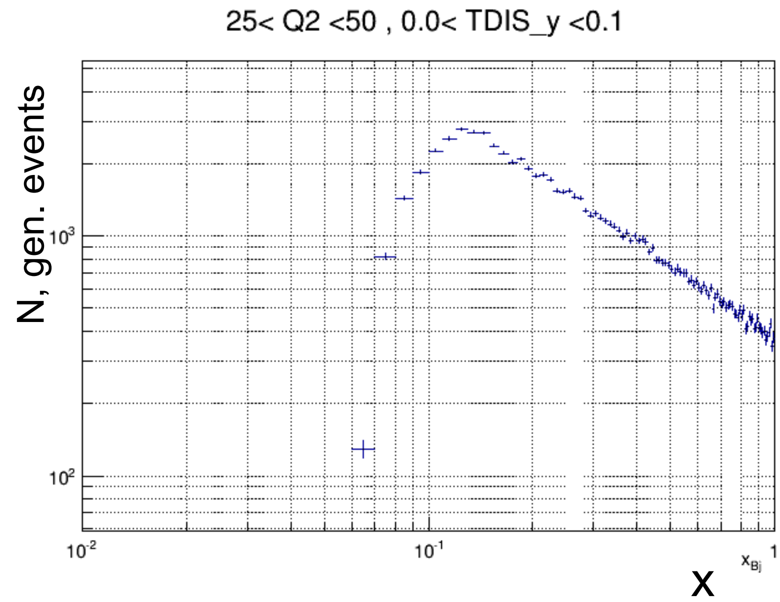
- *Subroutine calculating the* ***F2PI*** *as function of recoiled nucleon momentum, xbj, theta*
  - This is user parametrization by fit the Wally's codes 3Var_x.f() with integration of finite momentum range
  -typ = 3 ! COV DIP FORM FACTOR t-dep exponential
  -dis = 1 ! NEUTRAL EXCHANGE
  -FLAG = 0 --- **THE PION CONTRIBUTION** *| J = 0 + 1/2*



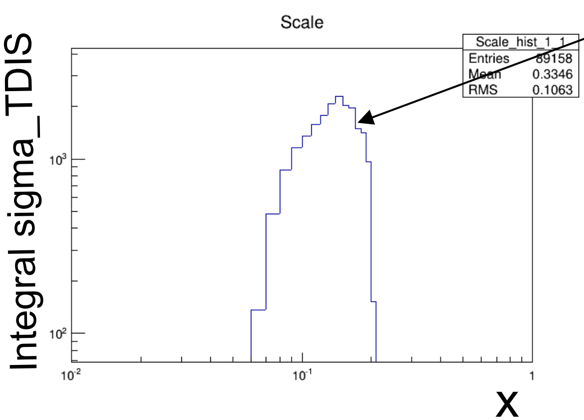
- *Subroutine calculating the* ***F2KP*** *as function of recoiled nucleon momentum, xbj, theta*
  -This is user parametrization by fit the Wally's codes 3KVar_x.f() with integration of finite momentum range
  -typ = 2 ! s-exp Form factor
  -dis = 0 ! Charge EXCHANGE
  -FLAG = 0 --- **THE KAON CONTRIBUTION** *| J = 0 + 1/2*

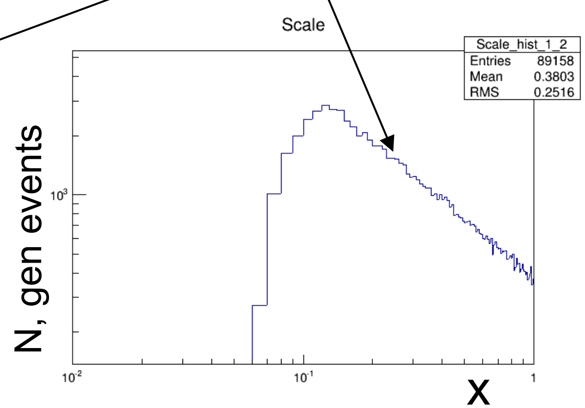
Cross section extraction from EIC Monte Carlo generated events

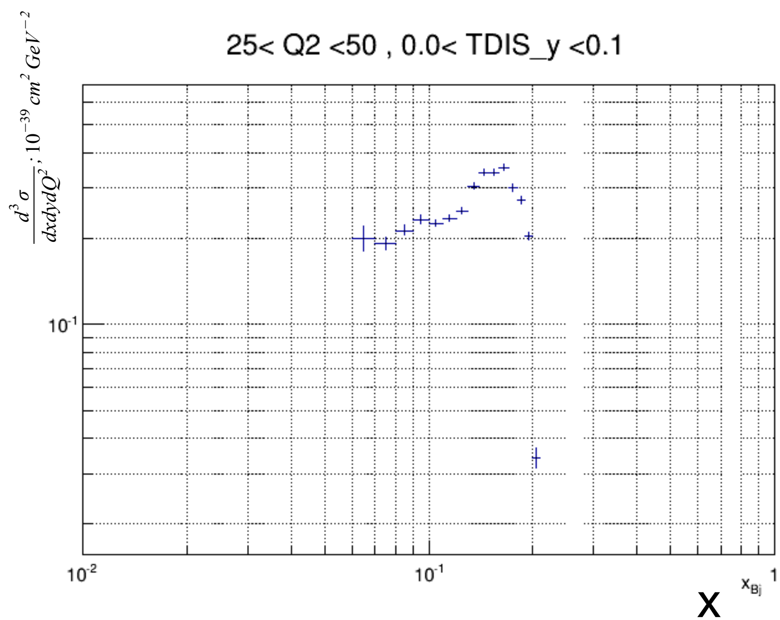




$$\frac{d^3\sigma}{dxdydQ^2} = \frac{d^3N}{dxdydQ^2} * \left(\frac{1}{L_{integ}}\right) * \overbrace{\left(\frac{N_{trials}}{\sigma_{integ}}\right)}^{weight}$$



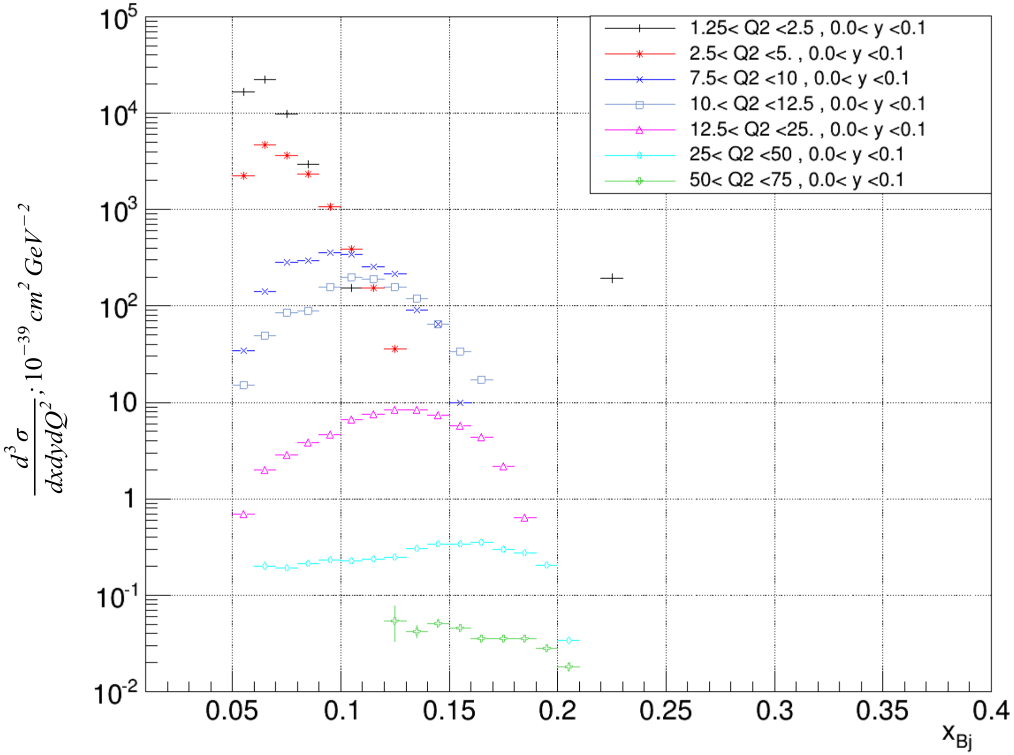




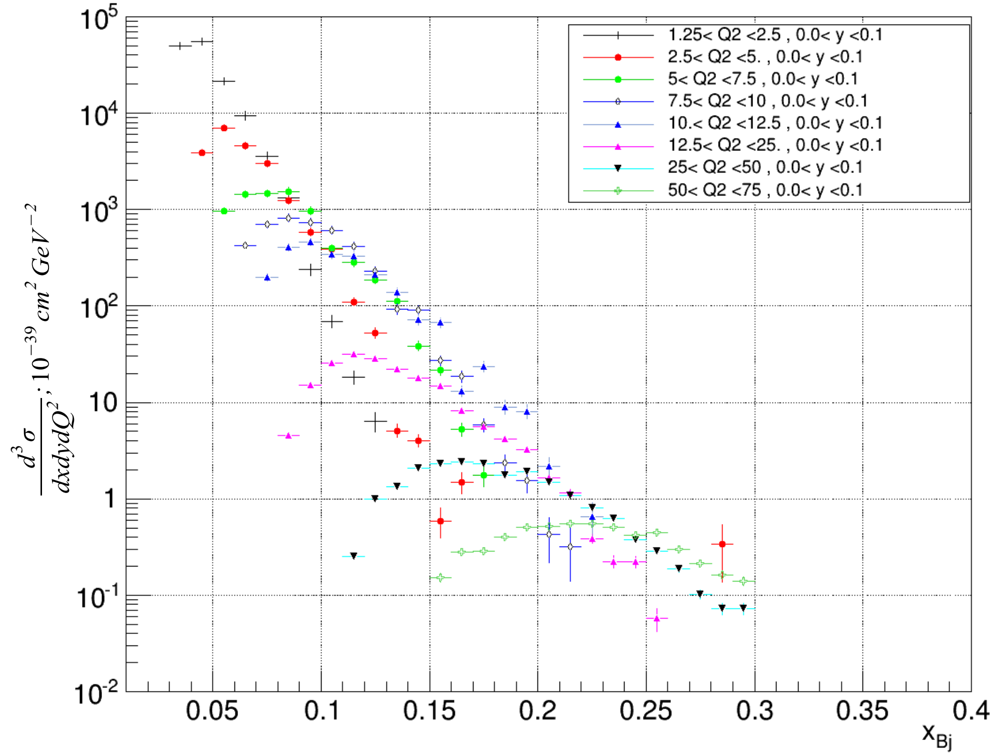
Extracted cross sections from EIC Monte Carlo generator pion and kaon hypotesis in different $dQ^2 dx\, dy$ bins

- At 0.0 < y < 0.1 range for higher Q2 (>80 GeV2) cross section extraction method produce a points at which a function takes an infinite value and can not be extracted

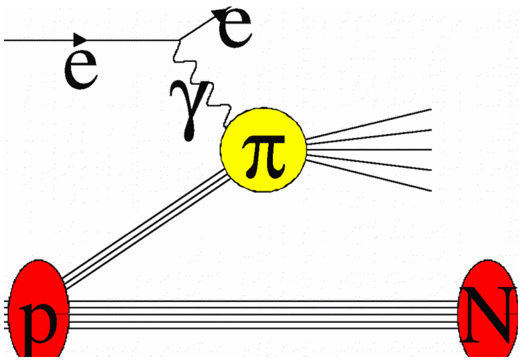
Pion



Kaon

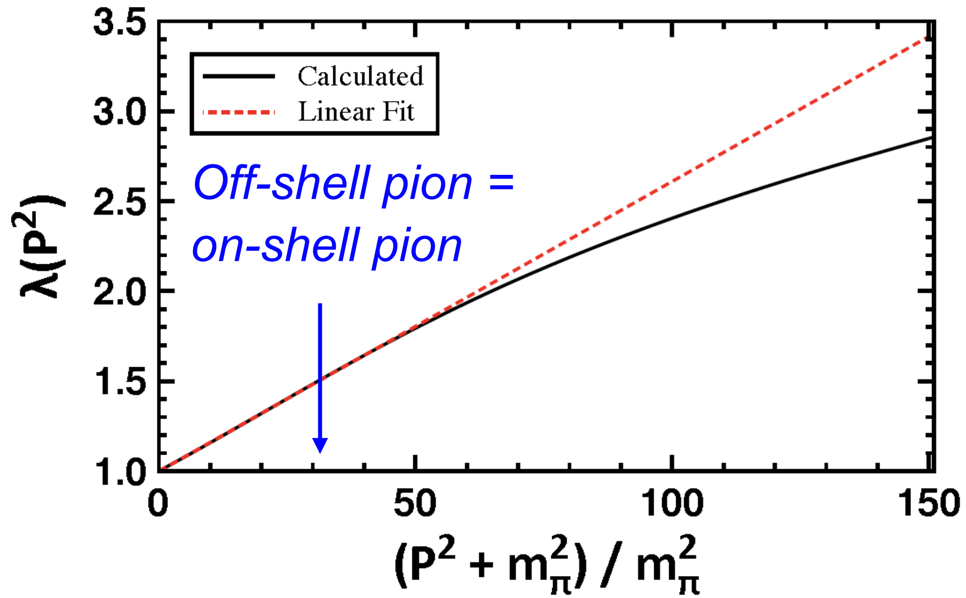


Experimental consideration: Off-shellness effects

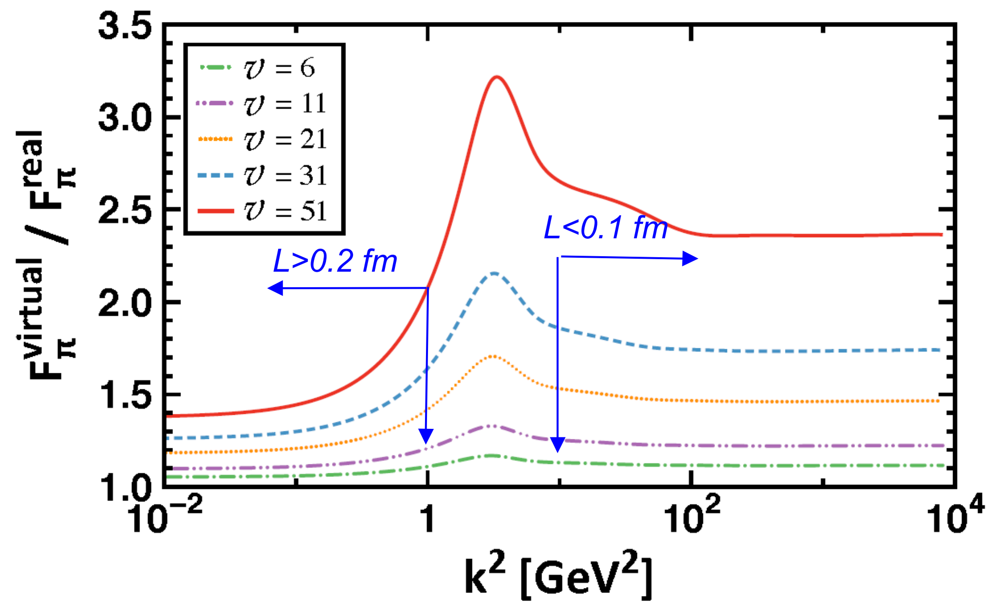


In the Sullivan process, the mesons in the nucleon cloud are virtual (off-shell) particles

S-X Qin, C.Chen, C. Mezrag, C.D. Roberts, arXiv:1702.06100 (2017)



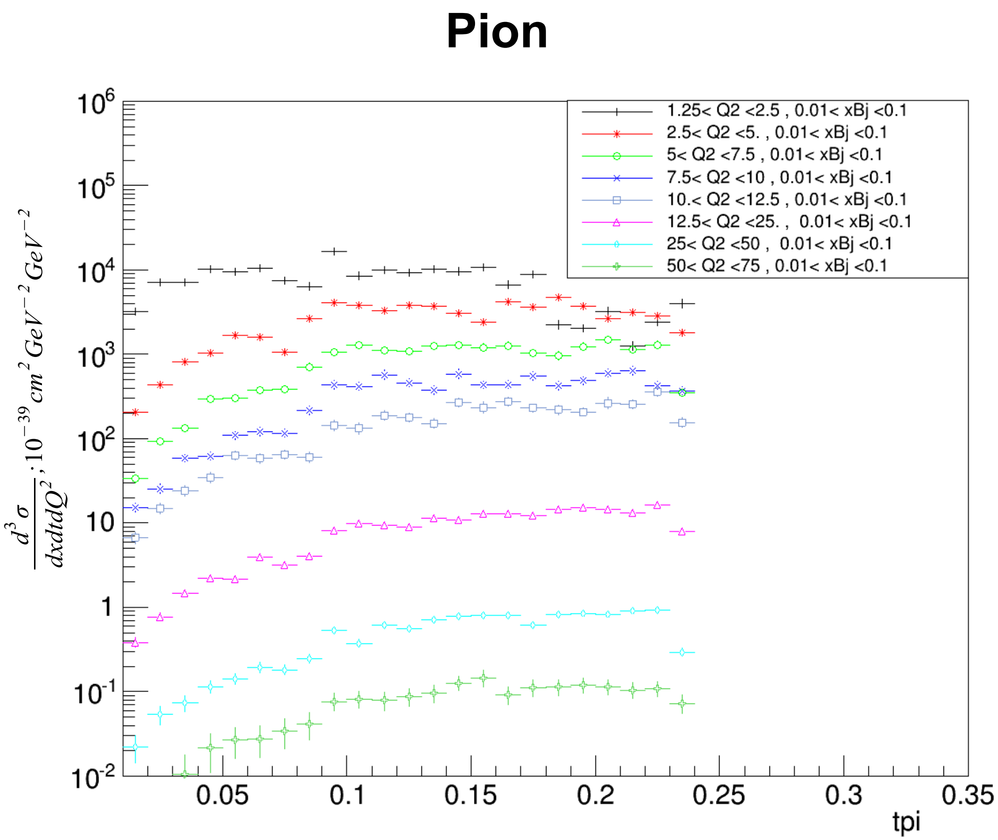
- Recent calculations estimate the effect in the BSE/DSE framework – as long as $\lambda(\nu)$ is linear in ν the meson pole dominates
  - Within the linearity domain, alterations of the meson internal structure can be analyzed through the amplitude ratio
- *Off-shell meson = On-shell meson* for t<0.6 GeV^2 (ν =31) for pions and t<0.9 GeV^2(ν_s~3) for kaons

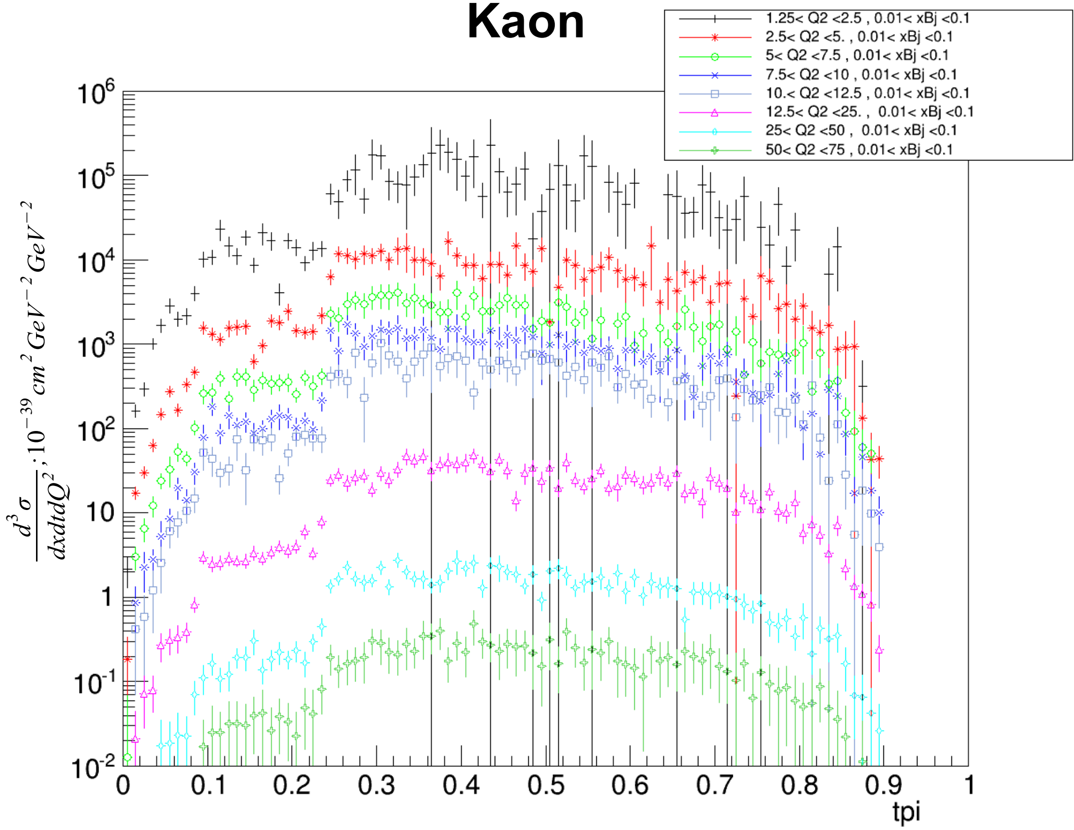


This means that pion and kaon structure functions can be accessed through the Sullivan process

Extracted cross sections from EIC Monte Carlo generator for pion and kaon hypotesis in different dQ^2 dx dt bins

- In pion scenario tpi cut related with xBj (artifact) is hardcoded in f2pi C++ function
  -no evidence of physics reason of the cut, investigate is ongoing





Plug event into GEMC: 5x100 GeV2, e/p beams

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    2    -98.1     3.66 2.04e+03  1.39e+05        0        2  2.05e+03       root Transportation
    3     -240     8.94 4.99e+03  1.39e+05        0 2.95e+03     5e+03 det1_beamline_magnet_ion_downstream_dipole1_front Transportation
    4     -240     8.94 4.99e+03  1.39e+05        0    2e-07     5e+03 det1_beamline_magnet_ion_downstream_dipole1_inner Transportation
    5     -312     11.6 6.49e+03  1.39e+05        0   1.5e+03  6.5e+03 det1_beamline_magnet_ion_downstream_dipole1_back Transportation
    6     -312     11.6 6.49e+03  1.39e+05        0    2e-07   6.5e+03       root Transportation
    7     -336     12.5 6.99e+03  1.39e+05        0      500     7e+03 det1_beamline_magnet_ion_downstream_quadrupole1_front Transportation
    8     -336     12.5 6.99e+03  1.39e+05        0    2e-07     7e+03 det1_beamline_magnet_ion_downstream_quadrupole1_inner Transportation
    9     -393     14.7 8.19e+03  1.39e+05        0  1.2e+03   8.2e+03 det1_beamline_magnet_ion_downstream_quadrupole1_back Transportation
   10     -393     14.7 8.19e+03  1.39e+05        0    2e-07   8.2e+03       root Transportation
   11     -441     16.4 9.19e+03  1.39e+05        0    1e+03   9.2e+03 det1_beamline_magnet_ion_downstream_quadrupole2_front Transportation
   12     -441     16.4 9.19e+03  1.39e+05        0    2e-07   9.2e+03 det1_beamline_magnet_ion_downstream_quadrupole2_inner Transportation
   13     -556     20.7 1.16e+04  1.39e+05        0  2.4e+03  1.16e+04 det1_beamline_magnet_ion_downstream_quadrupole2_back Transportation
   14     -556     20.7 1.16e+04  1.39e+05        0    2e-07  1.16e+04       root Transportation
   15     -604     22.5 1.26e+04  1.39e+05        0    1e+03  1.26e+04 det1_beamline_magnet_ion_downstream_quadrupole3_front Transportation
   16     -604     22.5 1.26e+04  1.39e+05        0    2e-07  1.26e+04 det1_beamline_magnet_ion_downstream_quadrupole3_inner Transportation
   17     -662     24.7 1.38e+04  1.39e+05        0  1.2e+03  1.38e+04 det1_beamline_magnet_ion_downstream_quadrupole3_back Transportation
   18     -662     24.7 1.38e+04  1.39e+05        0    2e-07  1.38e+04       root Transportation
   19     -700     26.1 1.46e+04  1.39e+05        0      800  1.46e+04 det1_beamline_magnet_ion_downstream_solenoid1_front Transportation
   20     -700     26.1 1.46e+04  1.39e+05        0    2e-07  1.46e+04 det1_beamline_magnet_ion_downstream_solenoid1_inner Transportation
   21     -815     30.4   1.7e+04 1.39e+05        0  2.4e+03   1.7e+04 det1_beamline_magnet_ion_downstream_solenoid1_back Transportation
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   23     -853     31.8 1.78e+04  1.39e+05        0      793  1.78e+04 det1_beamline_magnet_ion_downstream_dipole2_front Transportation
   24     -853     31.8 1.78e+04  1.39e+05        0    2e-07  1.78e+04 det1_beamline_magnet_ion_downstream_dipole2_inner Transportation
   25     -900     33.5 1.87e+04  1.39e+05        0      967  1.88e+04 det1_beamline_magnet_ion_downstream_dipole2_inner Decay

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    1     -992     37.5 2.18e+04  1.15e+05 1.07e-22 3.04e+03  3.04e+03 det1_beamline_magnet_ion_downstream_dipole2_back Transportation
    2     -992     37.5 2.18e+04  1.15e+05 7.07e-33    2e-07  3.04e+03       root Transportation
    3 -1.16e+03    56.7 3.63e+04  1.15e+05 5.15e-22 1.45e+04  1.76e+04 det1_beamline_magnet_ion_downstream_dipole3_front Transportation
    4 -1.16e+03    56.7 3.63e+04  1.15e+05 7.07e-33    2e-07  1.76e+04 det1_beamline_magnet_ion_downstream_dipole3_inner Transportation
    5 -1.31e+03    61.9 4.03e+04  1.15e+05 1.42e-22    4e+03  2.16e+04 det1_beamline_magnet_ion_downstream_dipole3_back Transportation
    6 -1.31e+03    61.9 4.03e+04  1.15e+05 7.09e-33    2e-07  2.16e+04       root Transportation
    7 -1.7e+04      404    3e+05  1.15e+05  9.2e-21  2.6e+05  2.82e+05 OutOfWorld Transportation

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    1 -1.31e+03    45.9 2.18e+04  2.41e+04 1.11e-22 3.06e+03  3.06e+03 det1_beamline_magnet_ion_downstream_dipole2_back Transportation
    2 -1.31e+03    45.9 2.18e+04  2.41e+04 7.45e-33 2.05e-07  3.06e+03       root Transportation
    3 -6.39e+04 1.2e+03    3e+05  2.41e+04 1.04e-20 2.85e+05  2.88e+05 OutOfWorld Transportation

**************************************************************************************
* G4Track Information:   Particle = e-,   Track ID = 3,   Parent ID = 0
**************************************************************************************

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    1     4.48     31.9    -5.87  6.89e+03 1.63e-24     32.8      32.8 vac_det1_beamline_pipe_eleside_VertexChamber Transportation
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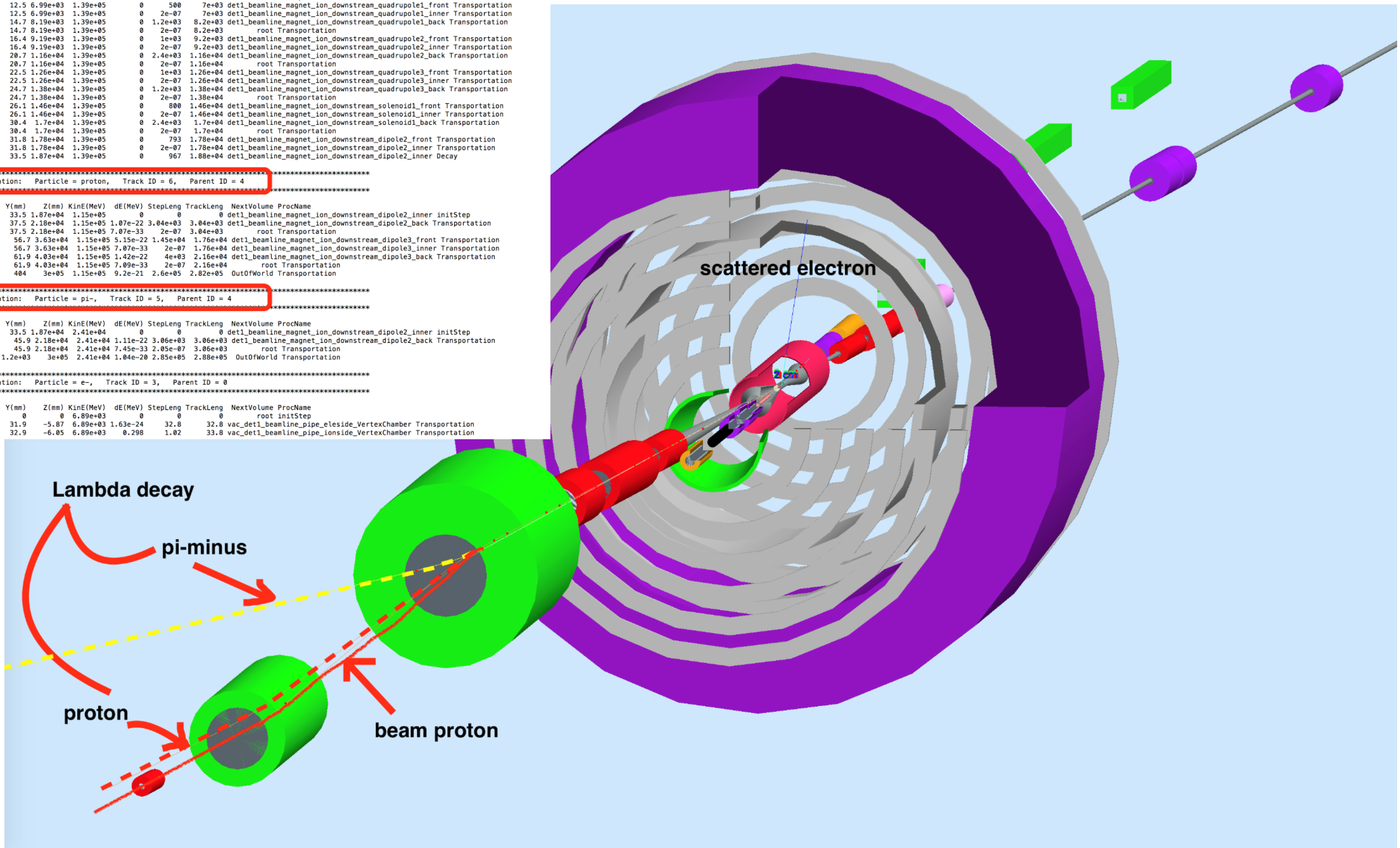
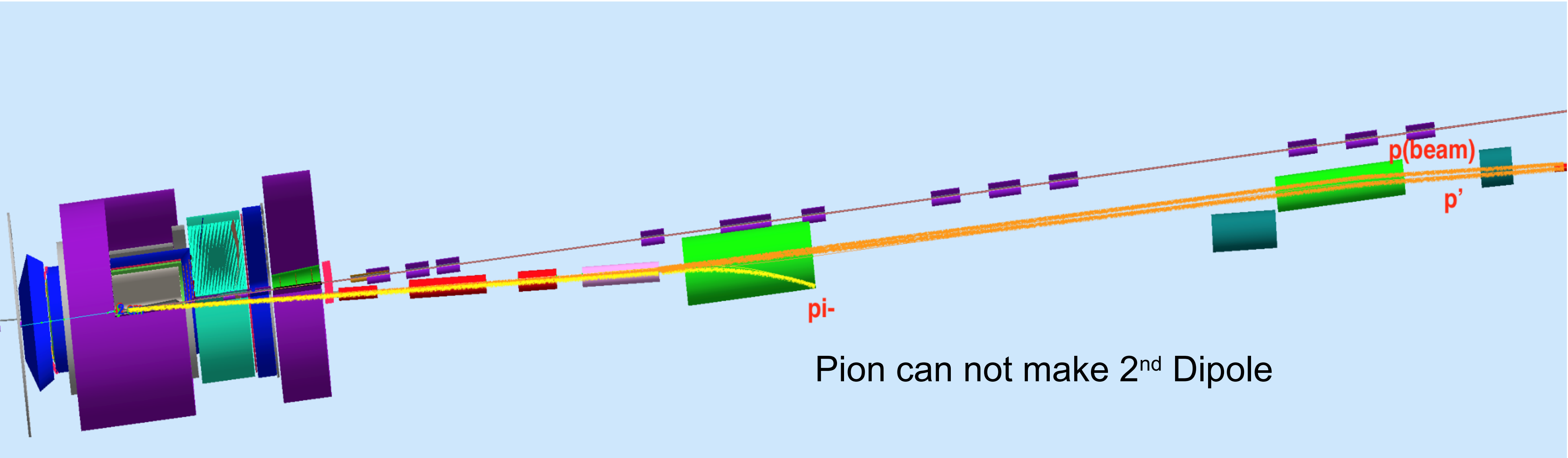


Figure from K.Park

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



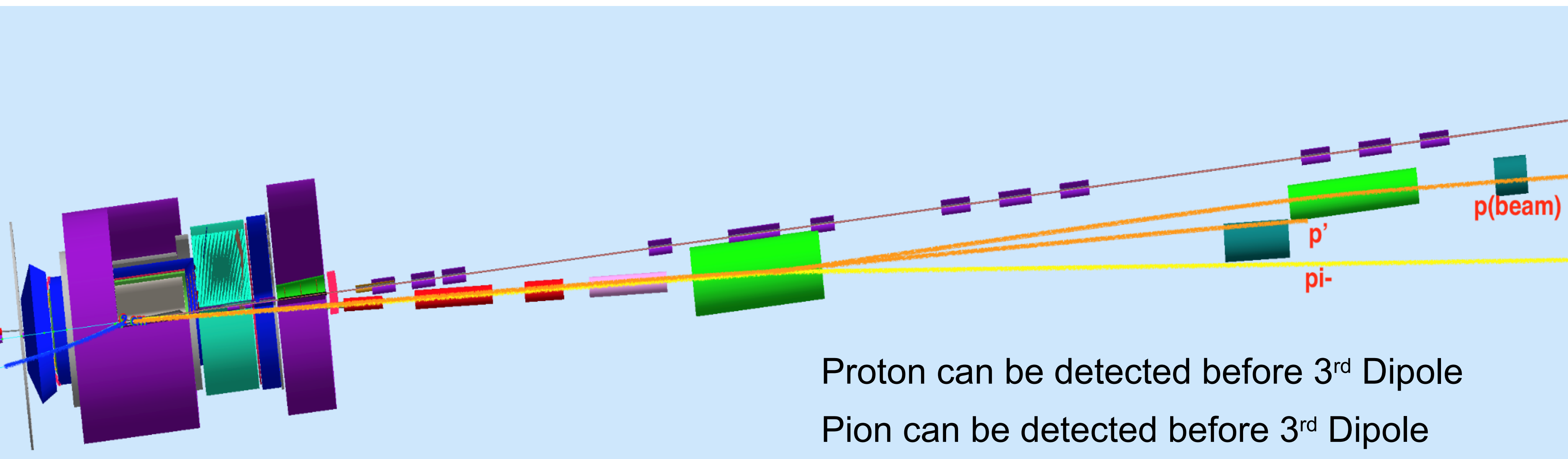


Figure from K.Park

Summary

- Nucleons and the lightest mesons - pions and kaons, are the basic building blocks of nuclear matter. We should know their structure functions
- The distributions of quarks and gluons in pions, kaons, and nucleons will be different
- Measurements of pion and kaon structure functions at JLEIC seem feasible
- Fast Monte Carlo available for projections – can be configured for flexible Q^2-x bins, several open questions on code resolved over the last year, some questions remain to be addressed, exploring model for kaon
- Detector Monte Carlo being investigated – could be done in global framework of e.g. JLEIC and similarly eRHIC
- Impact studies of pion kaon structure function on global fits ongoing – Richard's talk for more detail