Pion and Kaon Structure Functions at an EIC

... beyond the science of ...

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

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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 $\Lambda$N 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)

$u_V(x,Q_0^2)$

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

NA3 data

Predictions based on non-relativistic model with valence quarks only
World Data on pion structure function $F_2^\pi$

Pion Drell-Yan

DIS (Sullivan Process)

Data much more limited than nucleon...

FNAL E615

CERN NA3

[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 $x \to 1$ 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.

\[
\begin{align*}
g_{\pi NN} &= 13.1 \\
g_{Kp\Lambda} &= -13.3 \\
g_{Kp\Sigma^0} &= -3.5
\end{align*}
\]

(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.

<table>
<thead>
<tr>
<th>Process</th>
<th>Forward Particle</th>
<th>Geometric Detection Efficiency (at small (-t))</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^1\text{H}(e,e'^\pi^+)n)</td>
<td>N</td>
<td>&gt; 20%</td>
</tr>
<tr>
<td>(^1\text{H}(e,e'K^+){\Lambda})</td>
<td>(\Lambda)</td>
<td>50%</td>
</tr>
<tr>
<td>(^1\text{H}(e,e'K^+){\Sigma})</td>
<td>(\Sigma)</td>
<td>17%</td>
</tr>
</tbody>
</table>

See also talks by R. Yoshida and K. Park.
**Landscape for $p$, $\pi$, 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!

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Phase space for 5 GeV $e^-$ and 50 GeV $p$
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 $\nu$, 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$^2$ ($\nu_s\sim3$) 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

R. Trotta, A. Vargas, T. Horn

\[ Q^2 = 12 \]
\[ Q^2 = 30 \]
\[ Q^2 = 120 \]
\[ Q^2 = 240 \]
Pion/kaon SF – EIC kinematic reach

EIC kinematic reach down to $x=0.01$ or a bit below
World Data on pion structure function $F_2^\pi$

HERA

EIC

roughly $x_{\text{min}}$ for EIC projections

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

☐ EIC kinematic reach down to a few $x=10^{-3}$

☐ Lowest $x$ constrained by HERA
Constraining gluons with $Q^2$ dependence

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

$$F_2^\gamma = \sum_q e_q^2 x (q + \bar{q})$$
$$F_2^{\gamma Z} = 2 \sum_q e_q g_\gamma^q x (q + \bar{q})$$
$$x F_3^{\gamma Z} = 2 \sum_q e_q g_A^q x (q - \bar{q})$$

In the parton model:

- Use different couplings/weights
- Use isovector response

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

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

$$A = \frac{\sigma_{R,C,e^+}^{CC,e^-} \pm \sigma_{L,C,e^-}^{CC,e^-}}{\sigma_{R,N}^{NC} + \sigma_{L,N}^{NC}}$$
$$A = \frac{G_F^2 Q^4}{32 \pi^2 \alpha_e^2} \left[ \frac{F_2^{W^+} \pm F_2^{W^-}}{F_2^\gamma} - \frac{1 - (1 - y)^2}{1 + (1 - y)^2} \frac{x F_3^{W^+} \mp x F_3^{W^-}}{F_2^\gamma} \right]$$

longitudinally polarized $e^-$

$\gamma, Z^0$
Disentangling the Flavour-Dependence

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

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

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


Calculation by C.D. Roberts et al.

Colours denote different scales

Parton distributions in pion and kaon

$a_2$ picks up different behaviour of $u$ and $sbar$. Flavour decomposition in kaon possible?
Electroweak pion/kaon SF with positrons

Figure from K. Park
Detector Acceptance Simulation Example

Figures from K. Park

vD7

vD=14.1 m from IP
right after Q3
right before antiSolenoid

Occupancy $\theta$ beam proton

proton from Lambda
pion from Lambda

Beam proton

Entry: 100005
Mean: 56
Std Dev: 0.07612

Occupancy avg. y vs. avg. x for beam proton, proton from $\Lambda$

Color: Events from Lambda
Black: Beam Protons
vD7, location=14.1 m from IP
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:

\[ f_\pi m_{\pi}^2 = (m_u^\xi + m_d^\xi)\rho_\pi^\xi \]
\[ f_K m_{K}^2 = (m_u^\xi + m_s^\xi)\rho_K^\xi \]

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 \( m_Q \sim \frac{1}{3}m_N \sim 310 \text{ MeV} \), in the pion \( m_Q \sim \frac{1}{2}m_{\pi} \sim 70 \text{ MeV} \), in the kaon (with s quark) \( m_Q \sim 200 \text{ MeV} \) – **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 \( \zeta = 2 \text{ GeV} \)

- \( m_{\pi}^2 = 2.5 \times (m_u^\xi + m_d^\xi) \); \( m_K^2 = 2.5 \times (m_u^\xi + m_s^\xi) \)
- Experimental evidence: mass splitting between the current s and d quark masses

\[ m_K^2 - m_{\pi}^2 = (m_s^\xi - m_d^\xi)\rho_\pi^\xi f = 0.225 \text{ GeV}^2 = (0.474 \text{ GeV})^2 \quad m_s^\xi = 0.095 \text{ GeV}, m_d^\xi = 0.005 \text{ GeV} \]

In good agreement with experimental values
The issue at large-$x$: solved by resummation?

- Large $x_{\text{Bj}}$ 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 $\rightarrow$ EIC’s role here may be more consistency checks of assumptions made in extraction

- Additional Bethe-Salpeter predictions to check in $\pi/K$ Drell-Yan ratio

*Aicher, Schäfer and Vogelsang, arXiv:1009.2481*