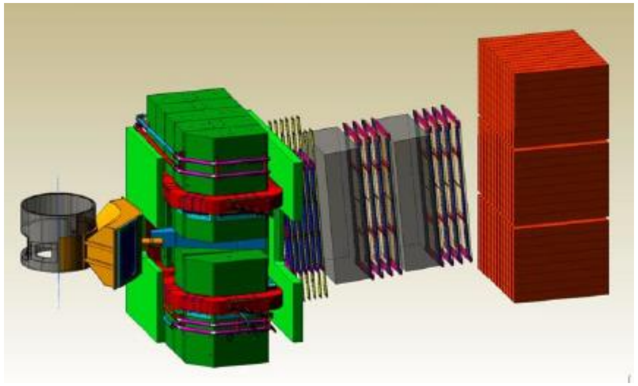
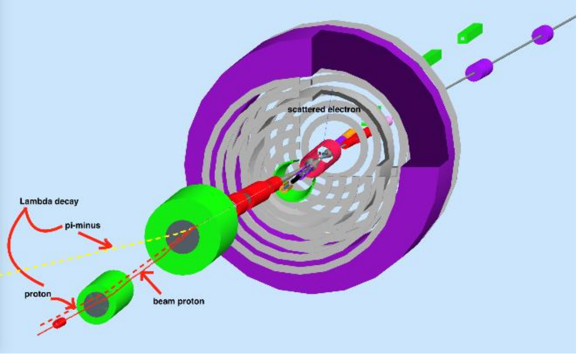
From 12 GeV to EIC:
Tagged Physics





Tanja Horn

THE CATHOLIC UNIVERSITY OF AMERICA

Jefferson Lab
Thomas Jefferson National Accelerator Facility

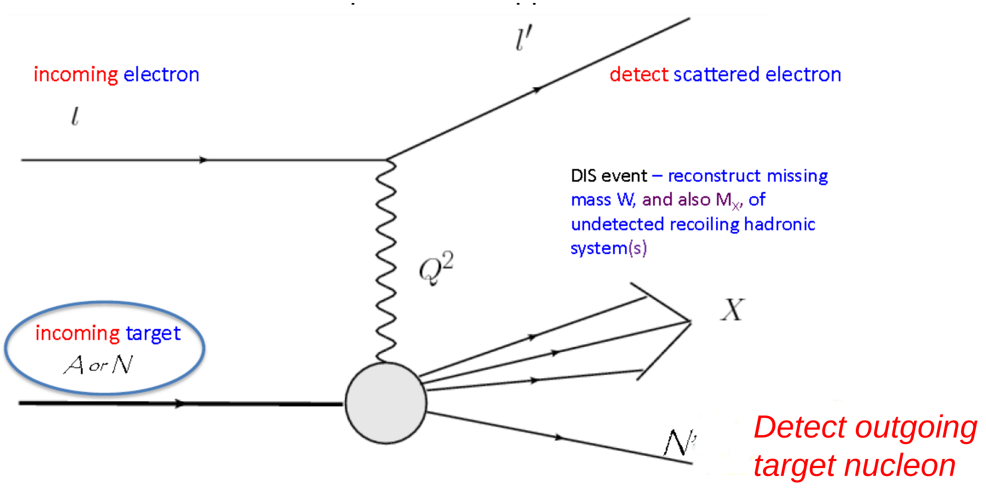
2018 JLab Users Group Meeting

Jefferson Lab, Newport News, VA
18-20 June 2018

Tagged Deep Inelastic Scattering (TDIS)

- ☐ Spectator tagging extremely powerful to explore the partonic structure of mesons/nucleons, short range NN correlations, nuclear modifications of quark-gluon densities, …

- ☐ Examples include:
  - ➢ Neutron
  - ➢ Pion and kaon



DIS event – reconstruct missing mass W, and also M_X, of undetected recoiling hadronic system(s)

Detect outgoing target nucleon

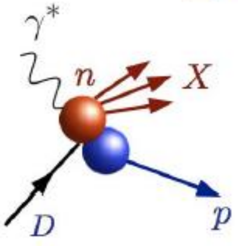
- ☐ Proton SF known with high precision experimentally

- ☐ Light meson structure largely unknown – yet basic building blocks of matter!

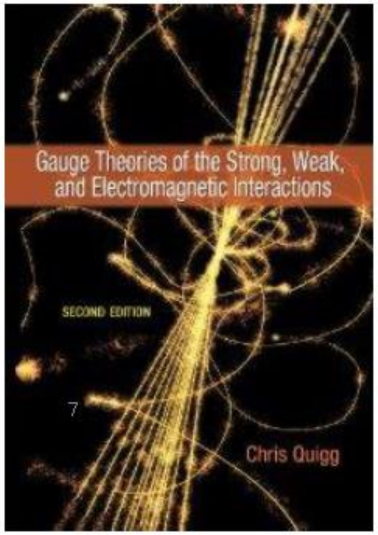
- ☐ Nucleon's pion/kaon content key role in nucleon/nuclear structure
  - ➢ Long range NN interaction; simplest QCD state; dynamical chiral symmetry breaking/goldstone boson
  - ➢ Access to momentum fractions carried by sea/glue

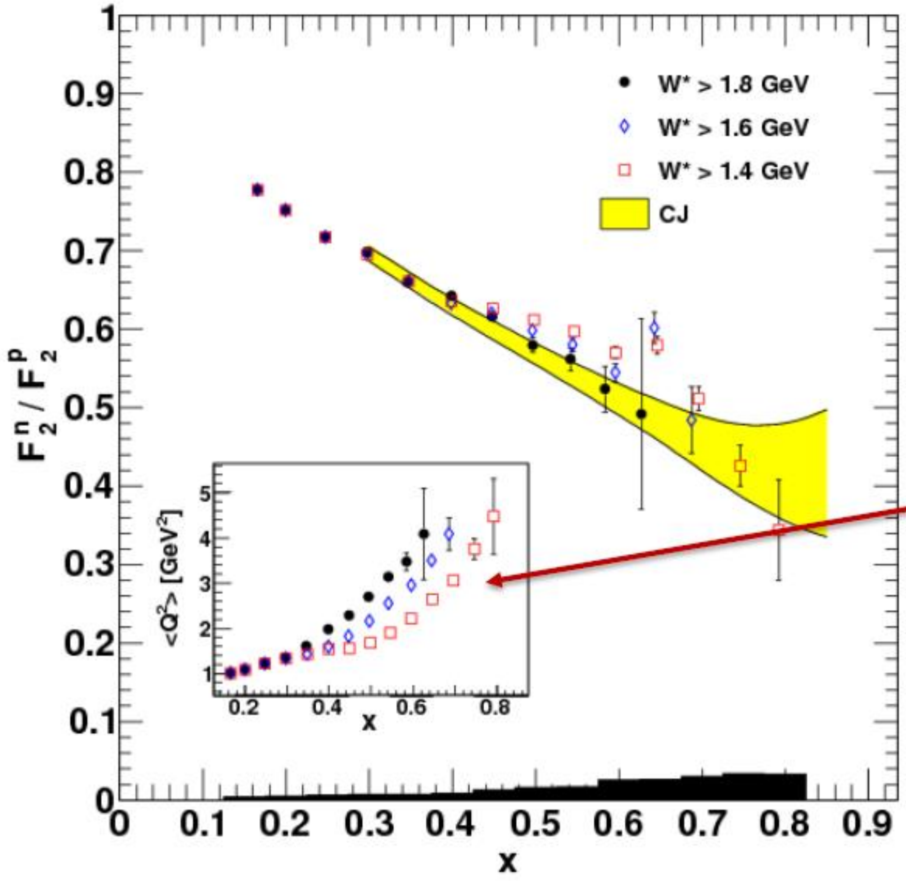
Example 1: TDIS to access nucleon valence structure

BONUS effective neutron target via TDIS *achieved!*



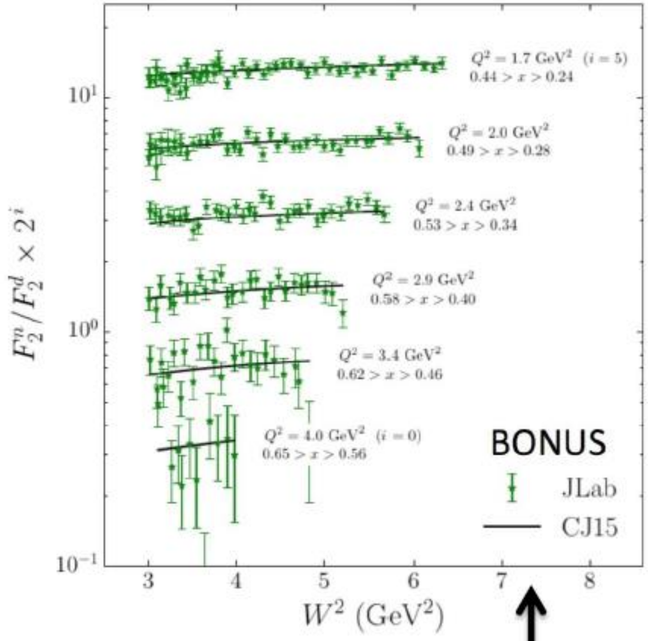
Phys.Rev. C92 (2015) no.1, 015211
Phys.Rev. C91 (2015) no.5, 055206
Phys. Rev. C89 (2014) 045206 – editor's suggestion
Phys. Rev. Lett. 108 (2012) 199902
Nucl. Instrum. Meth. A592 (2008) 273-286

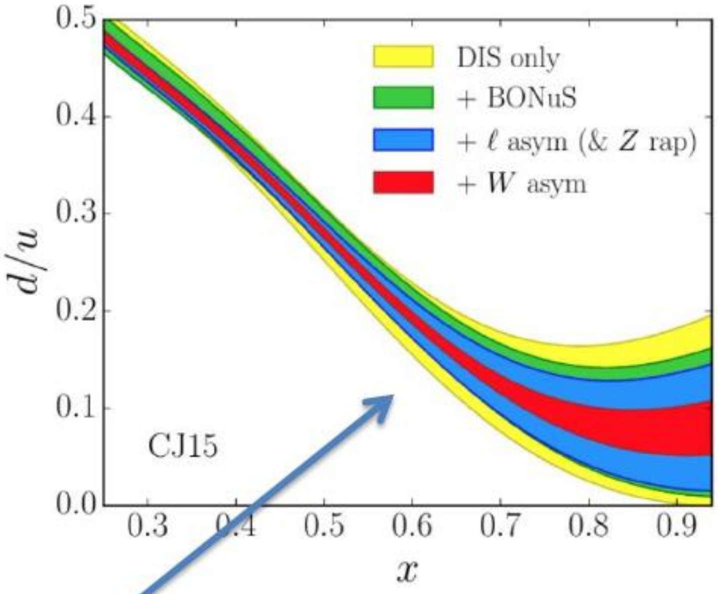




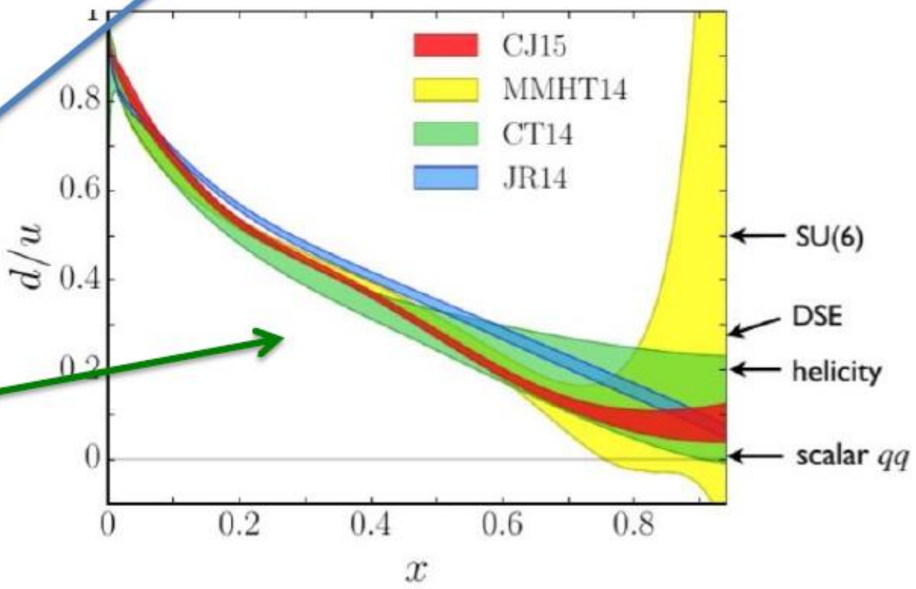
- Not quite high enough x, Q^2
- Nonetheless still powerful as input for global PDF fits…

Example 1: TDIS to access nucleon valence structure





- BONUS data well fit by CJ
- Effect of adding BONUS (also W, l asymmetries from D0)
- **Substantial reduction in d/u uncertainty at large x!**



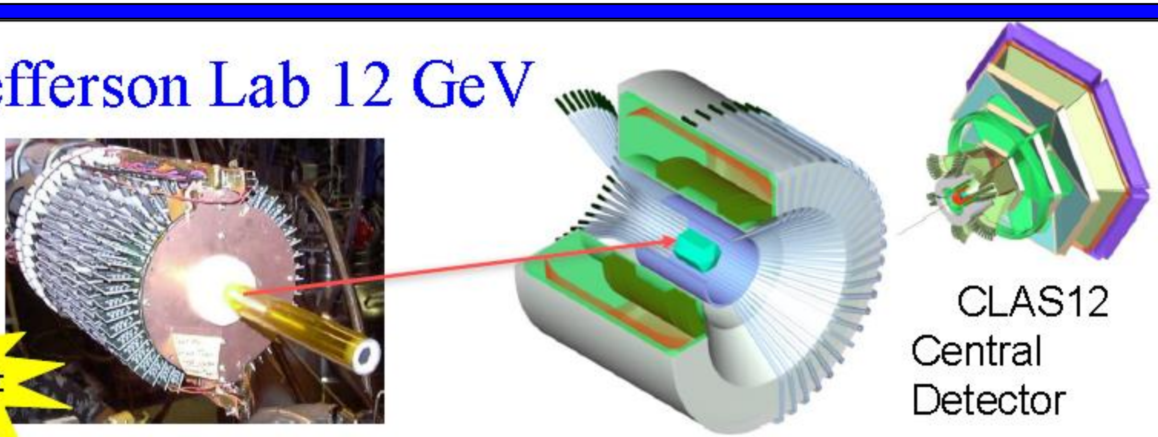
www.jlab.org/theory/cj/index.html

Example 1: TDIS to access nucleon valence structure

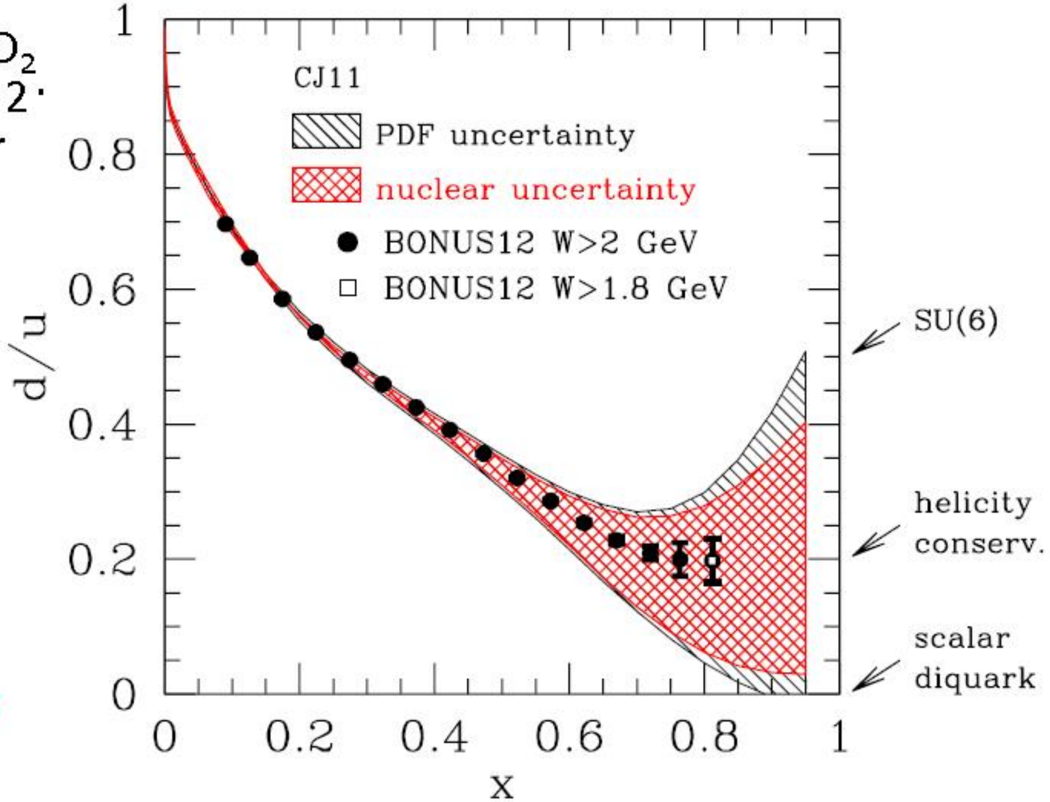
Approved for Jefferson Lab 12 GeV

E12-06-113
"BONUS12"

High Impact



- Data taking of 35 days on D_2 and 5 days on H_2 with $L = 2 \cdot 10^{34}$ cm^{-2} sec^{-1} planning for 2018
- BoNuS detector DAQ and trigger upgrade
- DIS region with
  - $Q^2 > 1$ GeV$^2/c^2$
  - $p_s < 100$ MeV/c
  - $\theta_{pq} > 110°$
- Largest value for $W^* > 1.8$ GeV gives max. $x^* = 0.83$



Example 1: TDIS to access nucleon structure

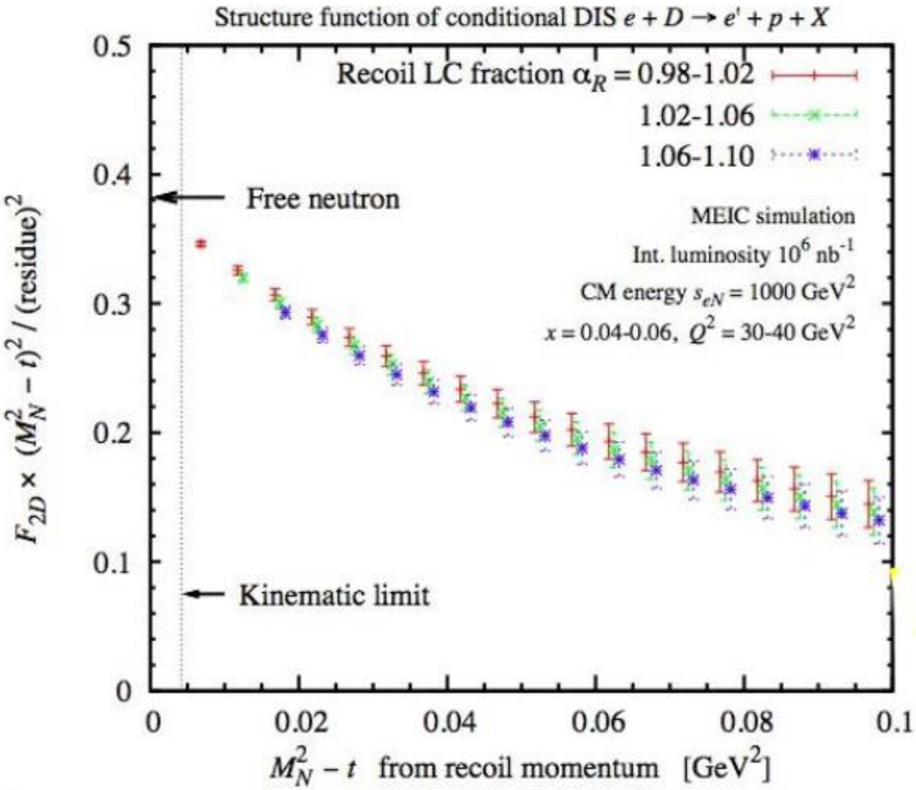
Tagged Neutron Structure at the Electron Ion Collider

See Spectator Tagging Project at https://www.jlab.org/theory/tag/

e + D → e′ + p + X *a la BONUS*

$\alpha_R \equiv 2(E_R + p^z_R)/(E_D + p^z_D)$

residue = free neutron



TDIS measurements require coverage for [protons] with:

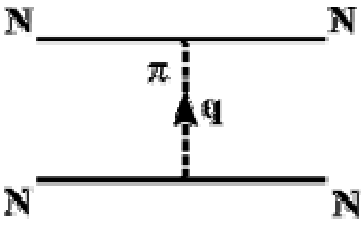
- low momenta (pT/pbeam ~ 0.8 – 1.2)
- good momentum resolution (ΔpT ~ 20 MeV)
- small intrinsic momentum spread in the ion beam for accurate reconstruction

(JL)EIC being designed with this physics in mind

– neutron structure functions up to Q^2 = 40 GeV^2

Example 2: Pion and Kaon

- The pion is responsible for the long–range part of the nuclear force, acting as the basis for meson exchange forces, and playing a critical role as an elementary field in nuclear structure Hamiltonians.



- As the lightest meson, it must be a valence $q\bar{q}$ bound state, but understanding its structure through QCD has been exceptionally challenging.

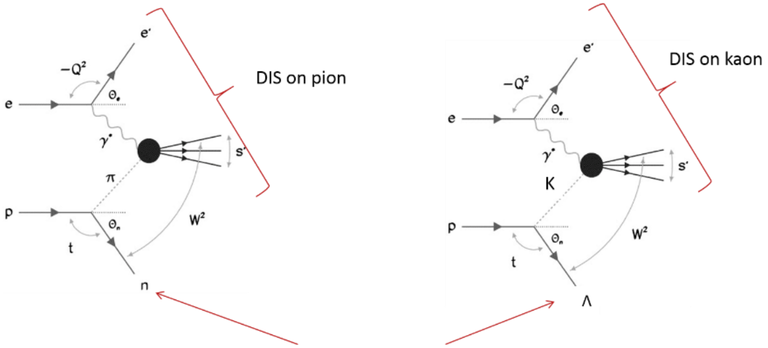
  - *E.g.*, with constituent quarks Q: in the nucleon $m_Q \sim \frac{1}{3} m_N \sim 310$ MeV, in the pion $m_Q \sim \frac{1}{2} m_\pi \sim 70$ MeV, in the kaon (with one s quark) $m_Q \sim 200$ MeV – **This is not real**.
  - The mass of bound states increases as √m with the mass of the constituents

$$\boxed{\begin{aligned} f_\pi m_\pi^2 &= (m_u^\zeta + m_d^\zeta)\rho_\pi^\zeta \\ f_K m_K^2 &= (m_u^\zeta + m_s^\zeta)\rho_K^\zeta \end{aligned}}$$

  - In both DSE and LQCD, the mass function of quarks is the same, regardless what hadron the quarks reside in – **This is real**. It is the Dynamical Chiral Symmetry Breaking (DχSB) that makes the pion and kaon masses light.
  - We exist because Nature has supplied two light quarks that combine to form the pion, which is unnaturally light and so easily produced

Towards the Pion Structure Function

- Is there anything besides the meson elastic form factors that can be learned by isolating the One Pion Exchange (OPE) contribution?



Need to measure these, so "Tagged DIS" (t is small)

- Sullivan [PRD **5**(1972)1732] was the first to consider the "Drell" process, with $\pi + X$ final states where m_X^2 grows linearly with Q^2.

$$\frac{d^4\sigma^{ep\to e'Xn}}{dx\, dQ^2\, dx_L\, dp_T} = \mathcal{K} F_2^{\mathrm{LN}(4)}(x, Q^2, x_L, p_T)(1+\delta_{\mathrm{LN}})$$

$$\mathcal{K} = \frac{4\pi\alpha^2}{xQ^4}\left(1 - y + \frac{y^2}{2}\right)$$

$$x_L = \frac{N\cdot k}{P\cdot k} \simeq \frac{E_n}{E_p}$$

$$t = (P-N)^2 \simeq -\frac{p_T^2}{x_L} - t_0$$

Conditional (or Tagged) Structure Function

$$\boxed{F_2^{\mathrm{LN}(3)}(x, Q^2, x_L) \equiv \int_0^{p_T^{\max}} F_2^{\mathrm{LN}(4)}(x, Q^2, x_L, p_T)\, dp_T}$$

Factorization of the OPE Cross Section

- Having established that the leading neutron data at high x_L are dominated by π^+ exchange, a OPE model can be used to determine the structure function of the pion, F_2^π

$$F_2^{LN(4)}\left(x,Q^2,x_L,t\right) = \underline{f_{\pi/p}(x_L,t)}\,\boxed{F_2^\pi\left(x/(1-x_L),Q^2\right)}\left(1-\Delta_{abs}(Q^2,x_L,t)\right)$$

  - $x_L = E_B/E_p$ fraction of beam energy carried by detected baryon
  - $F_2^{LN(4)}$ leading neutron 4-fold structure function
  - $f_{\pi/p}$ flux of pions with virtuality t emitted by proton
  - Δ_{abs} neutron absorption correction

$$g_{\pi pp}^2/(4\pi) = 14.5$$

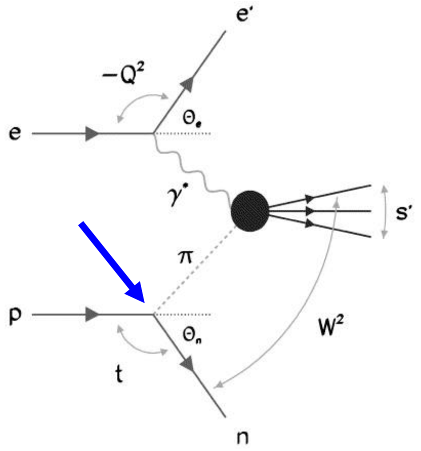
$$\alpha_\pi(t) = \alpha' t$$

$$\alpha' = 1\ \mathrm{GeV}^{-2}$$

- Many models of the pion flux factor have been suggested. They have general form:

$$f_{\pi/p}(x_L,t) = \frac{1}{4\pi}\frac{2g_{\pi pp}^2}{4\pi}\frac{-t}{(t-m_\pi^2)^2}(1-x_L)^{1-2\alpha_\pi(t)}\,[F(x_L,t)]^2$$

  - $F(x_L,t)$ model-dependent form factor that parameterizes distribution of pion cloud in proton
  - $\alpha(t)$ model-dependent power



Experimental Check of Flux Factor

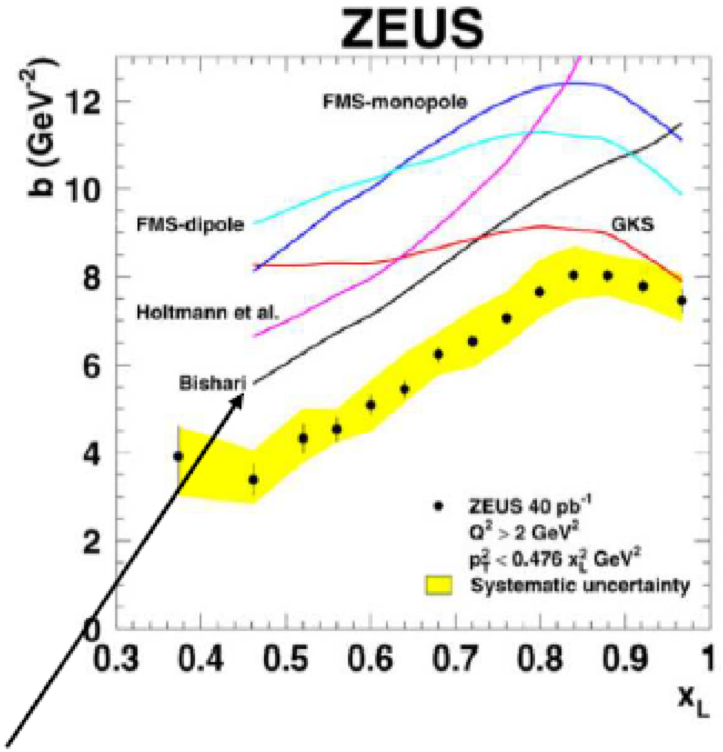
- **ZEUS@HERA did a study of the pion flux model used to extract the pion structure function**

- Assuming F_2^π is independent of t and that Δ_{abs} is small, the p_T distribution of produced neutrons is determined only by pion flux $f_{\pi/p}$.

$$\frac{1}{\sigma_{inc}}\frac{d^2\sigma_{LN}}{dx_L d^2_{p_T}} = a(x_L)e^{-b(x_L)p^2_{PT}}$$

- Although $f_{\pi/p}$ is not an exponential in p_T^2 at fixed x_L, the models can be binned in x_L and a,b compared to data fits.

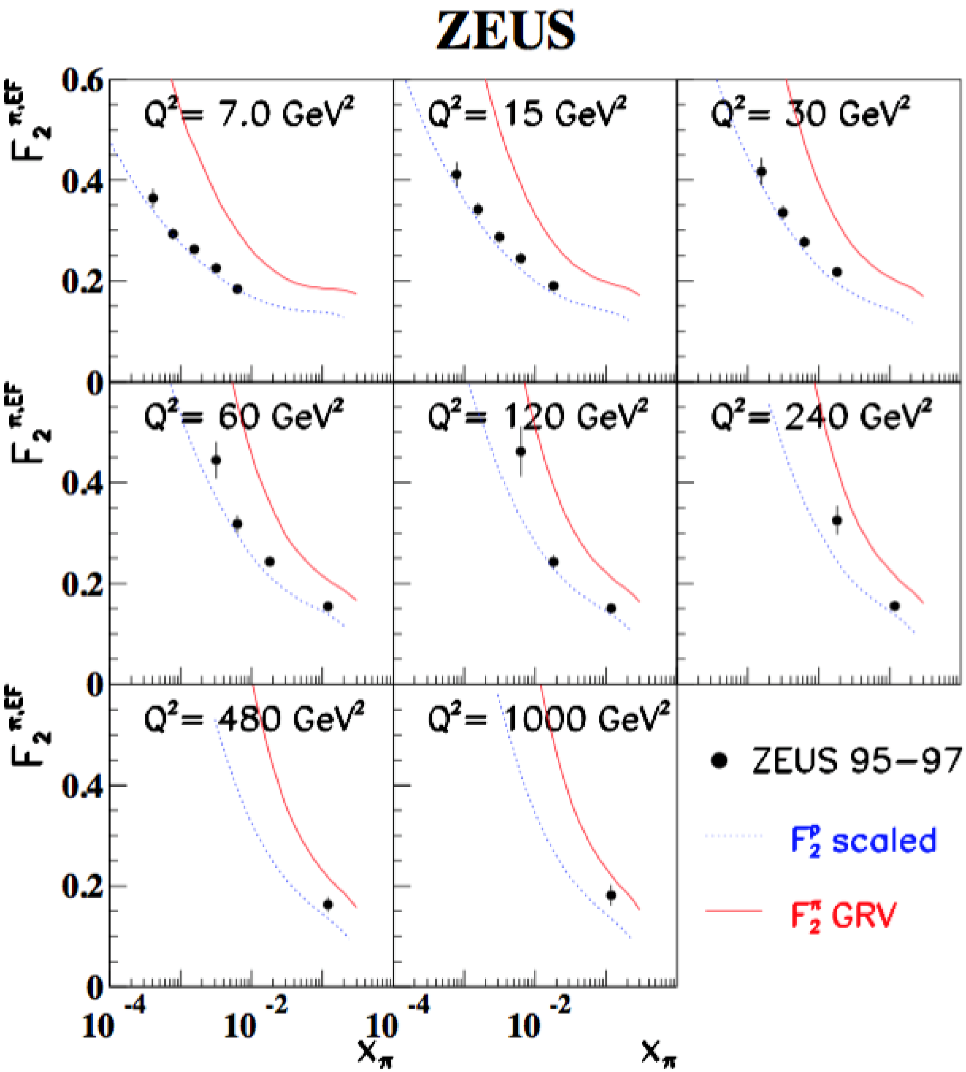
- No model fully describes the data. Simple model with $F(x_L,t)$=1 comes closest.



ZEUS Collaboration, NPB **776**(2007)1

takes care of” all other effects incl. off-shellness, but issues remain

“Pion F_2” as measured by ZEUS

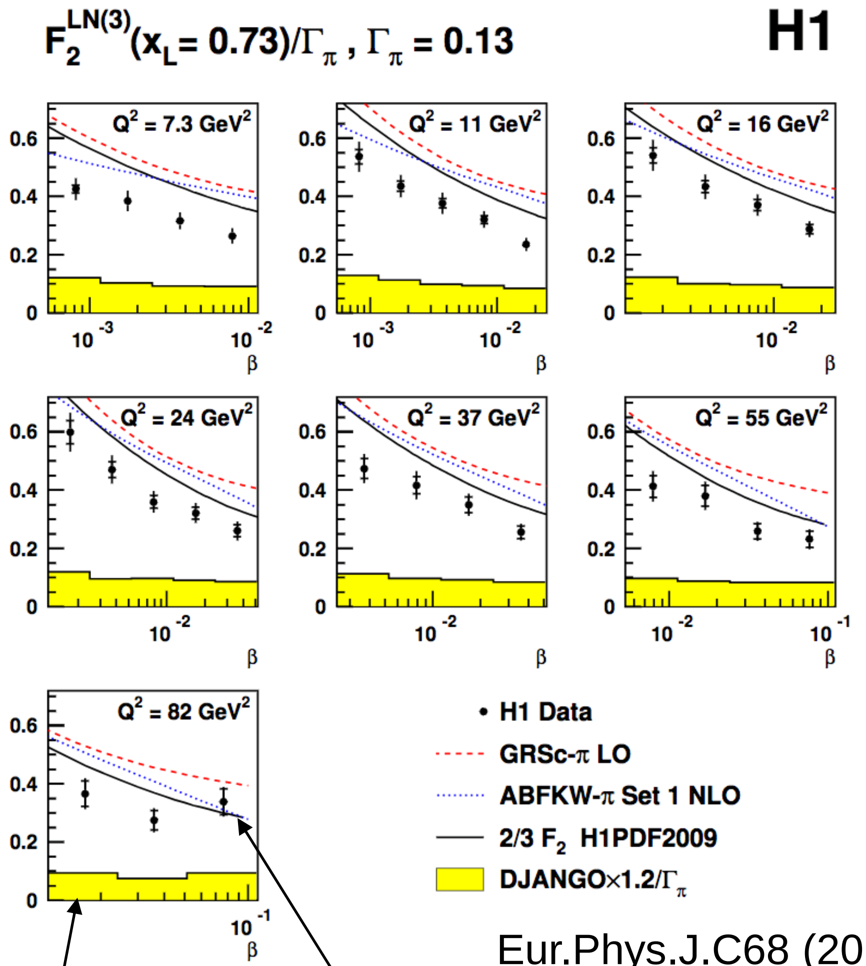


So now just using the “effective flux” (Bishari) and ignoring normalization problems…

Looks like a scaled down proton F_2

Doesn’t match expectation from DY data at higher x (“GRV”) as expected from the normalization issues.

Results from H1



Kinematics: $6<Q^2<100\ \text{GeV}^2$, $1.5\times10^{-4}<x<3\times10^{-2}$

$$f_{\pi^+/p}(x_L,t) = \frac{1}{2\pi}\frac{g^2_{p\pi n}}{4\pi}(1-x_L)\frac{-t}{(m_\pi^2-t)^2}\exp\left(-R^2_{\pi n}\frac{m_\pi^2-t}{1-x_L}\right)$$

Similar conclusion from H1

Eur.Phys.J.C68 (2010) 381

- $F_2^{LN(3)}$ is integrated over leading neutron angle (t), divided by integral of pion flux factor (Γ_π), to give F_2^π.
- $0.68<x_L<0.77$ cut used to select OPE dominance region.
- Neutron absorptive corrections not taken into account.
- Binned versus $\beta = x/(1-x_L)$, which can be interpreted as the fraction of exchanged particle's momentum carried by parton interacting with virtual photon.

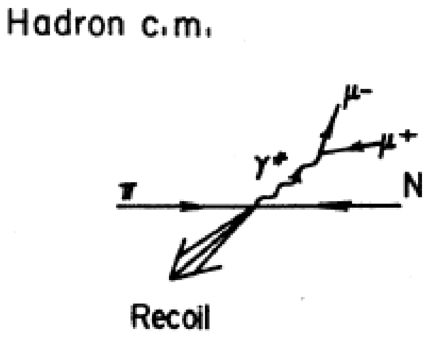
Various parameterizations of pion parton distribution functions.

Proton remnant fragmentation model

Pion Structure Function via Drell-Yan Method

FNAL E615: $\mu^+\mu^-$ production from 252 GeV π^- beam on Tungsten target

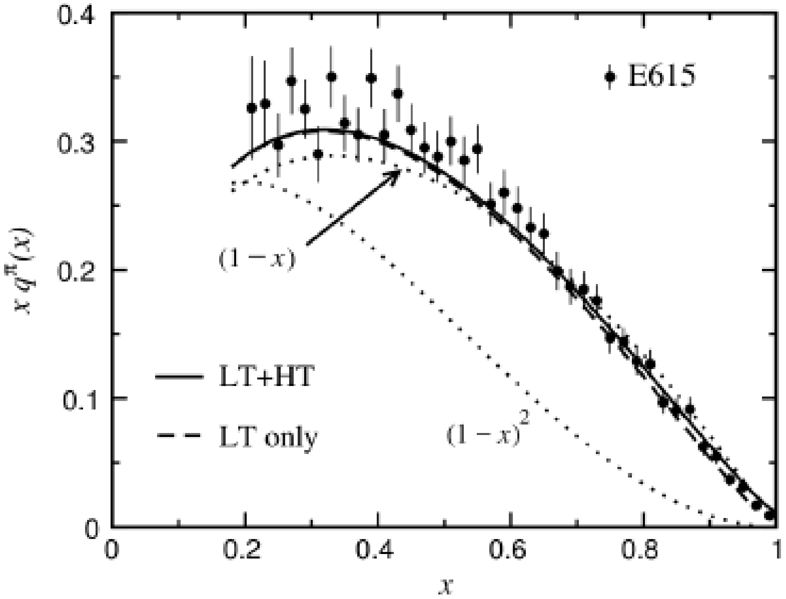
[J.S. Conway, et al., PRD **39**(1989)92]



$$\frac{d_2\sigma}{dx_\pi dx_N} = \frac{4\pi\alpha^2}{9s}\left[\frac{F_\pi^{val}(x_\pi)G_N(x_N)+F_\pi^{sea}(x_\pi)N_N(x_N)}{(x_\pi x_n)^2}\right]$$

where $F_\pi^{val}(x_\pi) = x_\pi \overline{u}^{val}(x_\pi) = x_\pi d^{val}(x_\pi)$, etc.

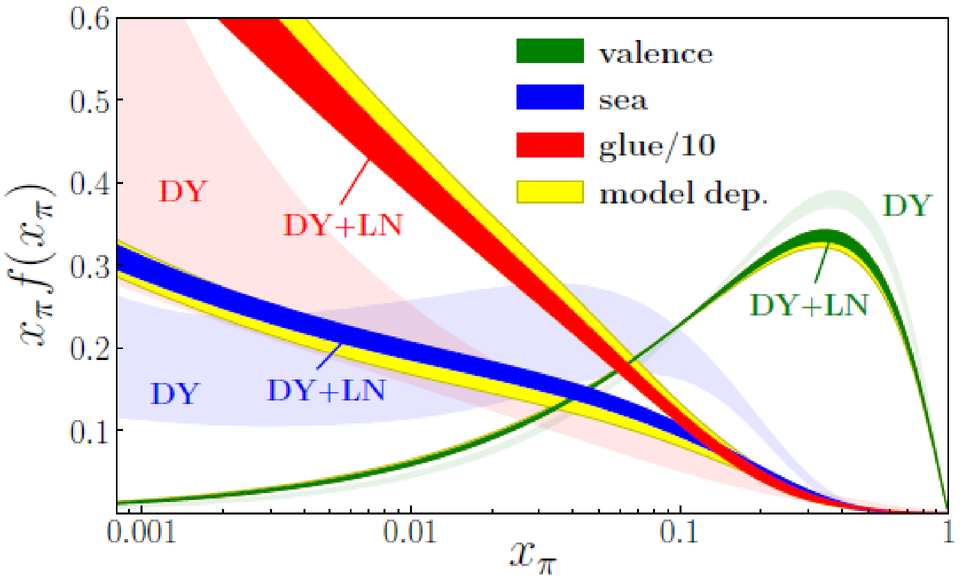
- LO Drell–Yan cross section formula underestimates observed σ^{exp} by factor of ~2, termed *K*–factor.
- Wijesooriya et al. show NLO terms very important as *x*→1, yields pion valence PDF with more curvature than LO fits [PRC **72**(2005)065203].
- **μμ mass resolution could translate into substantial uncertainty in *x*.**
- **A more precise experiment with better resolution is welcome.**



W. Melnitchouk, EPJA **17**(2003)223

First Global Fits and Web-based Self-Serve Pion PDF

- First MC global QCD analysis of pion PDFs
  - Using Fermilab DY and HERA Leading Neutron data



DY = πN Drell-Yan

LN = Leading Neutron

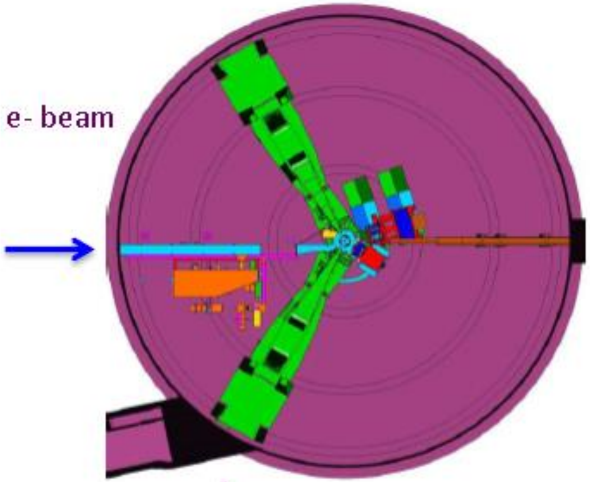
Barry, Sato, Melnitchouk, Ji (arXiV:1804.01965)

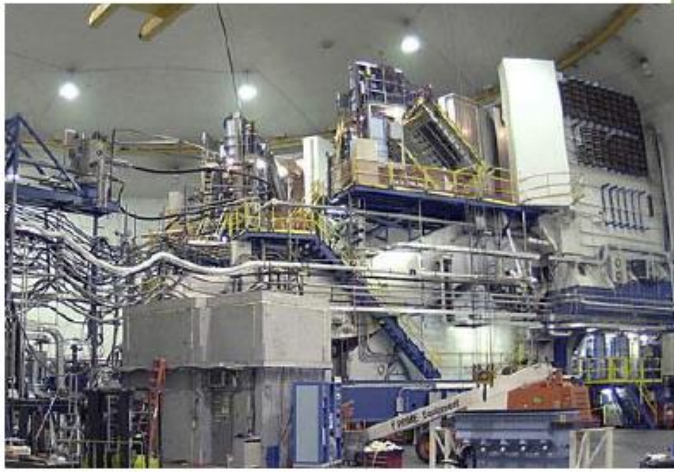
Web-based self-server performs a combined Leading-Neutron, Drell-Yan and new data analysis

Github: https://github.com/JeffersonLab/jamfitter

Jupyter notebook: https://jupyter.jlab.org/

Jlab Hall A TDIS Experiments (conditional approval)

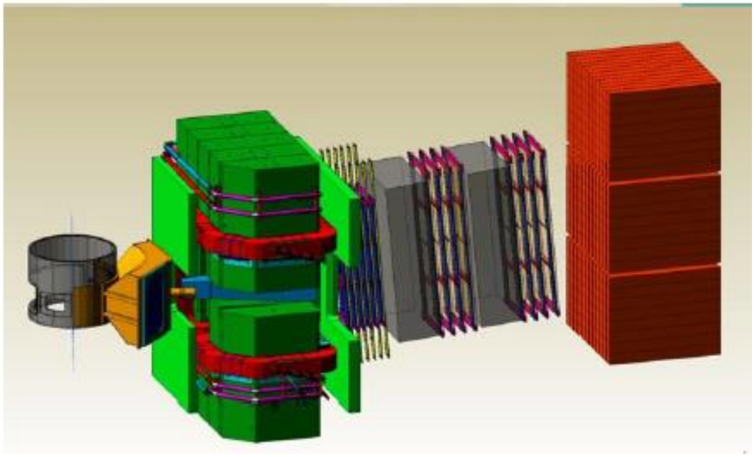




Superconducting solenoid

proton tag detection in BONUS-type RTPC at pivot

Scattered electron detection in Super Bigbite Spectrometer (SBS) – base equipment construction complete



Hall A with Super Bigbite:

✓ High luminosity,
 50 µAmp, $\mathcal{L}$ = 3 x 10^{36}/cm^2 s
✓ Large acceptance
 Super Bigbite ~70 msr, hadron spectrometer

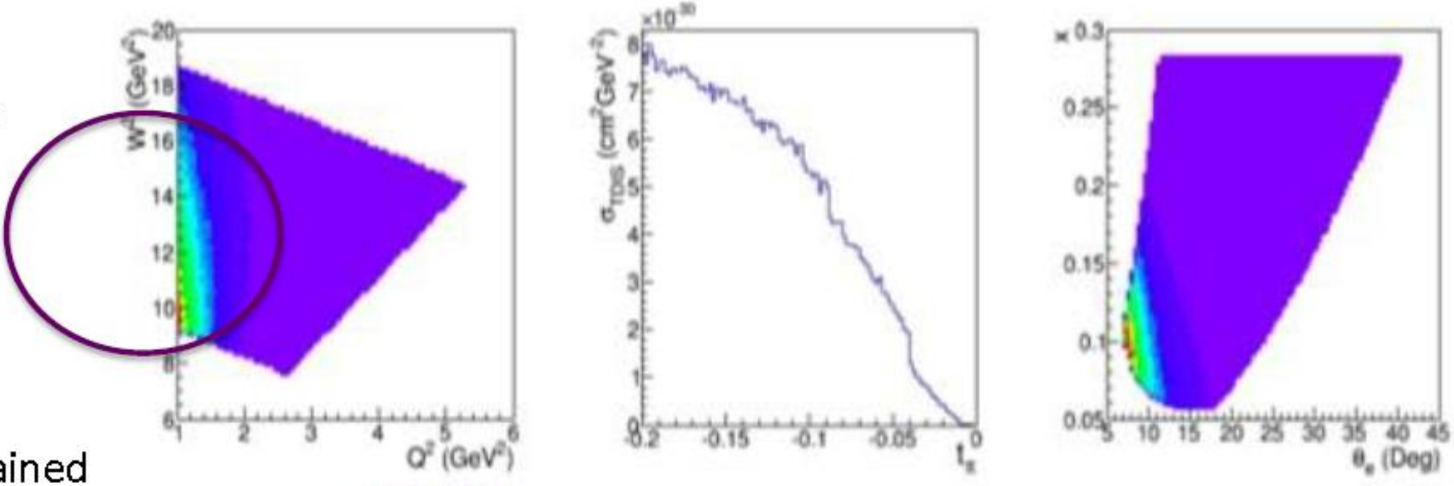
Need to…
 Add BONUS-type RTPC, requires solenoidal field
 Modify SBS for electron detection

Projected TDIS Kinematics

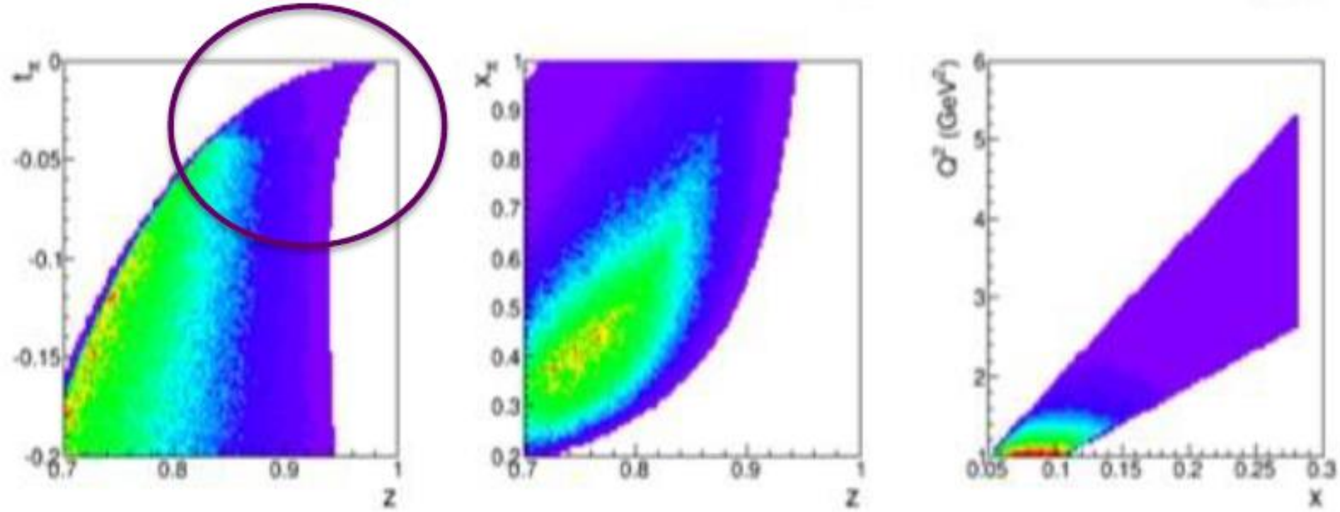
High W^2

- High M_x^2

- DIS!



All data obtained *simultaneously* at one E = 11 GeV setting, only a target change – will run hydrogen and deuterium (neutron)



Low t, high (1-z)

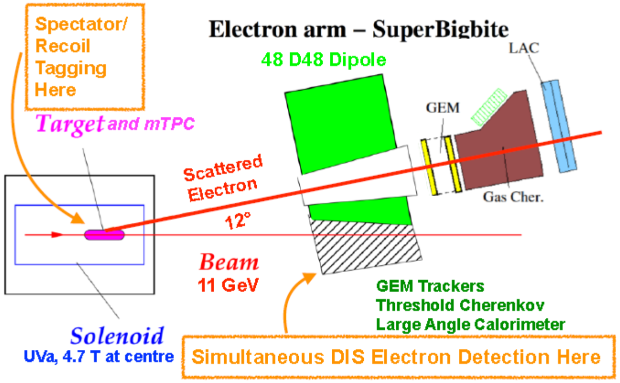
x range ~ 0.1

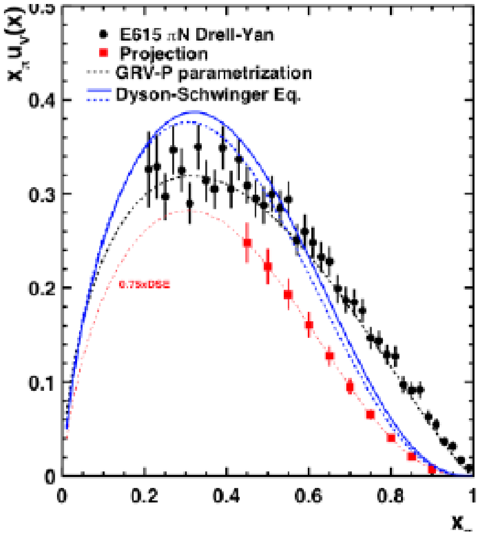
$1 < Q^2 < 2$ GeV^2

JLab 12 Projected Structure Functions

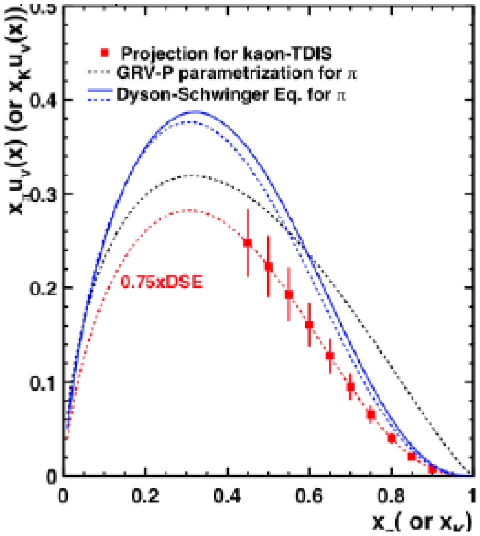
- A comparison of the x–dependence of the pion structure function deduced from Sullivan process and the pionic Drell–Yan process would provide a very stringent test of the OPE model.

- E12-15-006 (π), E12-15-006A (K) to measure $^1\mathrm{H}(e,e'p)X$, $^2\mathrm{H}(e,e'pp)X$ Tagged DIS for $8<W^2<18$ GeV^2, $1<Q^2<3$ GeV^2, $0.05<x<0.2$
- Super BigBite in Hall A for scattered e' Radial TPC for recoil p, pp, $\Lambda\rightarrow p\pi^-$





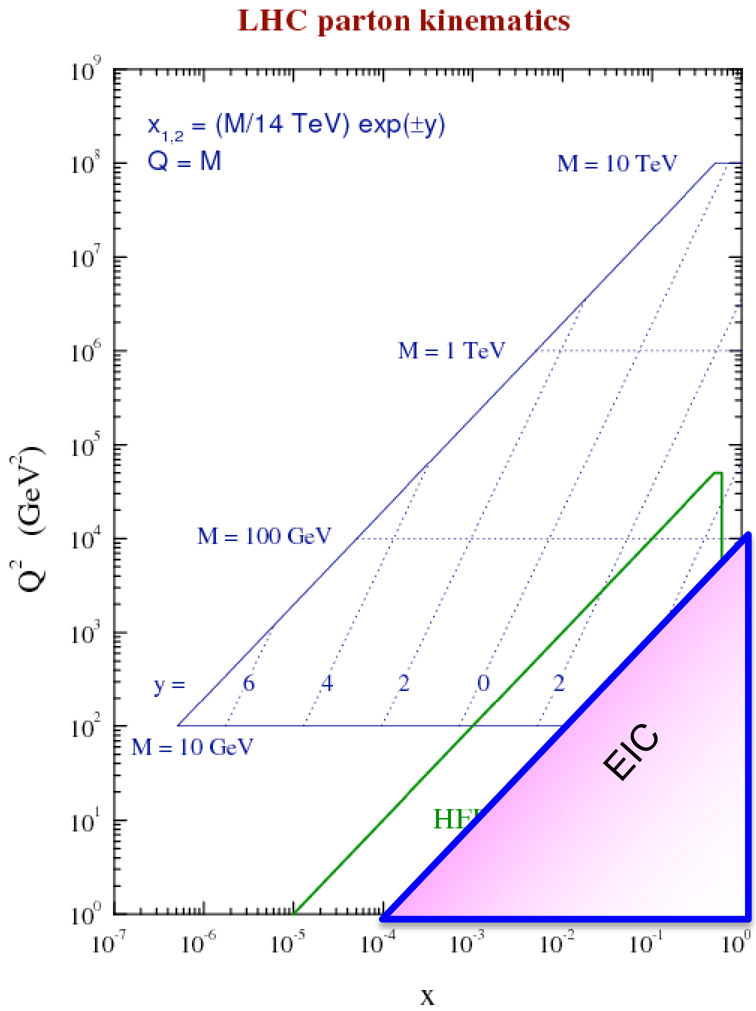
Pion



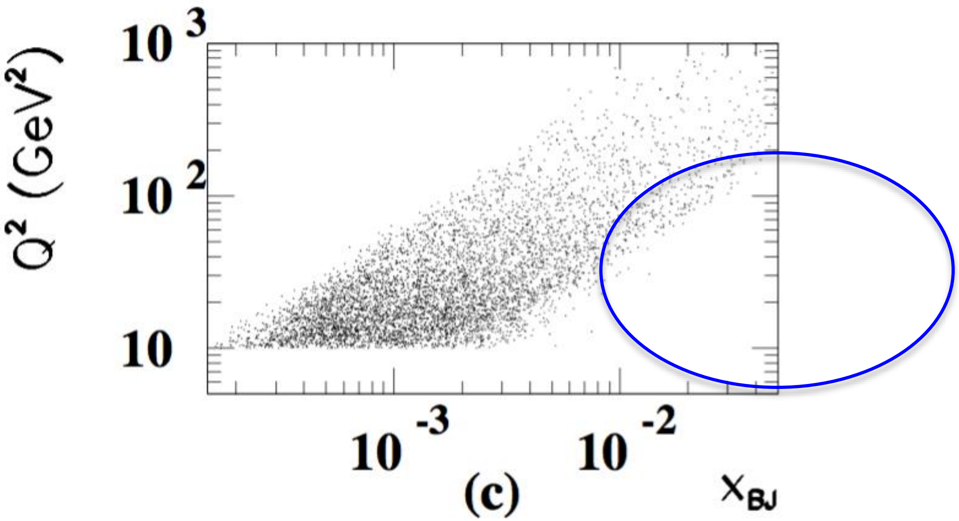
Kaon

- Projected valence quark distribution as a function of $x_{\pi/K}$
- Results from Drell Yan E615
- GRV-P parameterisation and DSE for pion only
- 5% systematic uncertainty in pion flux assumed, total systematic uncertainty of 8.4% included

Measurement Possibilities at EIC


LHC parton kinematics

Events at HERA



HERA did not plan on doing forward physics:

FNC came as an after-thought (poor acceptance, limited space)

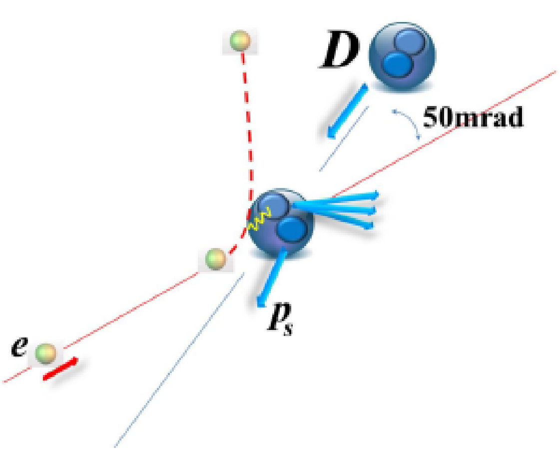
HERA had difficulty reaching higher-x

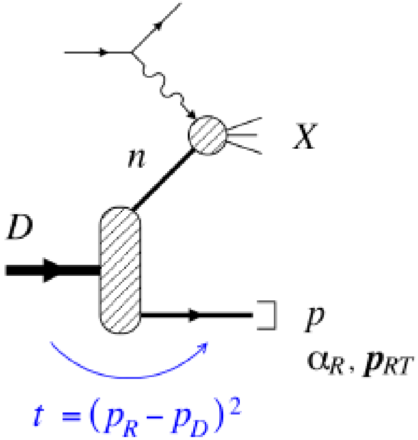
- Luminosity was relatively low
- Detectors were not designed for high-x measurements at lower Q^2

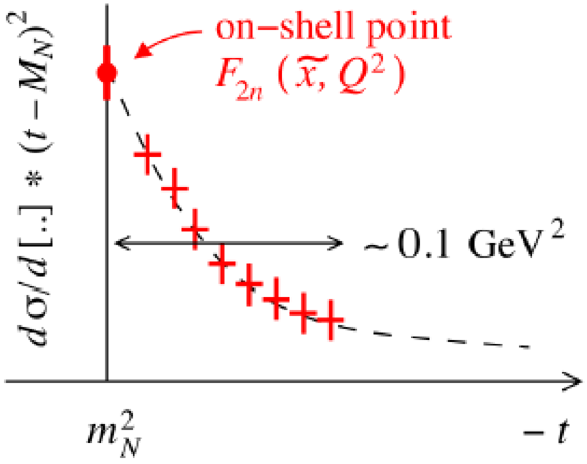
Quarks and Gluons in Pions and Kaons

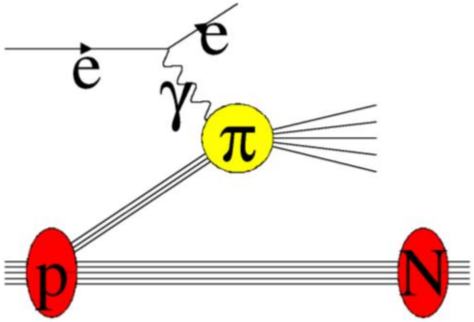
- ☐ **At low x to moderate x,** both the quark sea and the gluons are very interesting.
  - ➢ Are the sea in pions and kaons the same in magnitude and shape?
  - ➢ Is the origin of mass encoded in differences of gluons in pions, kaons and protons, or do they in the end all become universal?
- ☐ **At 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, effects of gluons come in as well. To measure these differences would be fantastic.

EIC – Versatility is Key







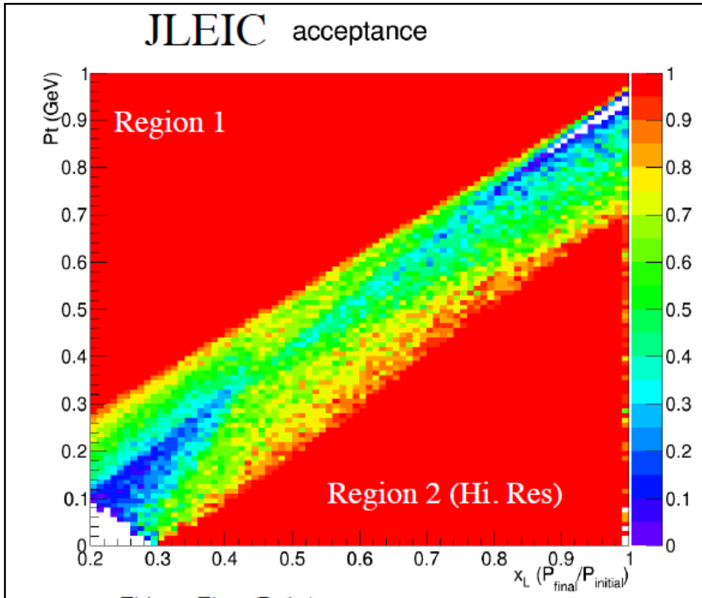


- Obtain F_2^n by tagging spectator proton from e-d, and extrapolate to on-shell neutron to correct for binding and motion effects.
- Obtain F_2^π and F_2^K by Sullivan process and extrapolate the measured t-dependence as compared to DSE-based models.

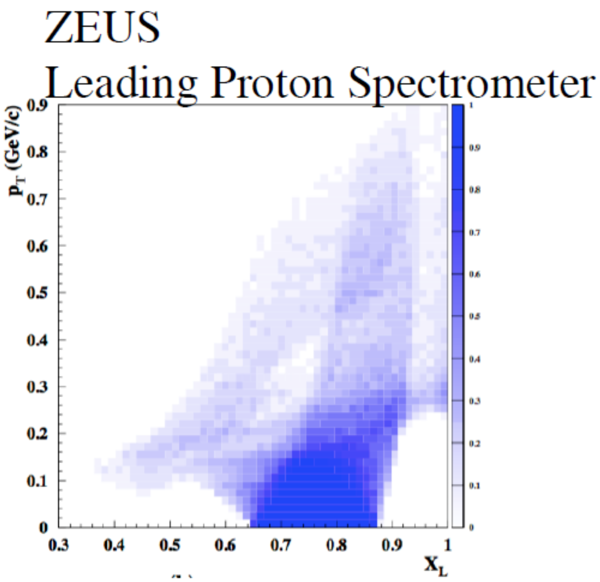
Need excellent detection capabilities, and good resolution in –t

Full Acceptance for Forward Physics!

Example: acceptance for p' in e + p → e' + p' + X



Zhiwen Zhao (Duke)

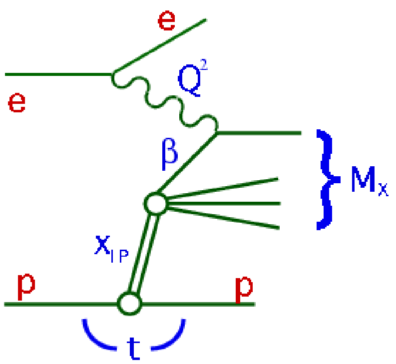


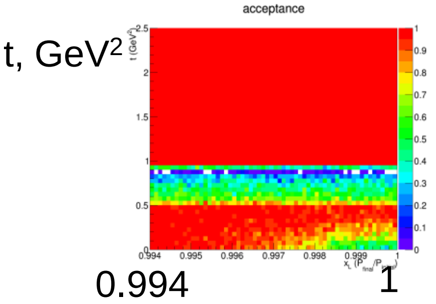
Acceptance in diffractive peak (X_L>~.98)

ZEUS: ~2%

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

Diffraction

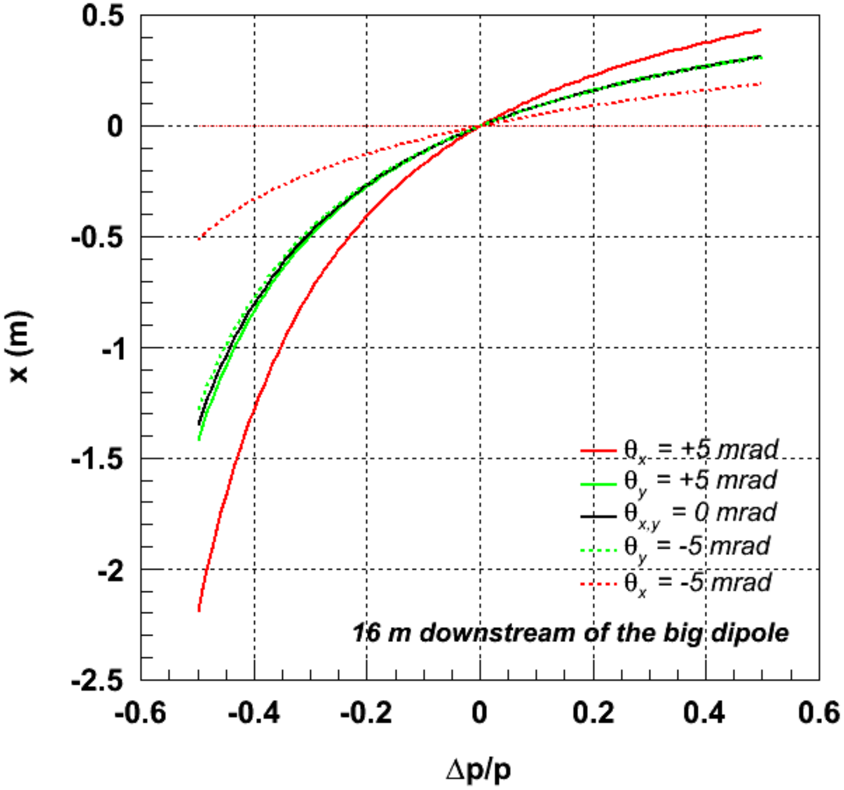




Huge gain in acceptance for diffractive physics and forward tagging to measure F_2^n!!!

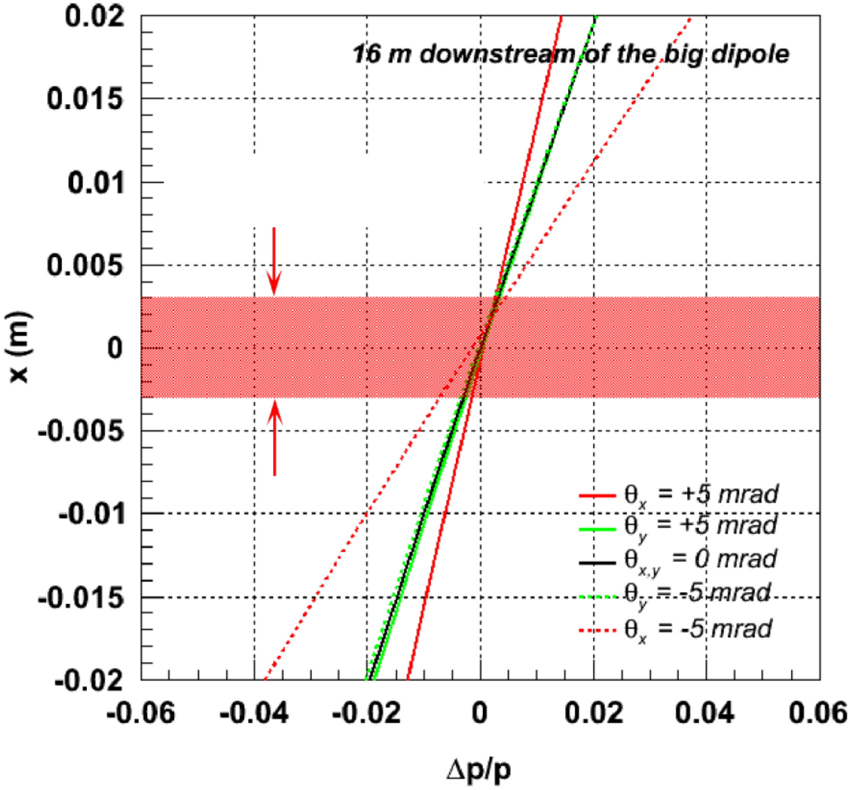
Resolution for Charged Particles

Protons with Δp/p spread launched at different angles to nominal trajectory



↓ electron beam

$|\Delta p/p| > 0.005$ @ $\theta_{x,y} = 0$



For ZEUS LPS: resolution in X_L was about 0.5% and Pt resolution was 5 MeV

Resolution for Neutral Particles

- $E_{EIC} = E_{HERA}/10$, so now neutrons are ~50 GeV

- $65\%/\sqrt{E} \rightarrow 9\%$ resolution

- ZEUS Uranium-Scintillator Calorimeter was $35\%/\sqrt{E}$ so 5% resolution.

- Is this good enough? Do we need something better? What is the position resolution we need?

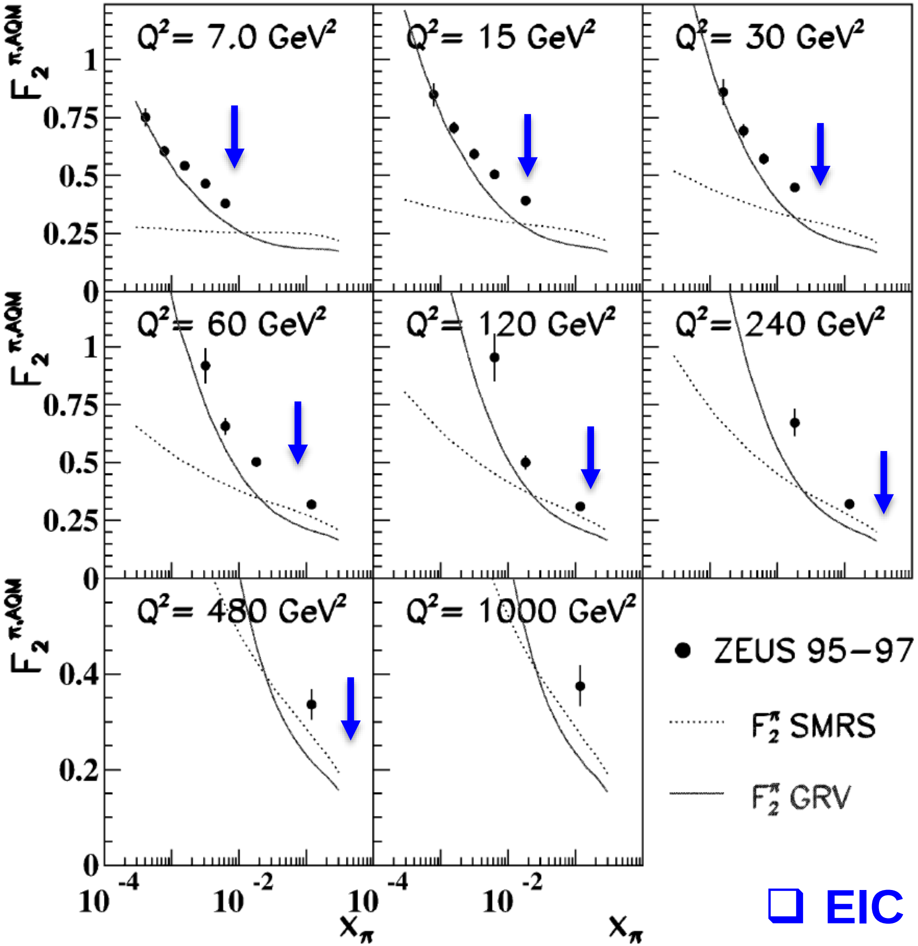
- What about $\Lambda \rightarrow n\, \pi$? 36% br. Is it possible? Better acceptance than $p\, \pi$? Can we reconstruct this?

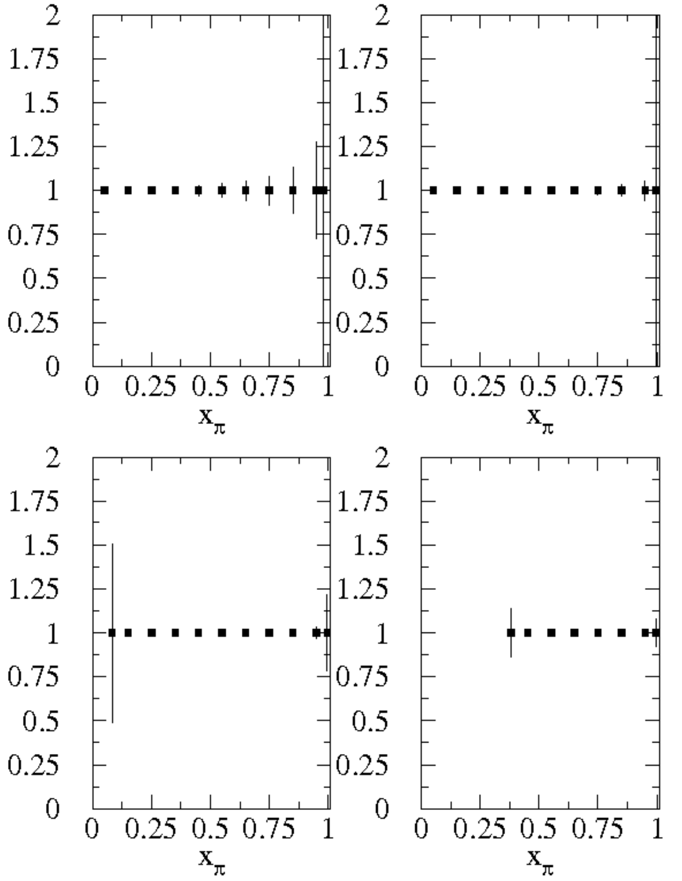
World Data on pion structure function F_2^{π}

HERA

↓ x_{min} for EIC

Here example for 5 GeV e^- and 50 GeV p





- **EIC kinematic reach down to a few $x=10^{-3}$**
- **Lowest x constrained by HERA**

Towards Kaon Structure Functions

- ☐ To determine projected kaon structure function data from pion structure function projections, we scaled the pion to the kaon case with the *coupling constants*

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

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

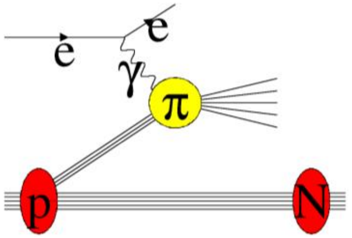
(these values can vary depending on what model one uses, so sometimes a range is used, *e.g.*, 13.1-13.5 for $g_{\pi NN}$)

- ☐ Good geometric detection

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%

- ☐ Folding this together: kaon projected structure function data will be roughly of similar quality as the projected pion structure function data for the small-t geometric forward particle detection acceptances at JLEIC.

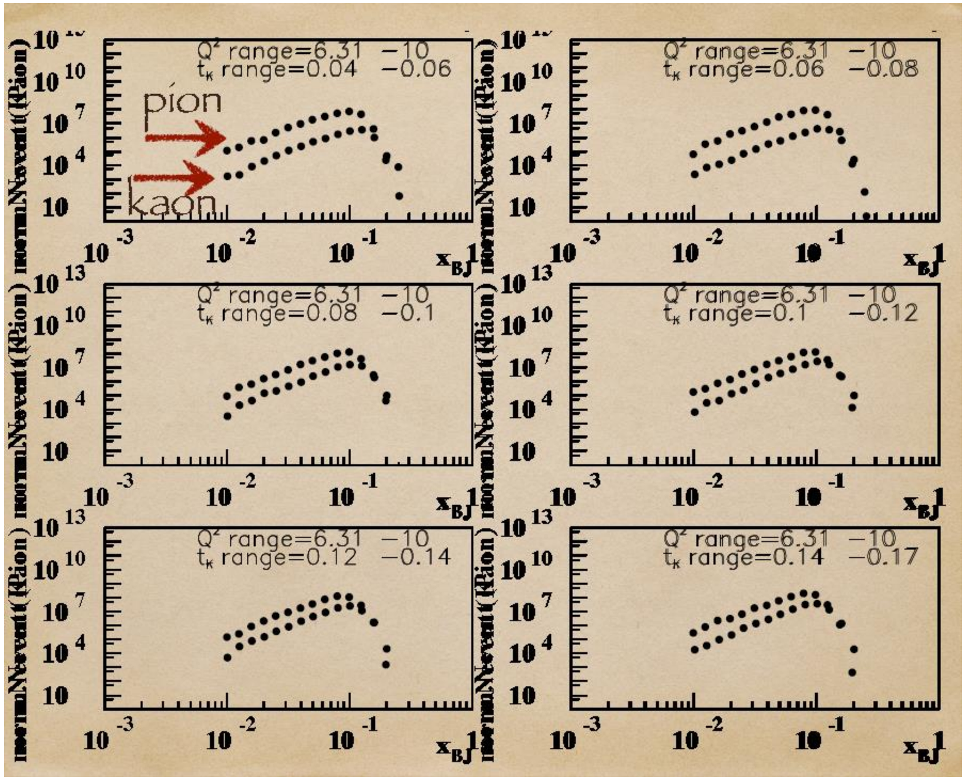
Sullivan process off-shellness corrections



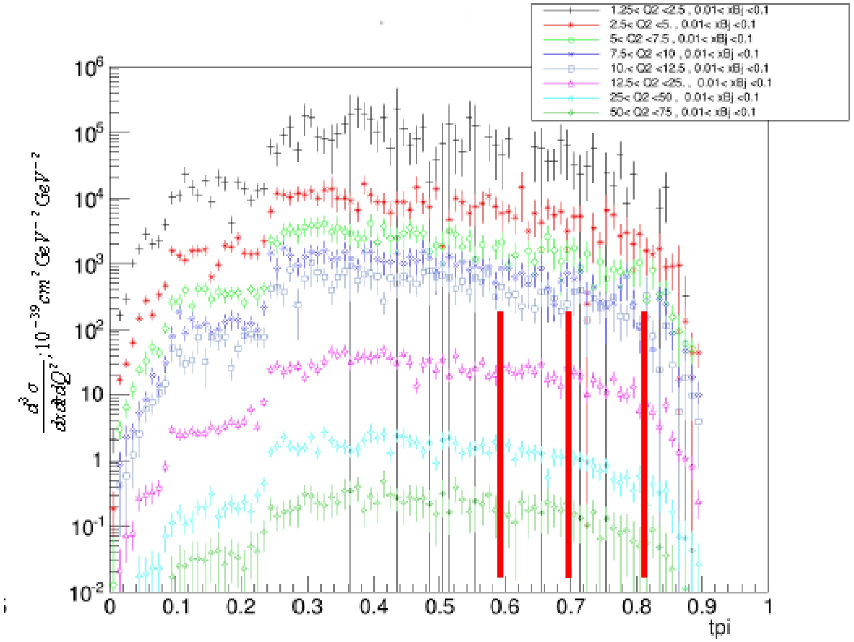
- Like nuclear binding corrections (neutron in deuterium)
- Bin in t to determine the off-shellness correction
- Compare with Pionic/kaonic D-Y

EIC kinematic reach down to x=0.01 or a bit below

Figure from K. Park

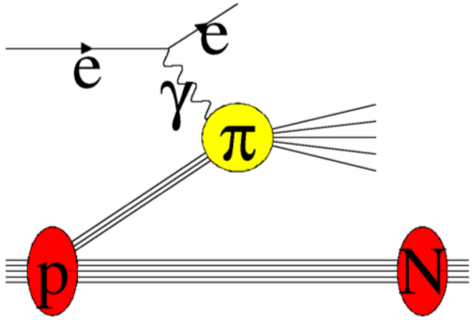


V. Berdnikov, T. Horn, R. Trotta

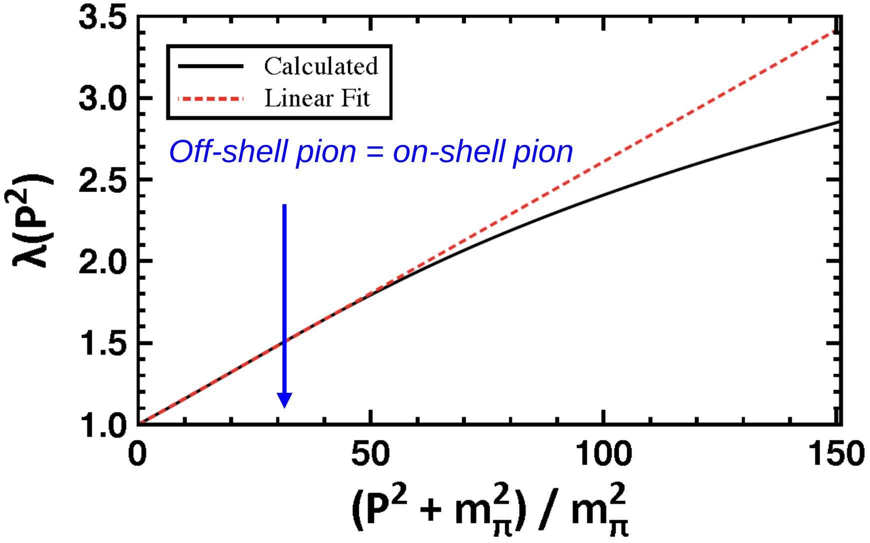


Off-shellness considerations

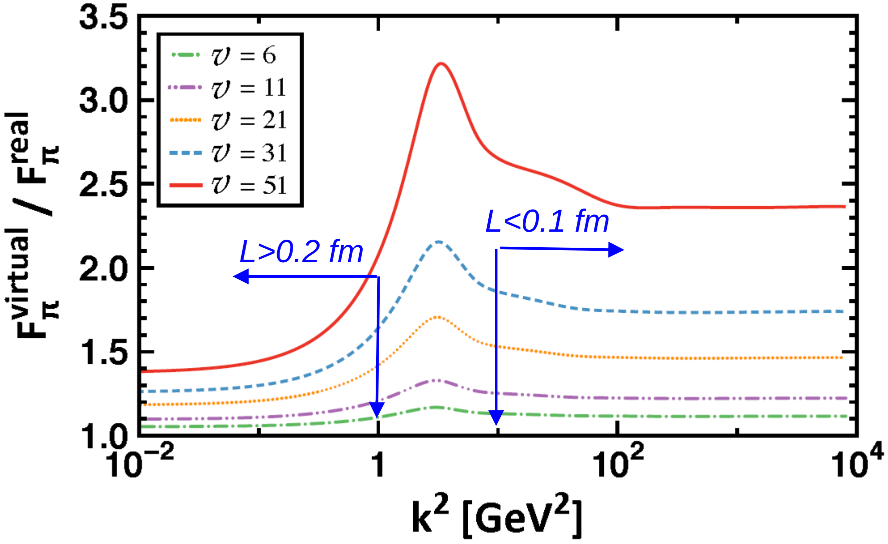
S-X Qin, C.Chen, C. Mezrag, C.D. Roberts, arXiv:1702.06100 (2017)



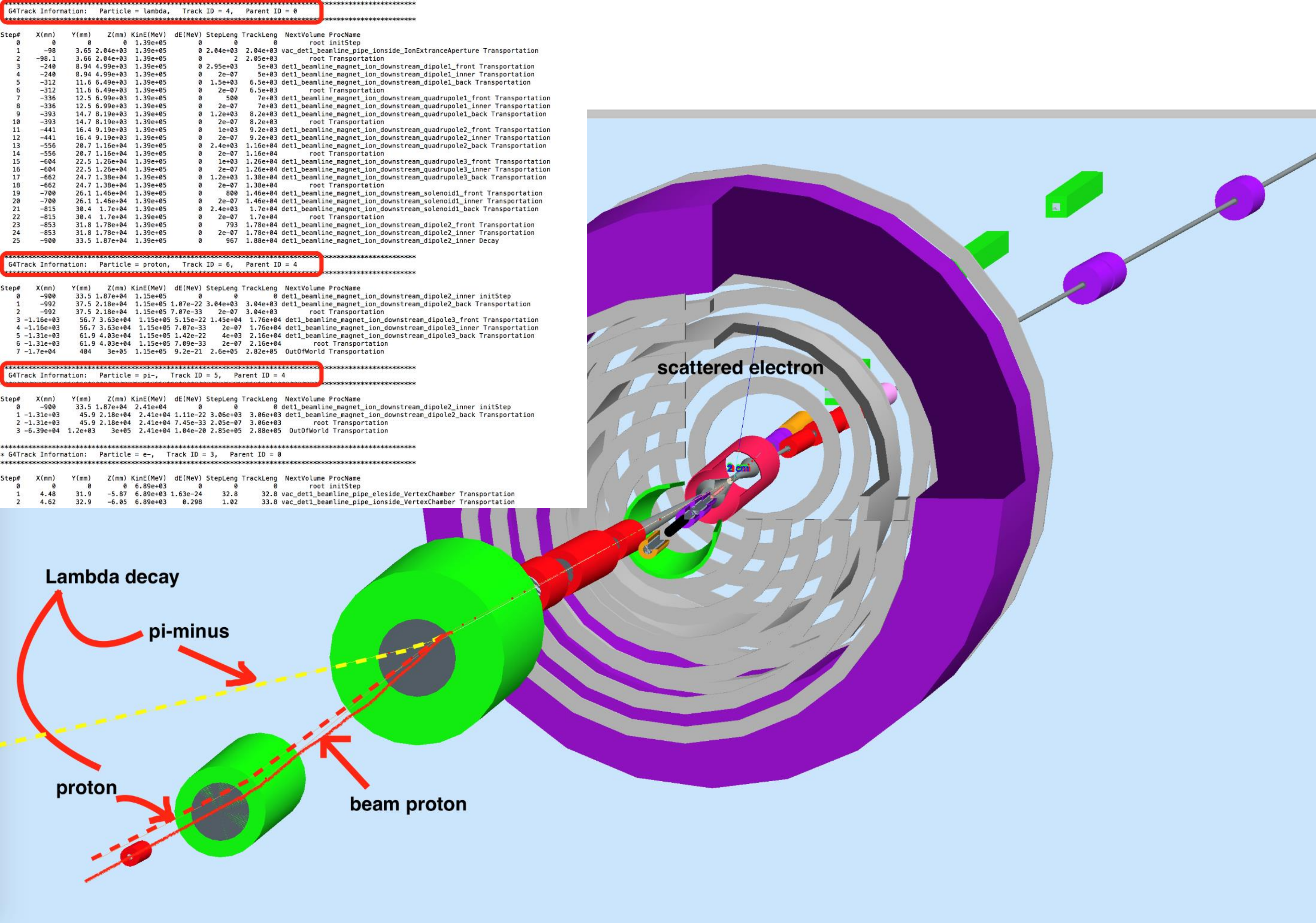
In the Sullivan process, the mesons in the nucleon cloud are virtual (off-shell) particles



- 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 ($\nu=31$) 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



```
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Step#    X(mm)    Y(mm)    Z(mm) KinE(MeV)  dE(MeV) StepLeng TrackLeng  NextVolume ProcName
    0        0        0        0  1.39e+05        0        0         0       root initStep
    1      -98     3.65 2.04e+03  1.39e+05        0 2.04e+03  2.04e+03 vac_det1_beamline_pipe_ionside_IonExtranceAperture Transportation
    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
   22     -815     30.4  1.7e+04  1.39e+05        0    2e-07   1.7e+04       root Transportation
   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

*******************************************************************************************
 G4Track Information:   Particle = proton,   Track ID = 6,   Parent ID = 4
*******************************************************************************************

Step#    X(mm)    Y(mm)    Z(mm) KinE(MeV)  dE(MeV) StepLeng TrackLeng  NextVolume ProcName
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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

*******************************************************************************************
 G4Track Information:   Particle = pi-,   Track ID = 5,   Parent ID = 4
*******************************************************************************************

Step#    X(mm)    Y(mm)    Z(mm) KinE(MeV)  dE(MeV) StepLeng TrackLeng  NextVolume ProcName
    0     -900     33.5 1.87e+04  2.41e+04        0        0         0 det1_beamline_magnet_ion_downstream_dipole2_inner initStep
    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
*******************************************************************************************

Step#    X(mm)    Y(mm)    Z(mm) KinE(MeV)  dE(MeV) StepLeng TrackLeng  NextVolume ProcName
    0        0        0        0  6.89e+03        0        0         0       root initStep
    1     4.48     31.9    -5.87  6.89e+03 1.63e-24     32.8      32.8 vac_det1_beamline_pipe_eleside_VertexChamber Transportation
    2     4.62     32.9    -6.05  6.89e+03    0.298     1.02      33.8 vac_det1_beamline_pipe_ionside_VertexChamber Transportation
```
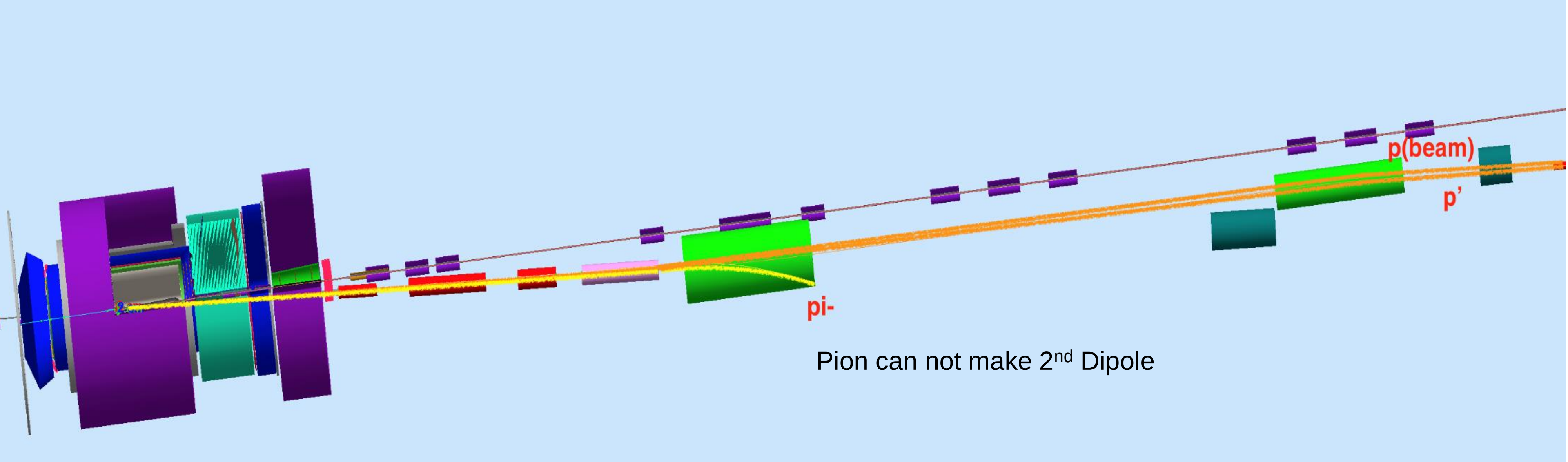
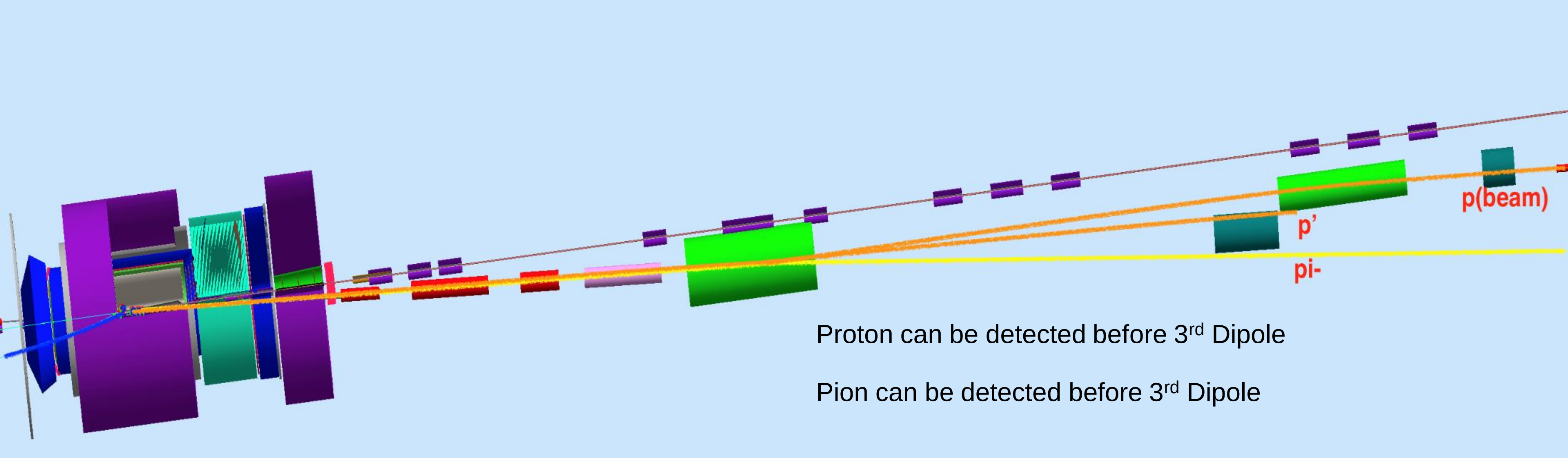

Detection of $^{1}\mathrm{H}(e,e'K^{+})\Lambda$, Λ decay to $p + \pi^{-}$



Pion can not make 2nd Dipole



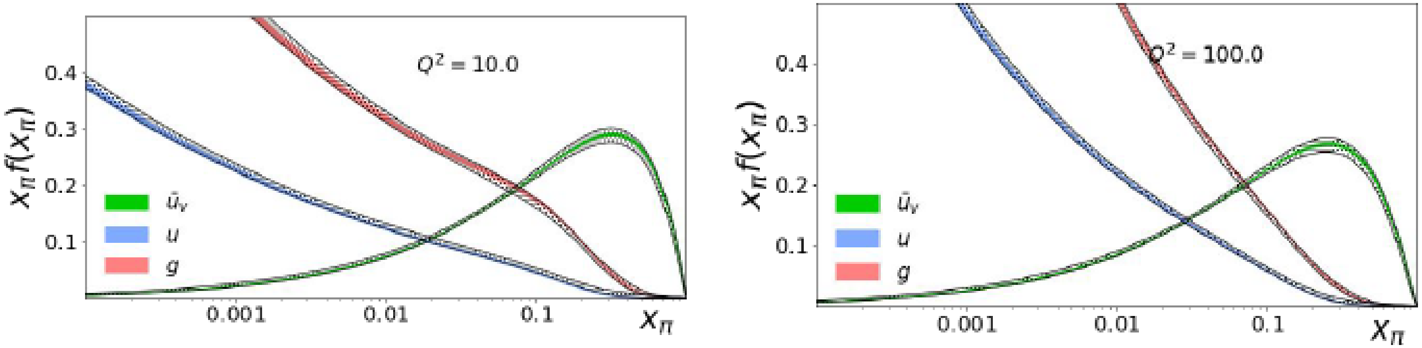
Proton can be detected before 3rd Dipole

Pion can be detected before 3rd Dipole

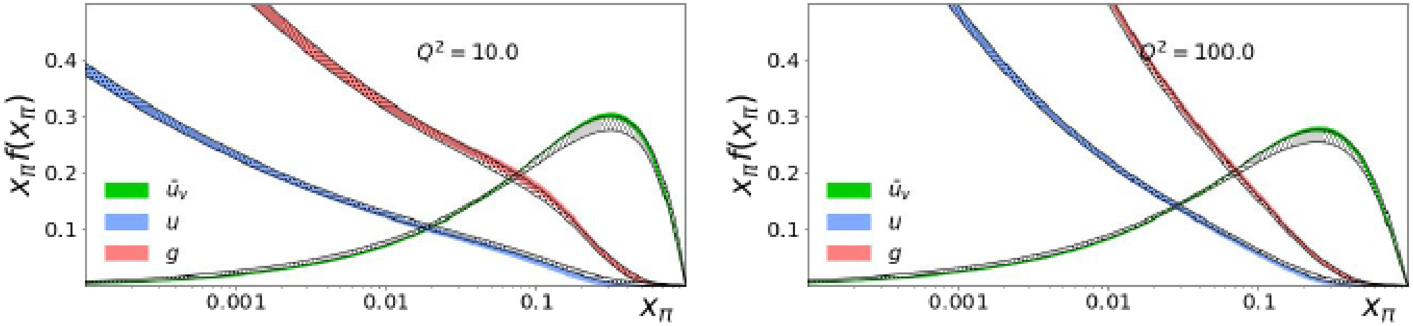
Figure from K.Park

Global Fits with Existing Data and EIC Projections

Kinematics: $\{0.01<x<0.08, 1.25<Q^2<80.0, 0.1<y_{DIS}<0.8\}$



Kinematics: $\{0.1<x<0.8, 12.5<Q^2<800, 0.1<y_{DIS}<0.8\}$



R. Trotta, N. Mecholsky, T. Horn, I. Pegg, N. Sato et al., 2018+

Work ongoing:

- The pion D-Y data, even if not many, already do constrain the curves surprisingly well – due to the various sum rules?
- Curves to improve with the EIC projections, especially for kaon as will have similar-quality data.

Precision gluon constraints of pion and kaon pdfs are possible.

Pion and Kaon Structure at EIC Workshops

https://www.jlab.org/conferences/pieic18/index.html

PIEIC2018

Workshop on Pion and Kaon Structure at an Electron - Ion Collider
May 24-25, 2018
The Catholic University of America
Washington, D.C.
Circular
This workshop will explore opportunities provided by the Electron - Ion Collider to study the quark and gluon structure of the pion and kaon. It follows and will stake stock of the progress **since the earlier June 1-2, 2017 workshop at Argonne National Lab**: http://www.phy.anl.gov/theory/pieic2017

Organizing Committee
Ian Cloet - ANL
Tanja Horn – CUA
Cynthia Keppel – JLab
Craig Roberts - ANL

Prospects

- ❑ Tagged measurements can give unique access to pion, kaon and (polarized) neutron structure

- ❑ Neutron Structure
  - ➢ ***BoNUS*** showed access to near-free neutron structure possible tagging spectator protons!
  - ➢ ***BoNUS12*** will push to constrain knowledge of u/d to large x~0.8, together with ***MARATHON***
  - ➢ ***ALERT*** run group approved to use tagging technique on few-body nuclei to study GPD of spin-0 He-4, tagged EMC effect etc.
  - ➢ Jlab ***LDRD*** made concentrated effort towards extraction of neutron structure at ***EIC*** by tagging

- ❑ Pion and Kaon Structure
  - ➢ Only limited measurements of pion structure function by tagging from HERA
  - ➢ Conditionally approved ***experiments at 12 GeV*** towards pion and kaon structure functions at large x – does resummation save the day for pion PDFs at large x?
  - ➢ Exciting prospects at ***EIC*** with tagging
    - o White Paper under development to outline science case
    - o Have to understand physical mass of pion, kaon, and nucleon (not in chiral limit)
    - o Strong consensus at PIEIC2018: understanding requires strong synergy between Lattice, QCD Continuum/Phenomenology, and EIC measurements

Summary and Outlook

- ☐ Nucleons and mesons are basic building blocks of matter – we should know their structure

- ☐ TDIS provides access to effective neutron, pion, kaon targets

- ☐ Very few experiments to date
  - ➢ Neutron and pion/kaon at 12 GeV in valence region
  - ➢ EIC will open up a new era

Collaboration with/thanks to: Elke Aschenauer, Ian Cloet, Rolf Ent, Yulia Furletova, Roy Holt, Thia Keppel, Nick Mecholsky, Rachel Montgomery, Kijun Park, Ian Pegg, Paul Reimer, Craig Roberts, Richard Trotta, Steve Wood, Rik Yoshida