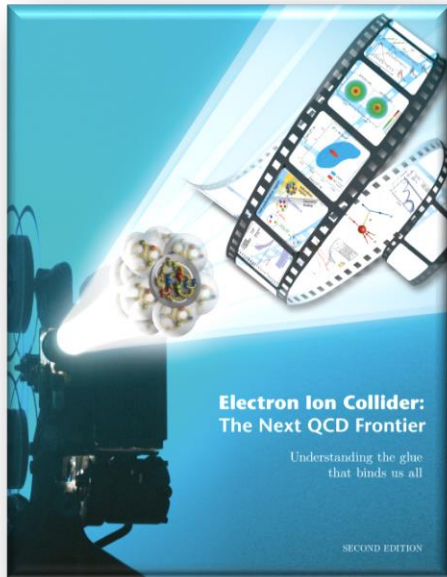


Pion and Kaon Structure Functions at an EIC



... beyond the science of ...

Tanja Horn

THE
CATHOLIC UNIVERSITY
of AMERICA



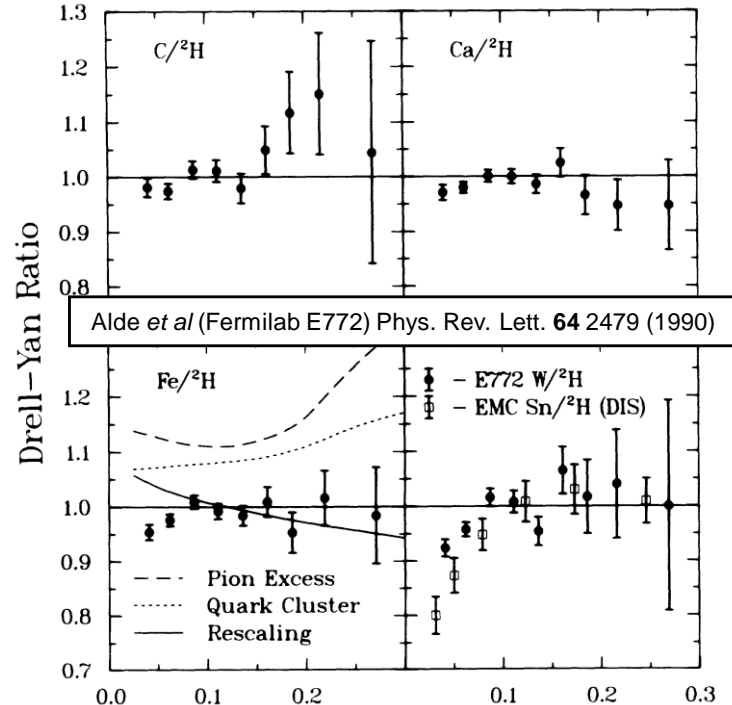
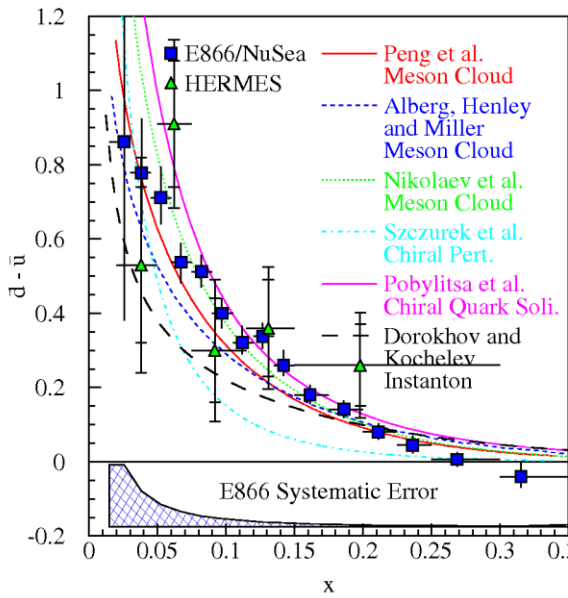
Collaboration with Ian Cloet, Rolf Ent, Roy Holt, Thia Keppel, Kijun Park, Paul Reimer, Craig Roberts, Richard Trotta, Andres Vargas

Thanks to: Yulia Furletova, Elke Aschenauer and Steve Wood

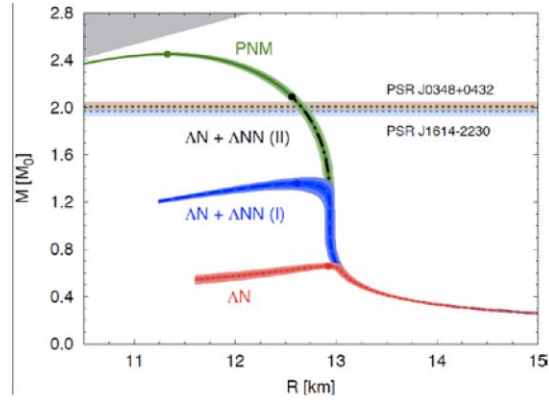
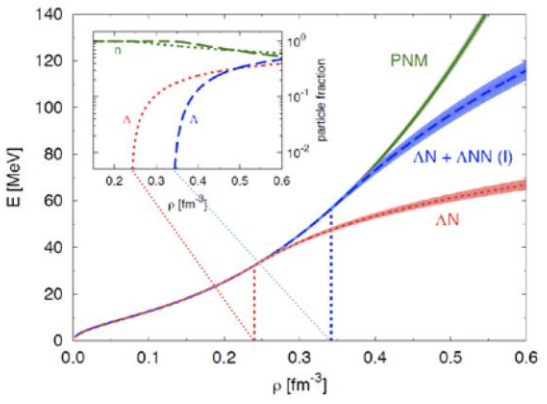
Why should you be interested in pions and kaons?

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

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

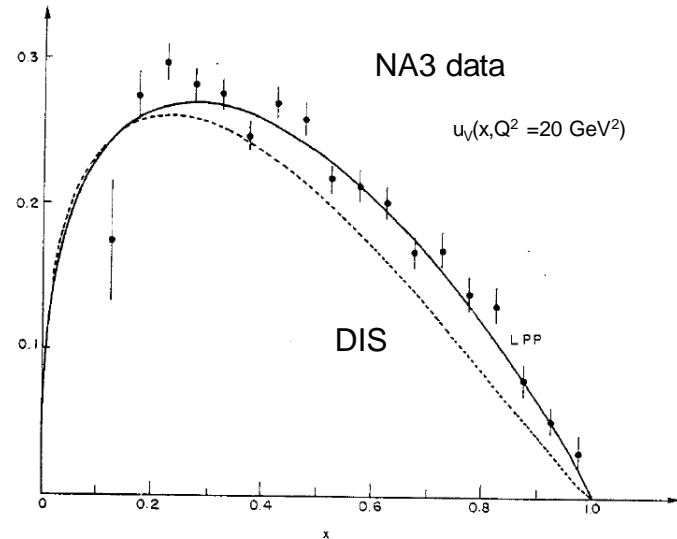
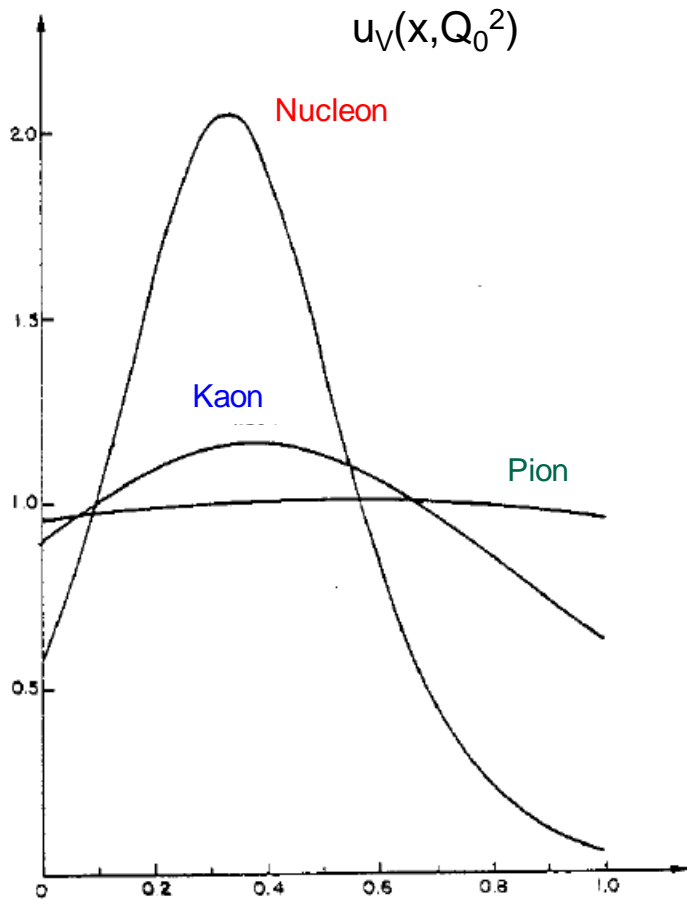


Equations of state and neutron star mass-radius relations



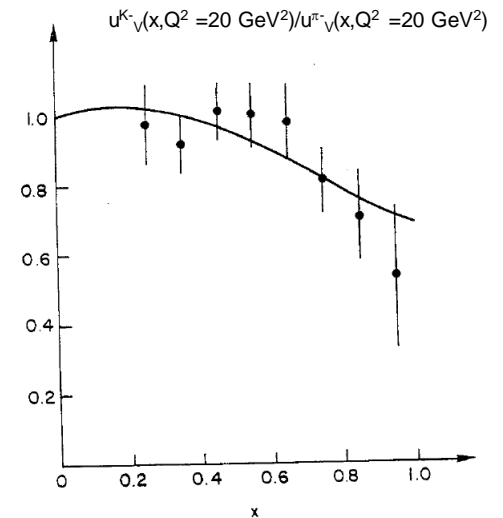
At some level an old story...

A model for nucleon, pion and kaon structure functions F. Martin, CERN-TH 2845 (1980)

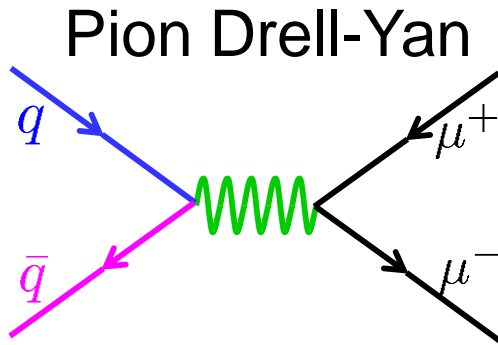


Predictions based on non-relativistic model with valence quarks only

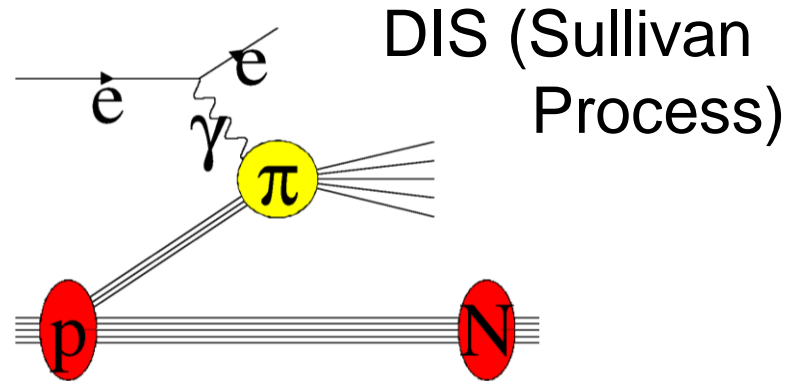
- pion/kaon differs from proton: 2- vs. 3- quark system
- kaon differs from pion owing to one heavy quark



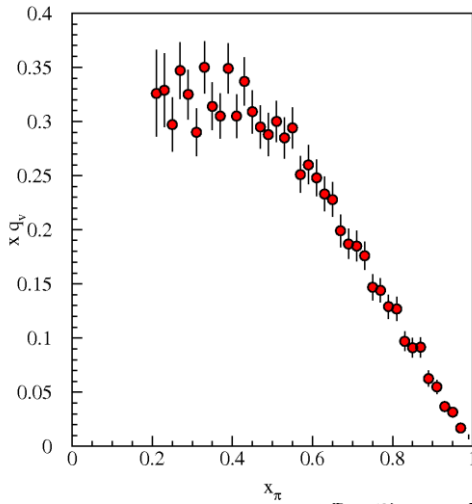
World Data on pion structure function F_2^π



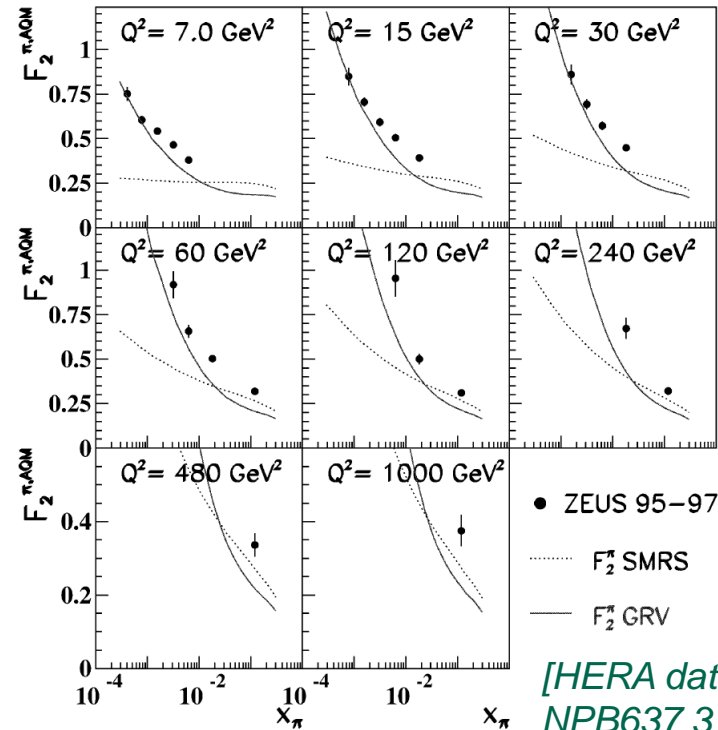
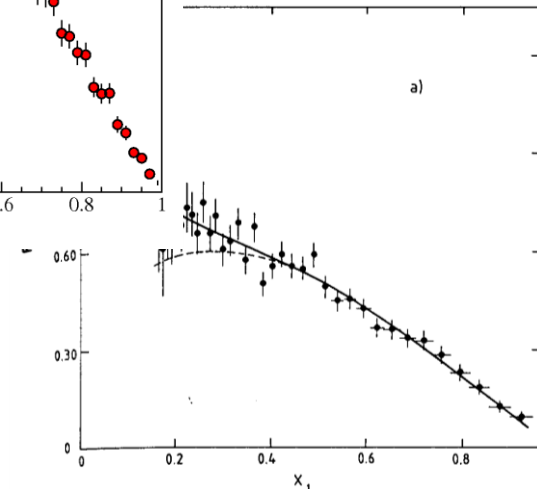
Data much more limited than nucleon...



FNAL E615



CERN NA3



• ZEUS 95-97
 F_2^π SMRS
 — F_2^π GRV
[HERA data [ZEUS, NPB637 3 (2002)]

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 $x \rightarrow 1$ 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.

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* and 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 $g_{\pi NN}$)

- 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 – to be checked for eRHIC.

See also talks by R. Yoshida and K. Park

Process	Forward Particle	Geometric Detection Efficiency (at small $-t$)
$^1\text{H}(e,e'\pi^+)n$	N	> 20%
$^1\text{H}(e,e'K^+)\Lambda$	Λ	50%
$^1\text{H}(e,e'K^+)\Sigma$	Σ	17%

Landscape for p , π , K structure function after EIC

Proton: much existing from HERA

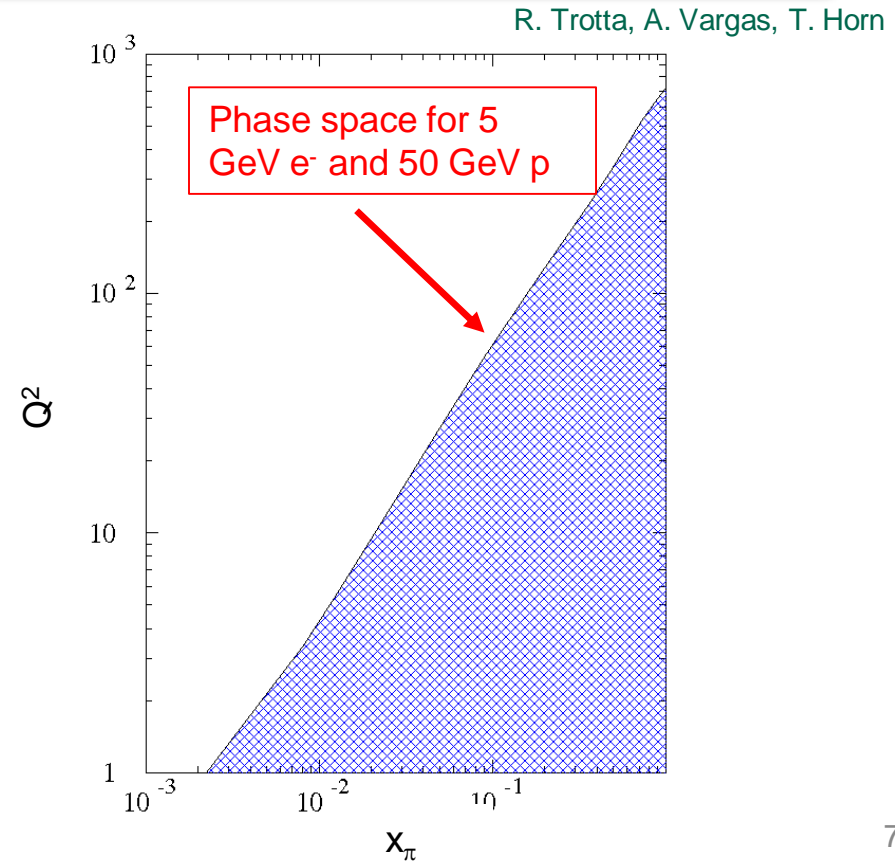
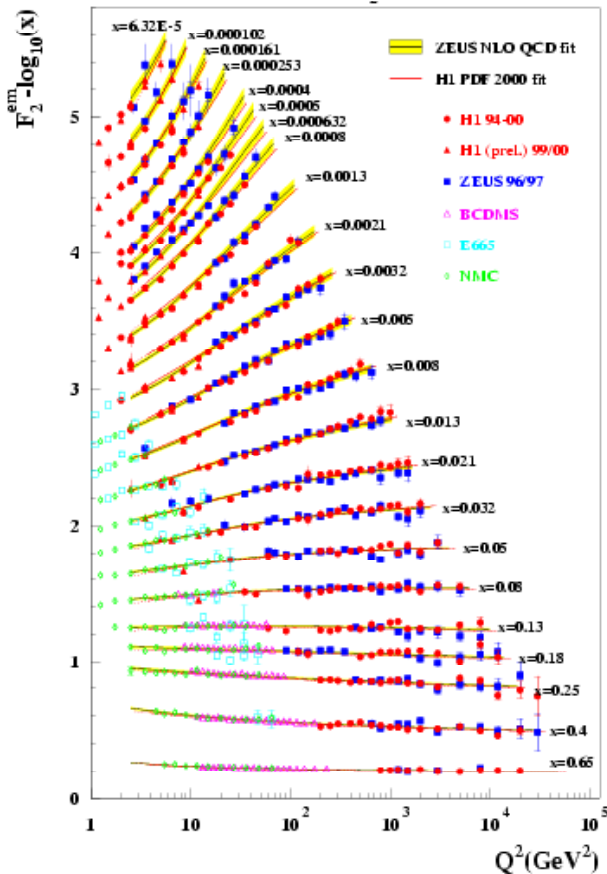
EIC will add:

- Better constraints at large- x
- Precise F_2^n neutron SF data

Pion and kaon: only limited data from:

- Pion and kaon Drell-Yan experiments
- Some pion SF data from HERA

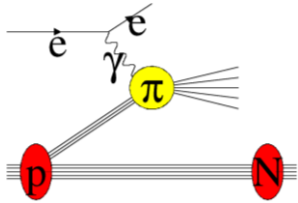
EIC will add large (x, Q^2) landscape for both pion and kaon!



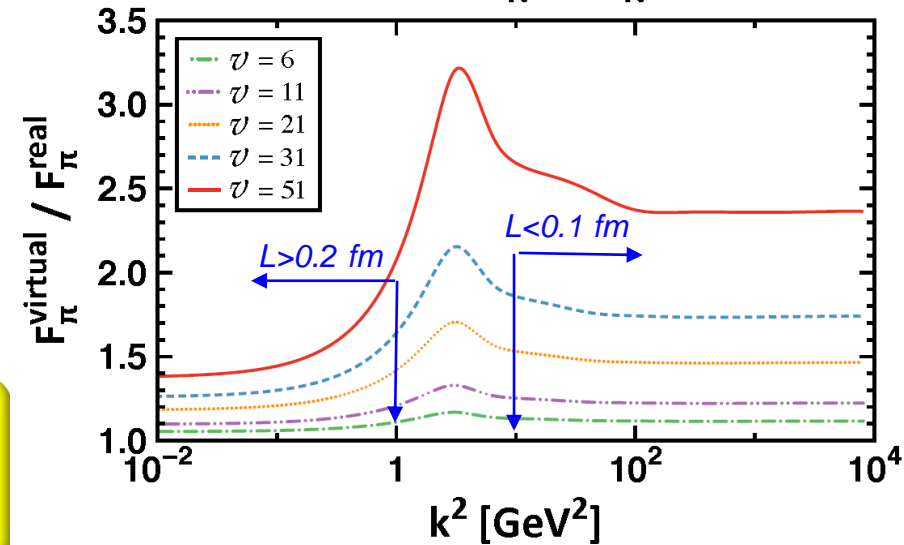
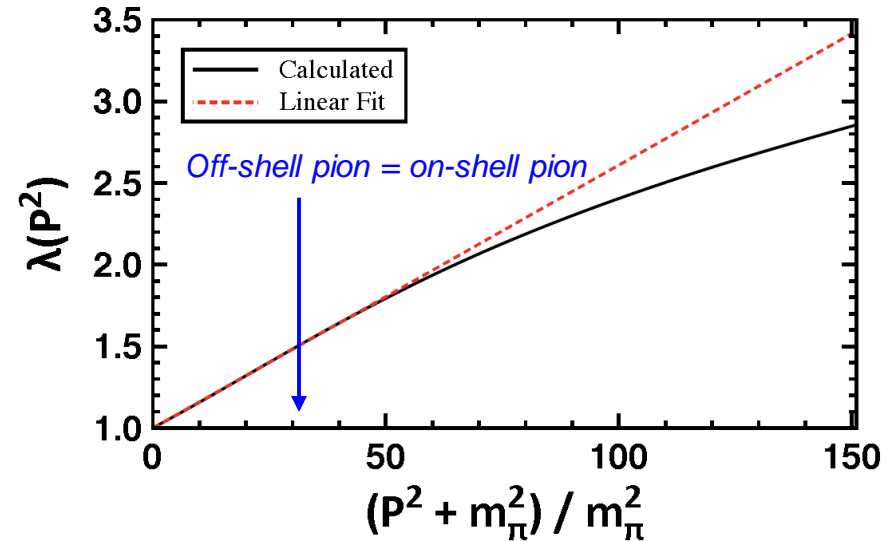
R. Trotta, A. Vargas, T. Horn

Off-shellness considerations

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

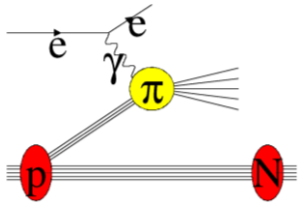


- ❑ In the Sullivan process, the mesons in the nucleon cloud are virtual (off-shell) particles
- ❑ Recent calculations estimate the effect in the BSE/DSE framework – as long as $\lambda(v)$ is linear in v , the meson pole dominates
 - Within the linearity domain, alterations of the meson internal structure can be analyzed through the amplitude ratio
- ❑ *Off-shell meson = On-shell meson* for $t < 0.6 \text{ GeV}^2$ ($v = 31$) for pions and $t < 0.9 \text{ GeV}^2$ ($v_s \sim 3$) for kaons



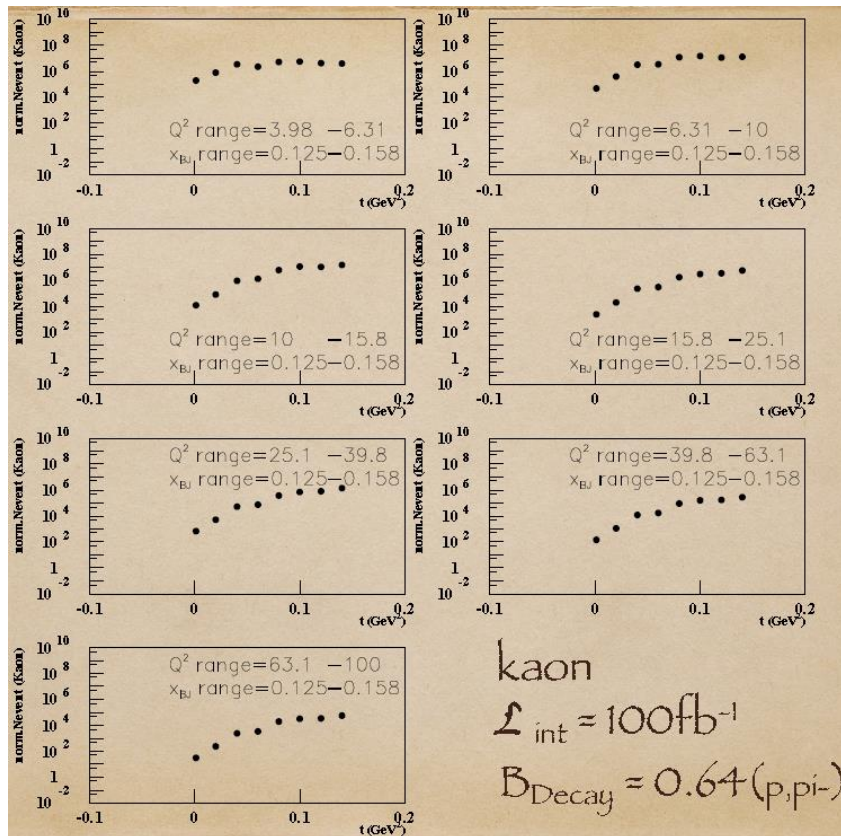
This means that pion and kaon structure functions can be accessed through the Sullivan process

Sullivan process off-shellness corrections



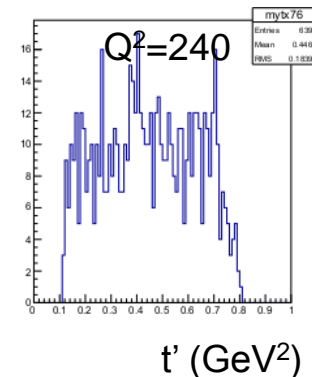
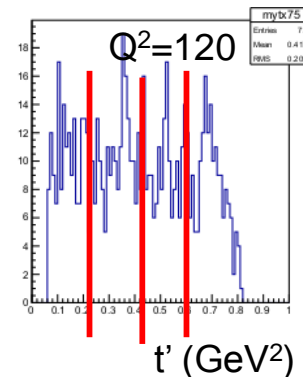
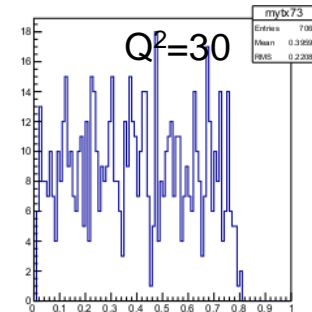
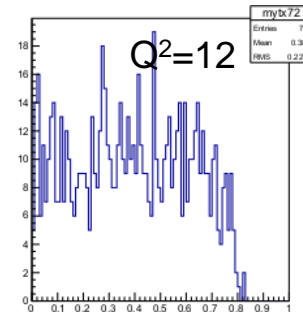
- Like nuclear binding corrections (neutron in deuterium)
- Bin in t to determine the off-shellness correction
- Pionic/kaonic D-Y

Figure from K. Park



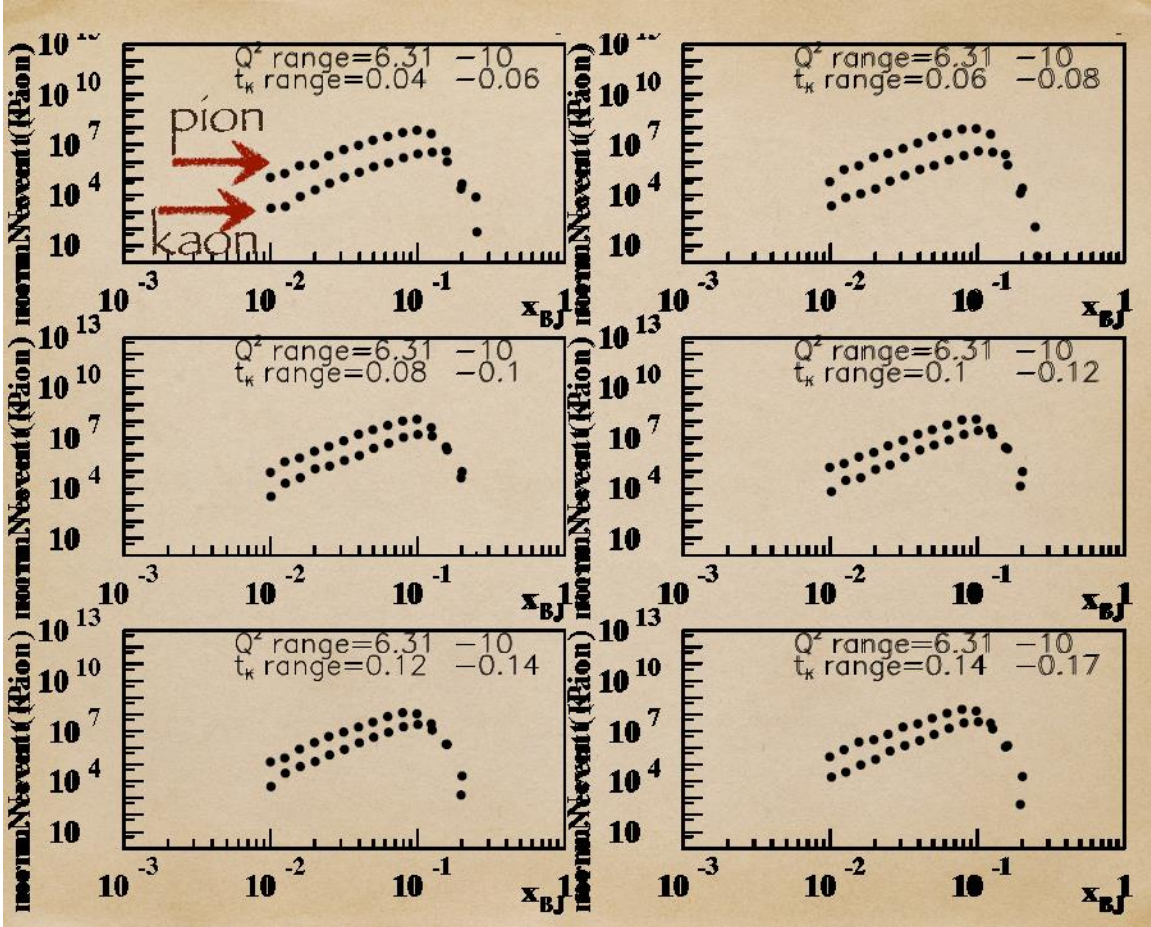
$x=0.75$

R. Trotta, A. Vargas, T. Horn



Pion/kaon SF – EIC kinematic reach

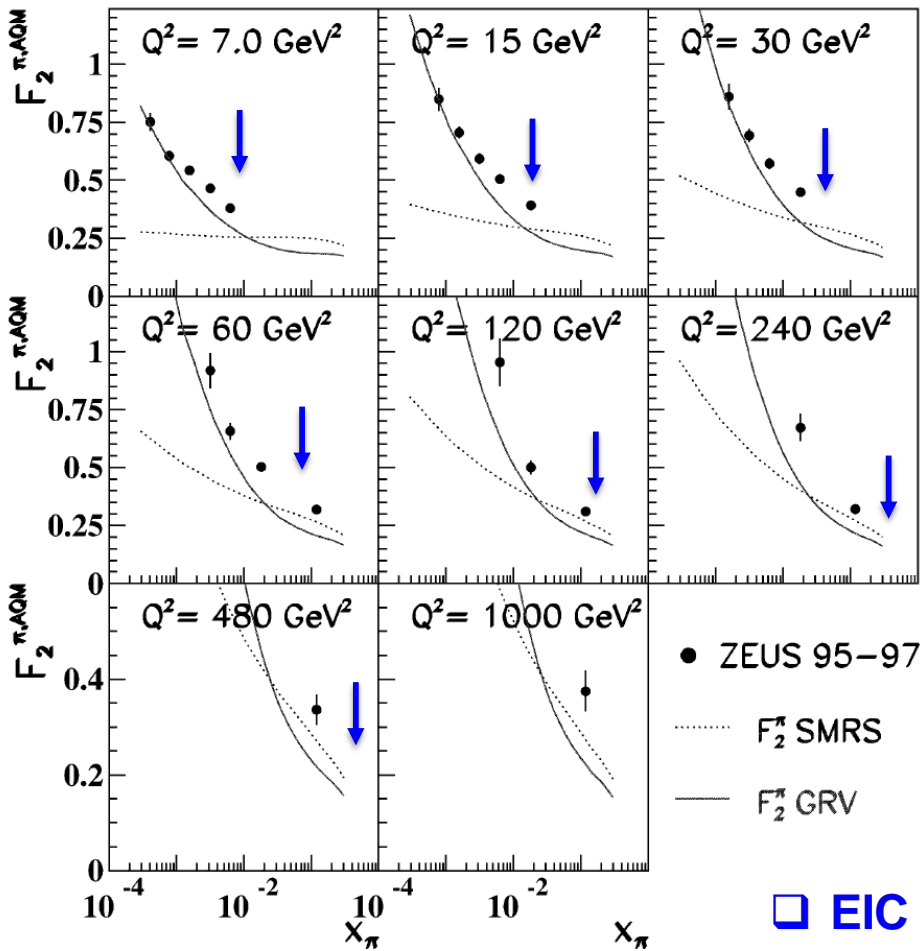
Figure from K. Park



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

World Data on pion structure function F_2^π

HERA



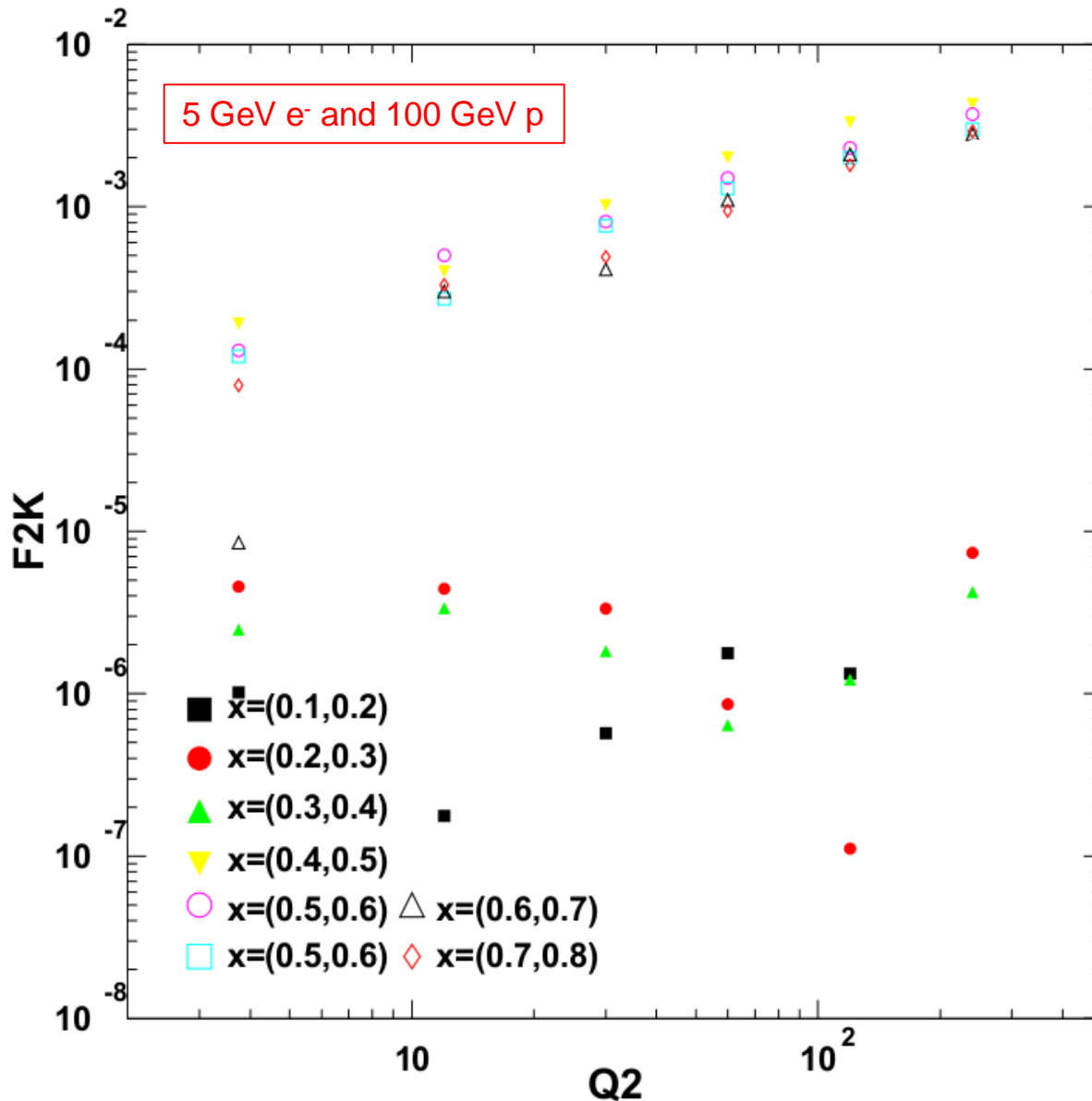
EIC

↓ roughly x_{min} for EIC projections

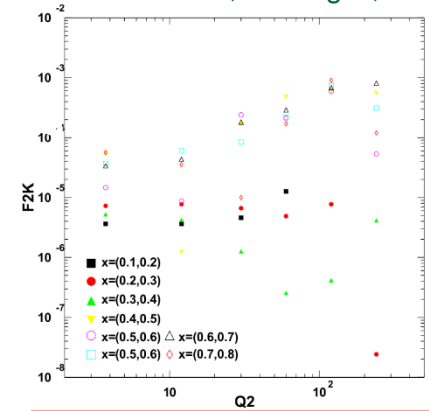
For 5 GeV e^- and 50 GeV p
@ luminosity $10^{34} \text{ s}^{-1} \text{ cm}^{-2}$

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

Constraining gluons with Q^2 dependence

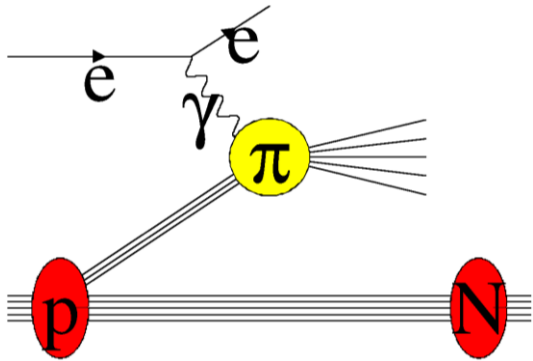


R. Trotta, A. Vargas, T.Horn



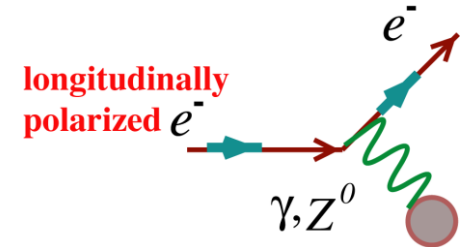
□ For small x -range Q^2 evolution may not be enough – direct photons?

Electroweak Pion and Kaon Structure Functions



- ❑ The Sullivan Process will be sensitive to u and d for the pion, and likewise u and s for the kaon.
- ❑ Logarithmic scaling violations may give insight on the role of gluon pdfs
- ❑ Could we make further progress towards a flavour decomposition?

- 1) Using the Neutral-Current Parity-violating asymmetry A_{PV}
- 2) Determine $x F_3$ through neutral/charged-current interactions



In the parton model:

$$F_2^\gamma = \sum_q e_q^2 x (q + \bar{q})$$

$$F_2^{\gamma Z} = 2 \sum_q e_q g_V^q x (q + \bar{q})$$

$$x F_3^{\gamma Z} = 2 \sum_q e_q g_A^q x (q - \bar{q})$$

Use different couplings/weights

Use isovector response

$$F_2^{W^+} = 2x(\bar{u} + d + s + \bar{c}) \quad F_3^{W^+} = 2(-\bar{u} + d + s - \bar{c}) \quad F_2^{W^-} = 2x(u + \bar{d} + \bar{s} + c) \quad F_3^{W^-} = 2(u - \bar{d} - \bar{s} + c)$$

- 3) Or charged-current through comparison of electron versus positron interactions

$$A = \frac{\sigma_R^{CC,e^+} \pm \sigma_L^{CC,e^-}}{\sigma_R^{NC} + \sigma_L^{NC}}$$

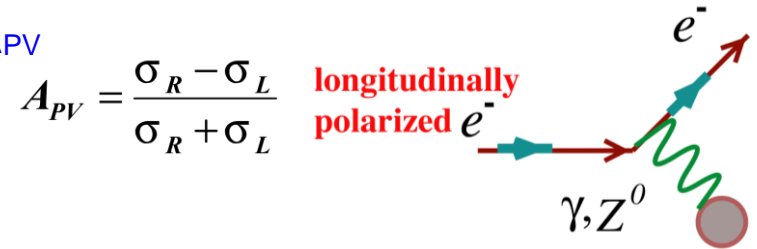
$$A = \frac{G_F^2 Q^4}{32 \pi^2 \alpha_e^2} \left[\frac{F_2^{W^+} \pm F_2^{W^-}}{F_2^\gamma} - \frac{1 - (1-y)^2}{1 + (1-y)^2} \frac{x F_3^{W^+} \mp x F_3^{W^-}}{F_2^\gamma} \right]$$

Disentangling the Flavour-Dependence

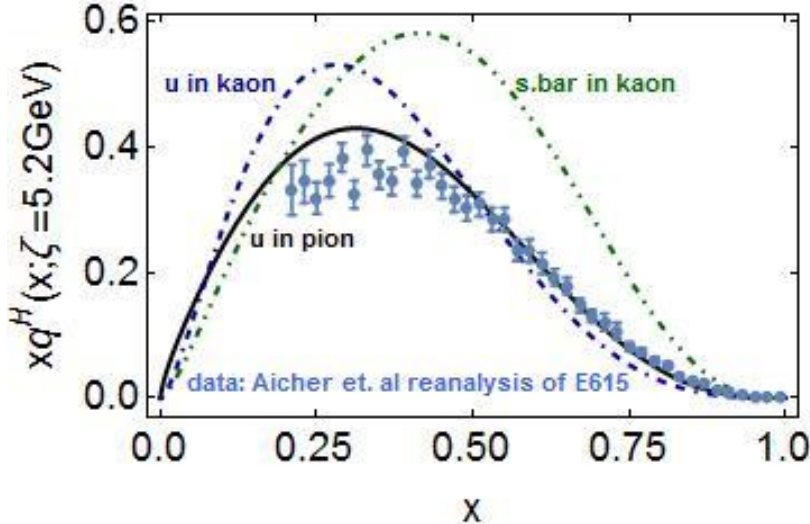
1) Using the Neutral-Current Parity-violating asymmetry A_{PV}

$$a_{2\pi}(x) = \frac{2 \sum_q e_q g_V^q (q + \bar{q})}{\sum_q e_q^2 (q + \bar{q})} \simeq \frac{6 u_{\pi}^+ + 3 d_{\pi}^+}{4 u_{\pi}^+ + d_{\pi}^+} - 4 \sin^2 \theta_W,$$

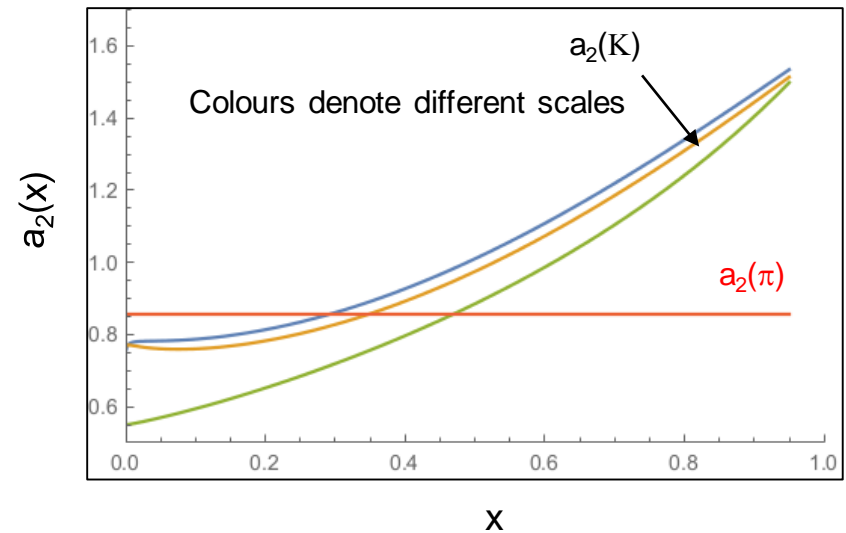
$$a_{2K}(x) = \frac{2 \sum_q e_q g_V^q (q + \bar{q})}{\sum_q e_q^2 (q + \bar{q})} \simeq \frac{6 u_K^+ + 3 s_K^+}{4 u_K^+ + s_K^+} - 4 \sin^2 \theta_W.$$



C. Chen et al., Phys. Rev. D93 (2016), 11



Calculation by C.D. Roberts et al.



Parton distributions in pion and kaon

a_2 picks up different behaviour of u and $s\bar{b}$.
Flavour decomposition in kaon possible?

Electroweak pion/kaon SF with positrons

NC, $e^+p \approx 10 \times 100 \text{ GeV}^2$

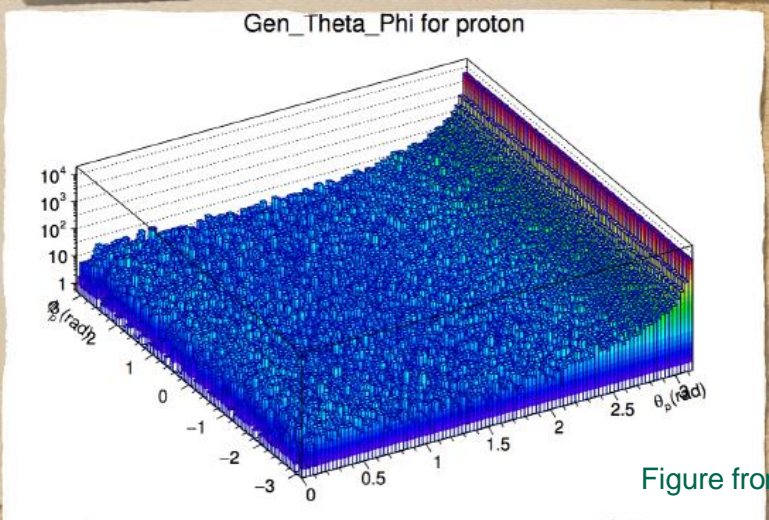
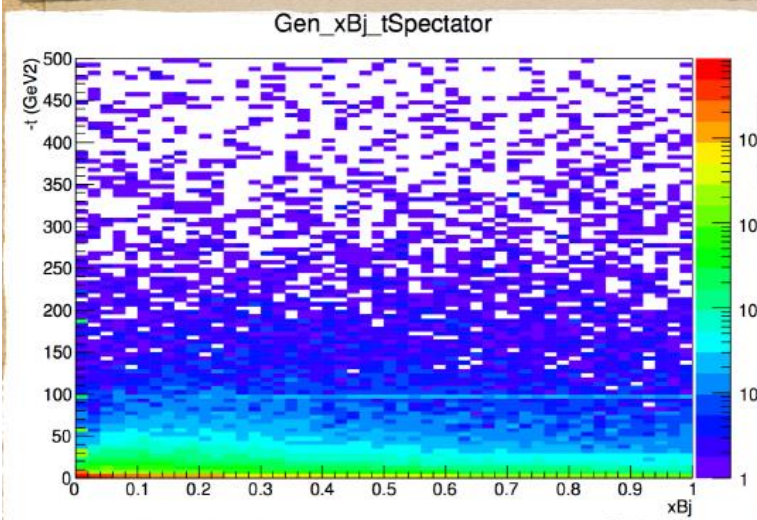
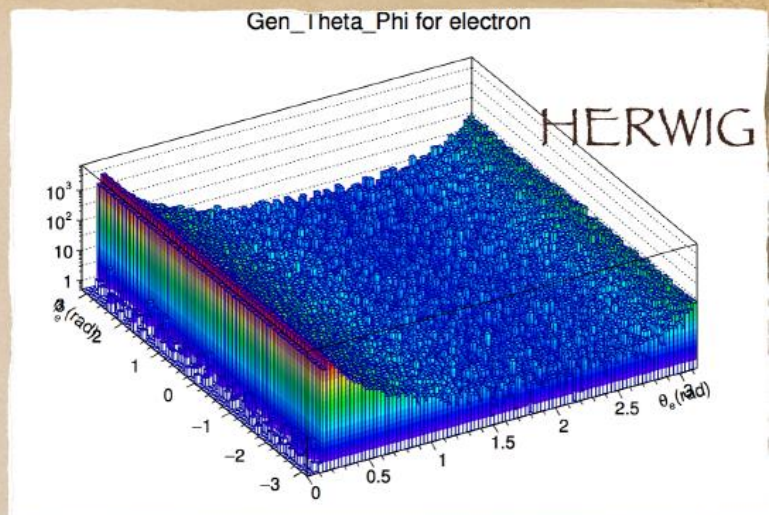
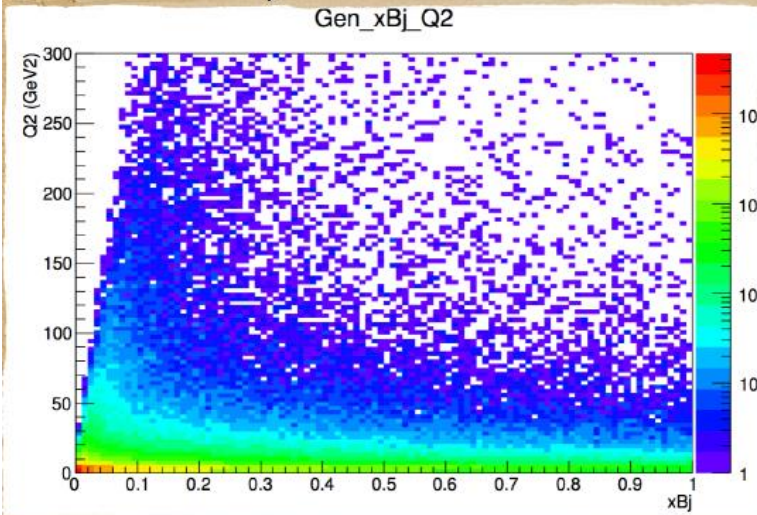
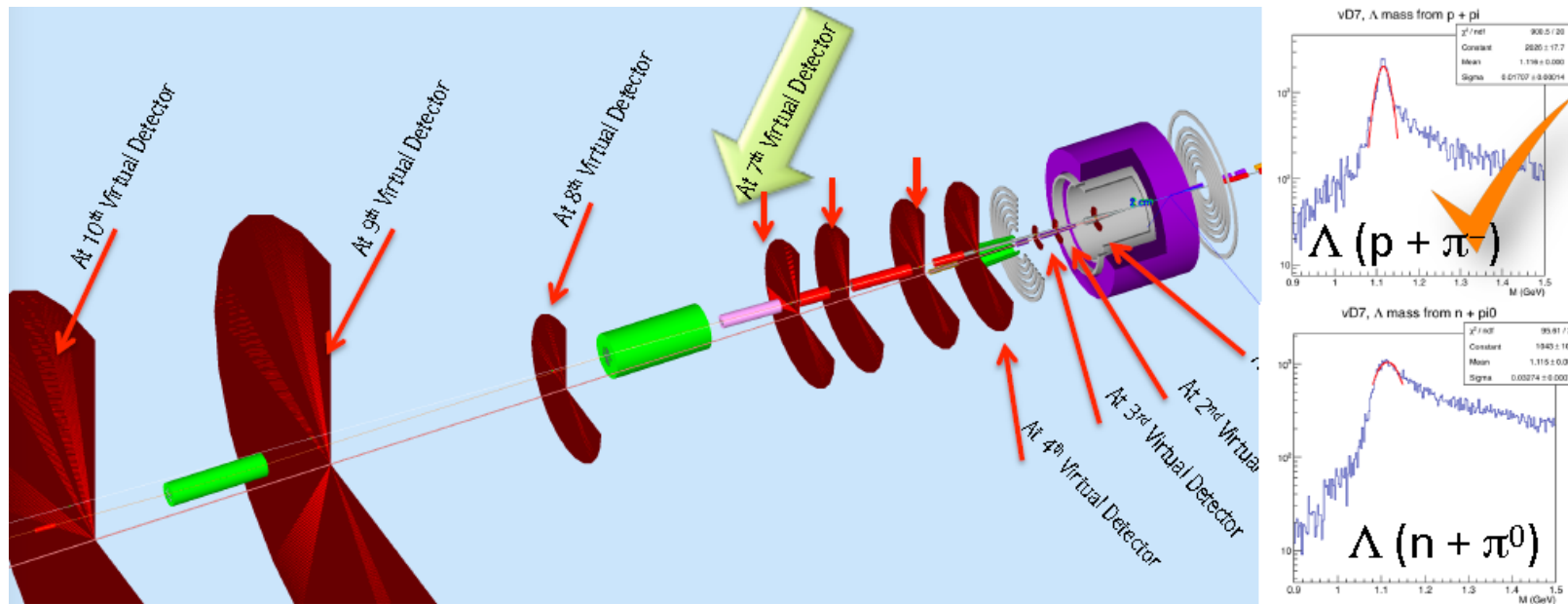


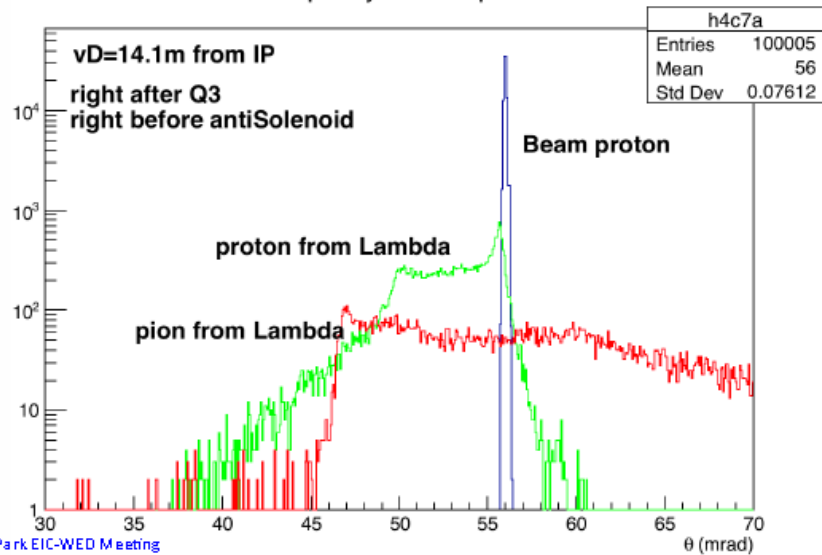
Figure from K. Park

Detector Acceptance Simulation Example

Figures from K. Park



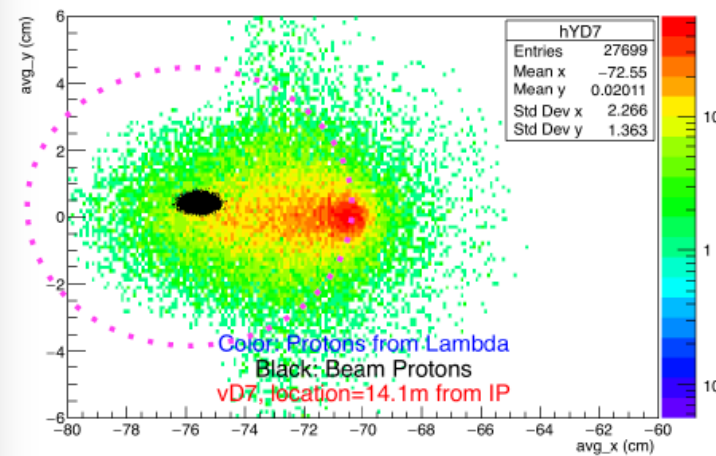
Occupancy θ beam proton



K. Park EIC-WED Meeting

vD7

Occupancy avg_y vs. avg_x for beam proton, proton from Λ



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.
- ❑ Is the origin of mass encoded in differences of gluons in pions, kaons and nucleons (at non-asymptotic Q^2)?
- ❑ Some effects may be trivial – the heavier-mass quark in the kaon “robs” more of the momentum, and the structure functions of pions, kaons and protons at large- x should be different, but confirming these would provide textbook material.
- ❑ Using electroweak processes, e.g., through parity-violating probes or neutral vs. charged-current interactions, disentangling flavour dependence seems achievable

Origin of mass of QCD's pseudoscalar Goldstone modes

- Exact statements from QCD in terms of current quark masses due to PCAC:

[Phys. Rep. 87 (1982) 77; Phys. Rev. C 56 (1997) 3369; Phys. Lett. B420 (1998) 267]

$$f_\pi m_\pi^2 = (m_u^\zeta + m_d^\zeta) \rho_\pi^\zeta$$

$$f_K m_K^2 = (m_u^\zeta + m_s^\zeta) \rho_K^\zeta$$

- Pseudoscalar masses are generated dynamically – If $\rho_p \neq 0$, $m_\pi^2 \sim \sqrt{m_q}$

- The mass of bound states increases as \sqrt{m} with the mass of the constituents
- In contrast, in quantum mechanical models, e.g., constituent quark models, the mass of bound states rises linearly with the mass of the constituents
- E.g., in models 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 s quark) $m_Q \sim 200$ MeV – **This is not real.**
- 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 ($D\chi$ SB) that makes the pion and kaon masses light.

- Assume $D\chi$ SB similar for light particles: If $f_\pi = f_K \approx 0.1$ and $\rho_\pi = \rho_K \approx (0.5 \text{ GeV})^2$ @ scale $\zeta = 2 \text{ GeV}$

- $m_\pi^2 = 2.5 \times (m_u^\zeta + m_d^\zeta)$; $m_K^2 = 2.5 \times (m_u^\zeta + m_s^\zeta)$
 - Experimental evidence: mass splitting between the current s and d quark masses
- $$m_K^2 - m_\pi^2 = (m_s^\zeta - m_d^\zeta) \frac{\rho^\zeta}{f} = 0.225 \text{ GeV}^2 = (0.474 \text{ GeV})^2 \quad m_s^\zeta = 0.095 \text{ GeV}, m_d^\zeta = 0.005 \text{ GeV}$$

In good agreement with experimental values

The issue at large-x: solved by resummation?

- ❑ Large x_{Bj} structure of the pion is interesting and relevant
 - Pion cloud & antiquark flavor asymmetry
 - Nuclear Binding
 - Simple QCD state & Goldstone Boson
- ❑ Even with NLO fit and modern parton distributions, pion did not agree with pQCD and Dyson-Schwinger

❑ Soft Gluon Resummation saves the day!

- JLab 12 GeV experiment can check at high-x
 - Resummation effects less prominent at DIS → EIC's role here may be more consistency checks of assumptions made in extraction
- ❑ Additional Bethe-Salpeter predictions to check in π/K Drell-Yan ratio

