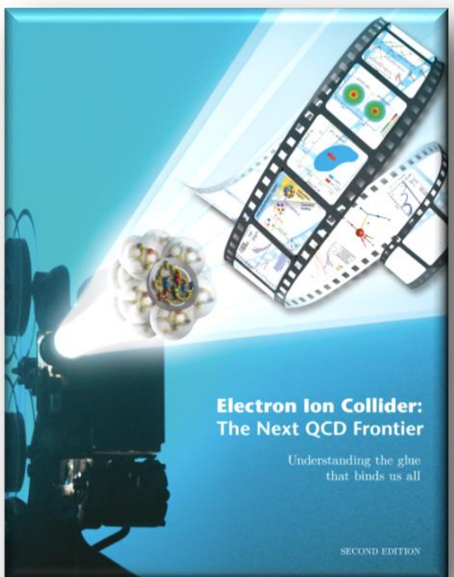
Pion and Kaon Structure Functions at an EIC



… beyond the science of …

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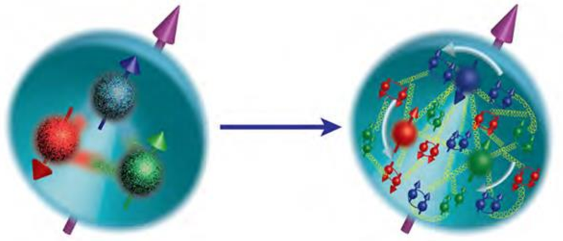
Collaboration with Ian Cloet, Roy Holt, Paul Reimer, Rolf Ent, Kijun Park, Thia Keppel
Thanks to: Craig Roberts, Yulia Furletova, Elke Aschenauer and Steve Wood

25th International Workshop on Deep Inelastic Scattering and Related Topics

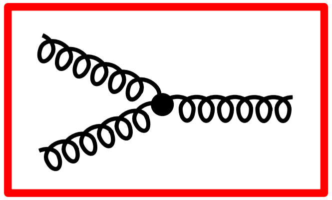
3-7 April 2017, Birmingham, UK

QCD Science Questions

- How are the gluons and sea quarks, and their intrinsic spins distributed in space & momentum inside the nucleon?
  - Role of Orbital Angular Momentum?



- What happens to the gluon density in nuclei at high energy? Does it saturate into a gluonic form of matter of universal properties?



How about the distributions of quarks and gluons in the lightest mesons - pions and kaons?

Why should you be interested in pions and kaons?

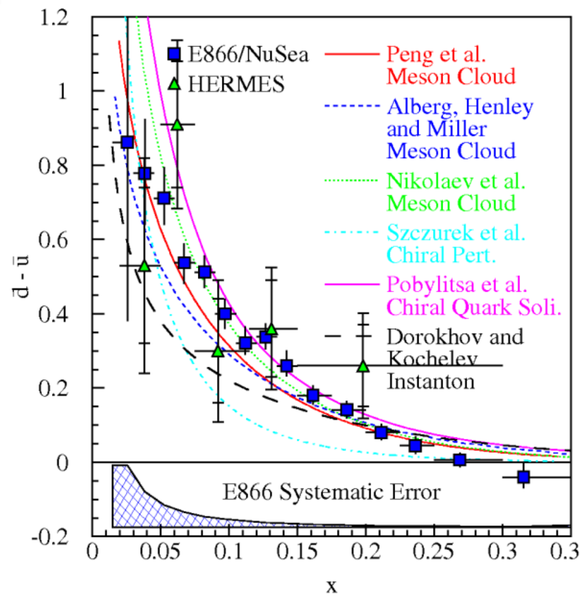
Protons, neutrons, pions and kaons are the main building blocks of nuclear matter

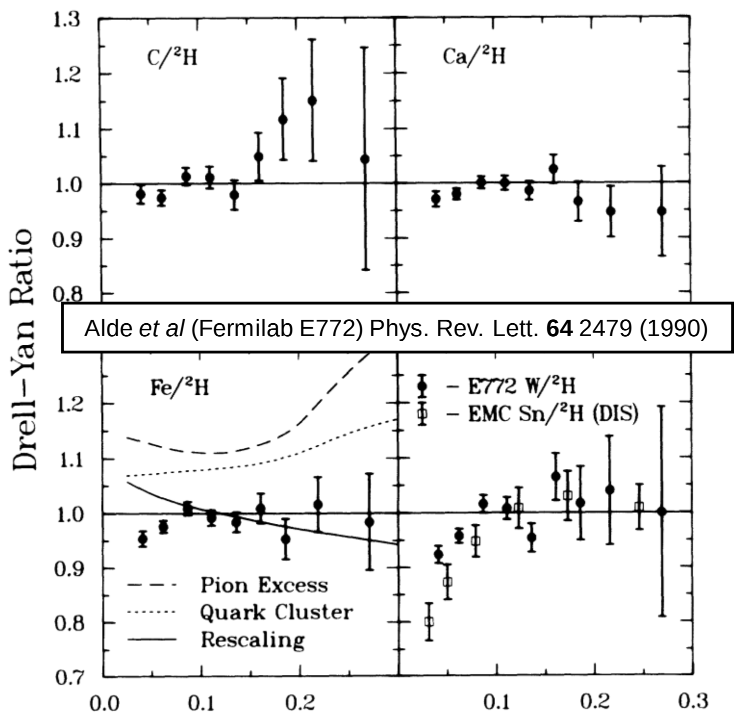
1) The pion, or a meson cloud, explains light-quark asymmetry in the nucleon sea

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 ΛN interaction – correlated with the Equation of State and astrophysical observations

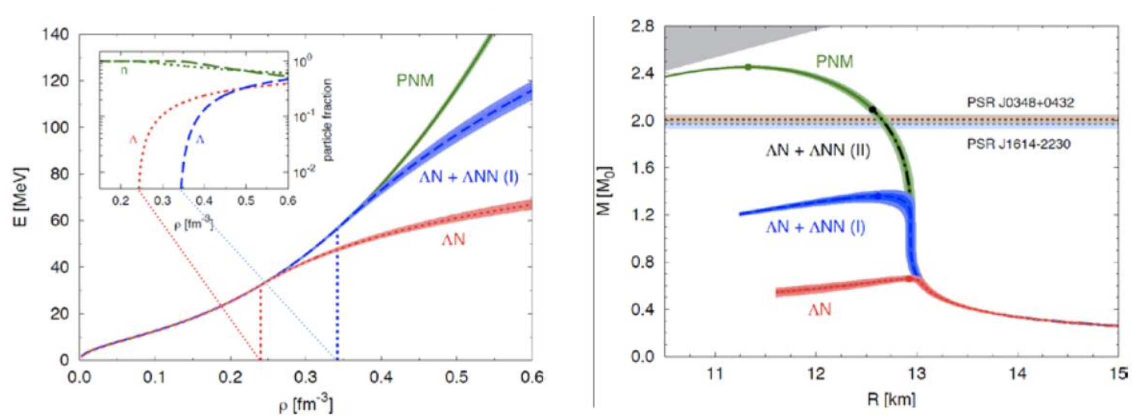
4) Mass is enigma – cannibalistic gluons vs massless Goldstone bosons





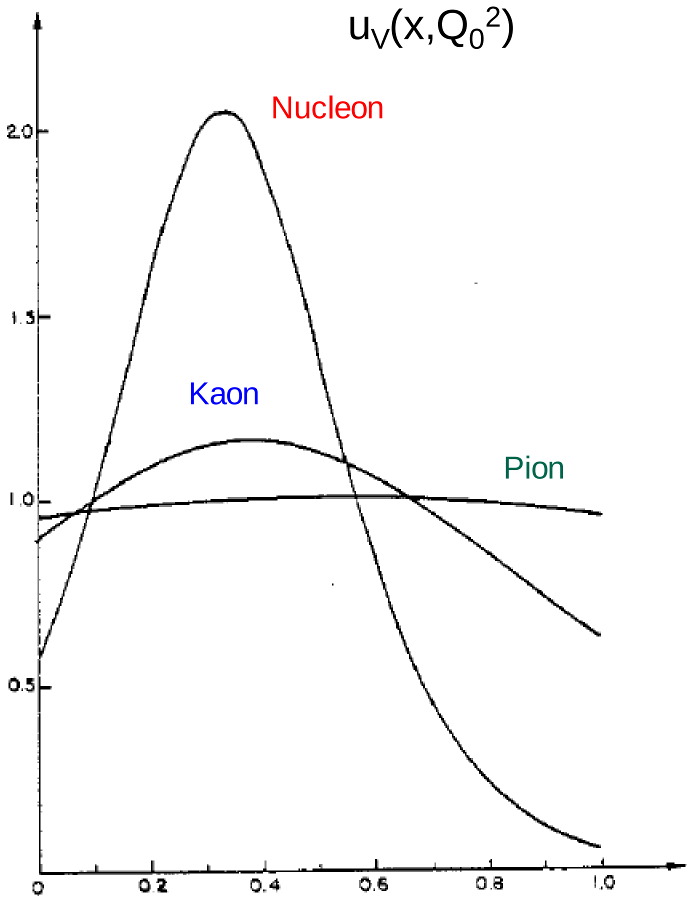
Alde *et al* (Fermilab E772) Phys. Rev. Lett. **64** 2479 (1990)

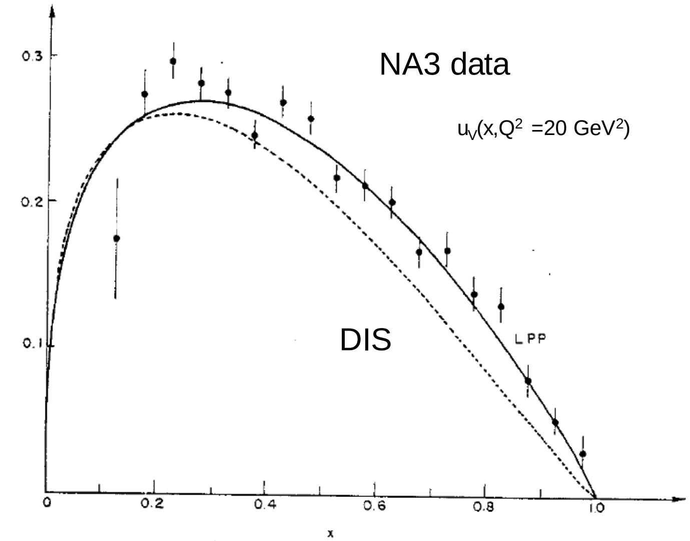
Equations of state and neutron star mass-radius relations



At some level an old story…

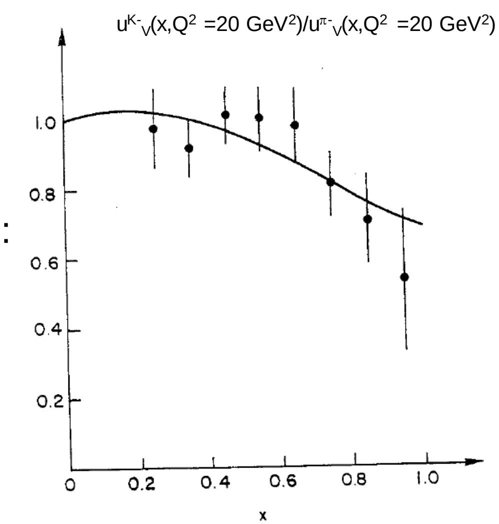
A model for nucleon, pion and kaon structure functions
F. Martin, CERN-TH 2845 (1980)





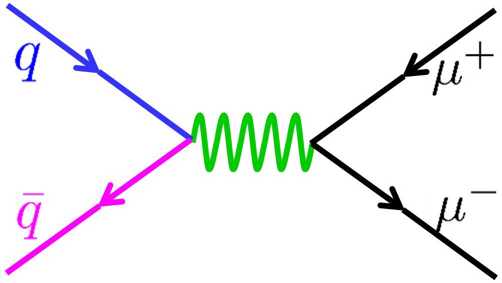
Predictions based on non-relativistic model with valence quarks only

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

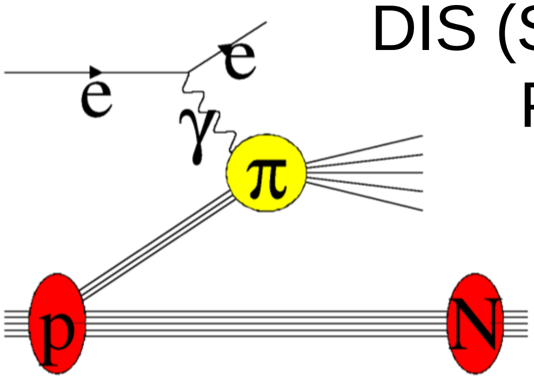


World Data on pion structure function F_2^{π}

Pion Drell-Yan

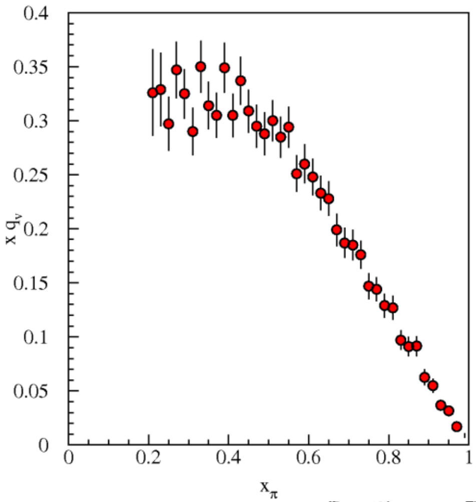


DIS (Sullivan Process)

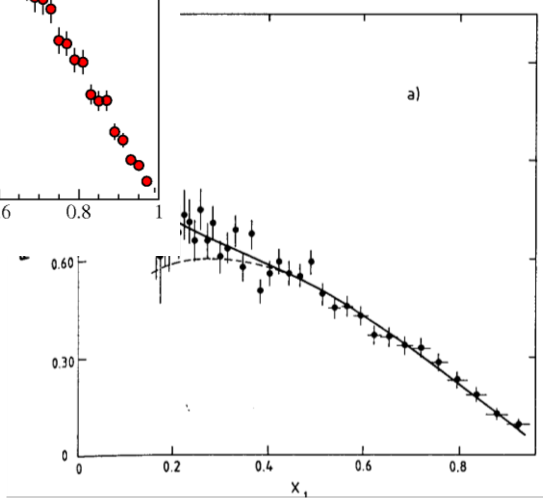


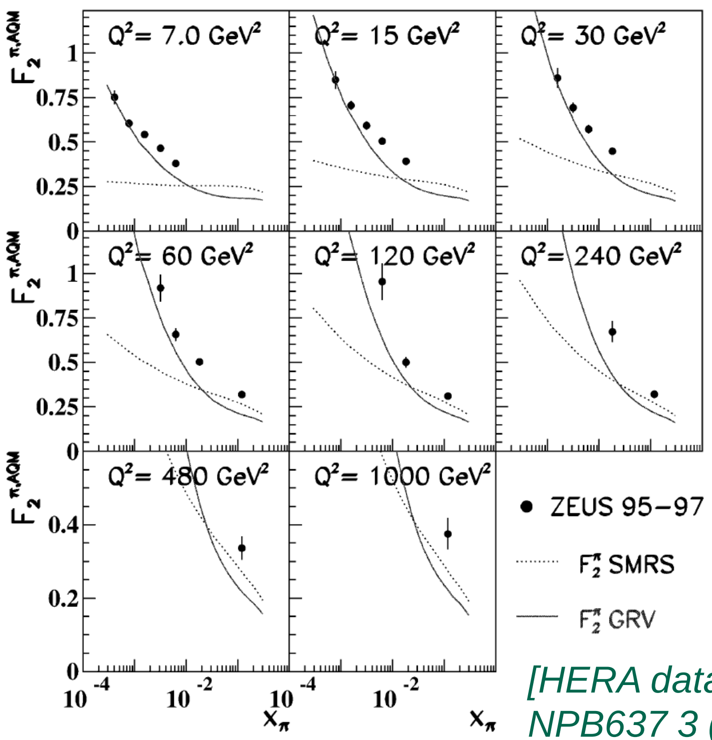
Data much more limited than nucleon…

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 $x \rightarrow 1$ limits

See talk by C. Keppel

  - 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.

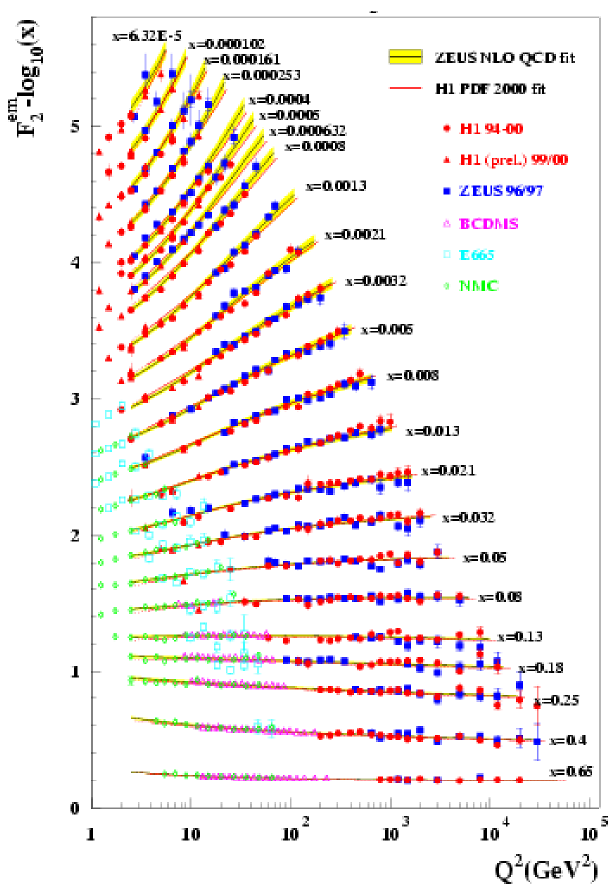
Landscape for p, π, K structure function after EIC

Proton: much existing from HERA

EIC will add:

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

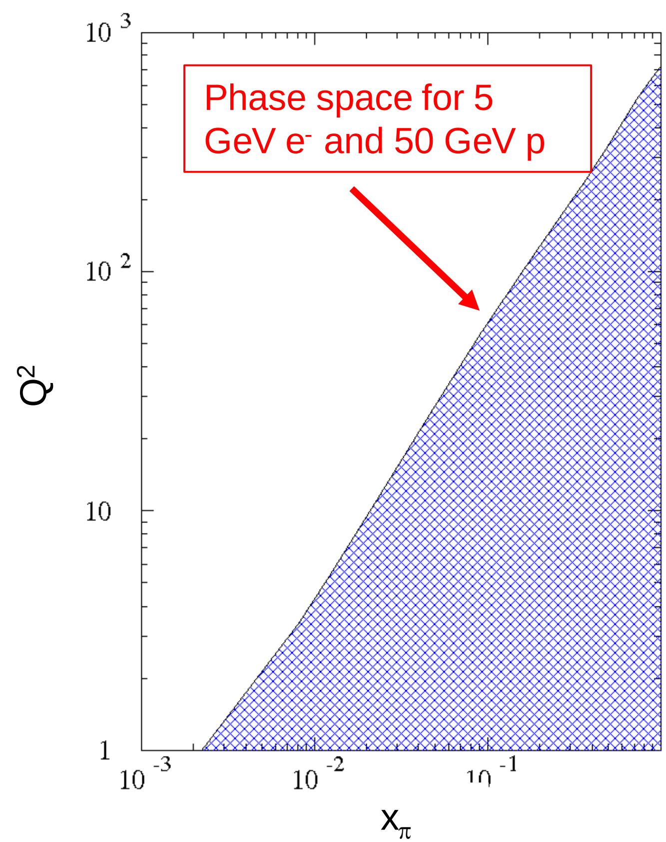
See talk by R. Yoshida



Pion and kaon: only limited data from:

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

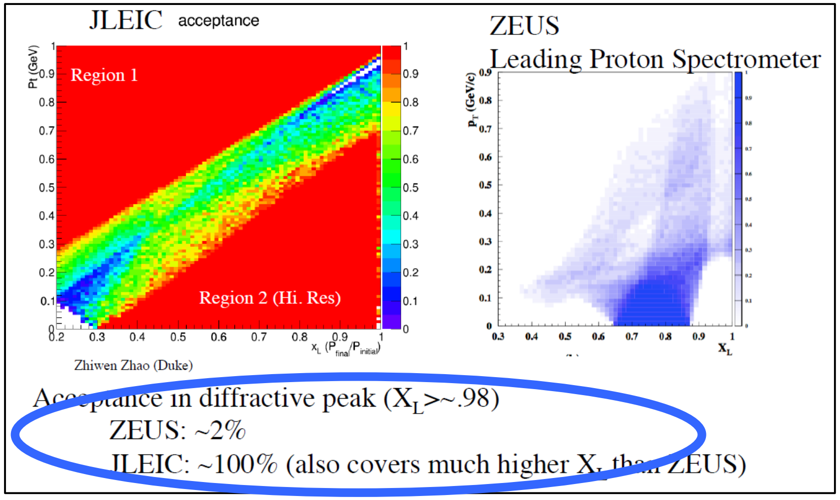
EIC will add large (x,Q^2) landscape for both pion and kaon!



EIC: Good Acceptance for n, Λ, Σ detection

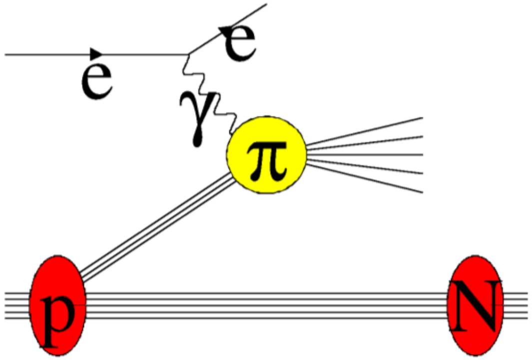
See talk by R. Ent

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

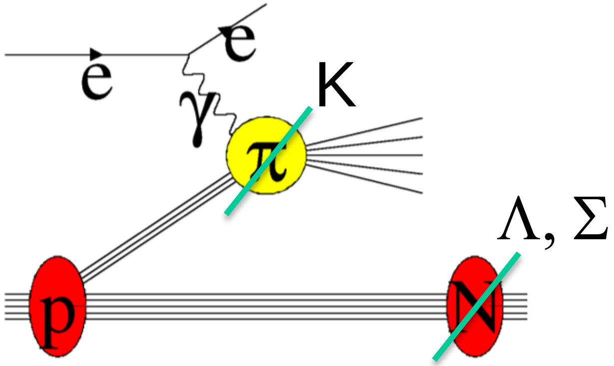


Huge gain in acceptance

Sullivan process for pion SF

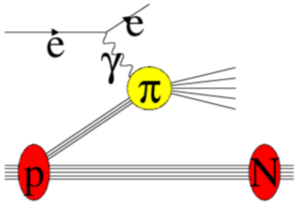


And similar process for kaon SF

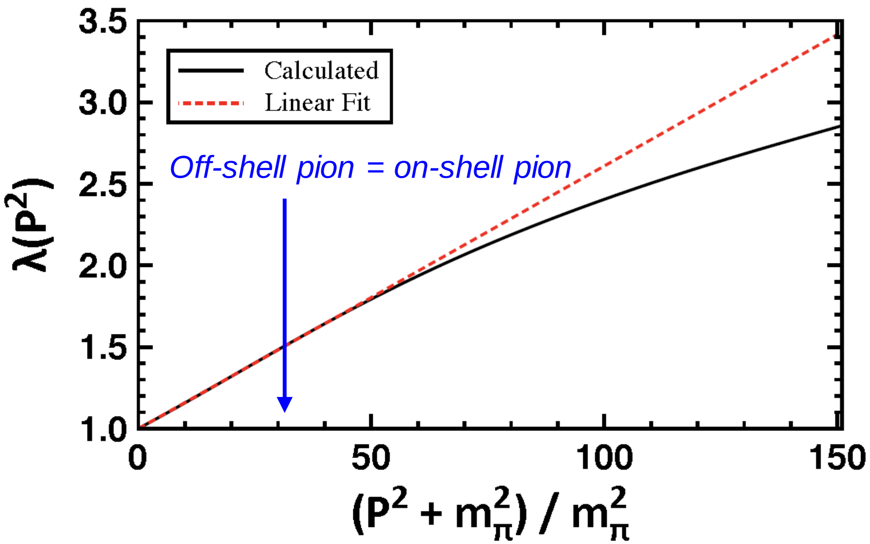


Process	Forward Particle	Geometric Detection Efficiency (at small –t)
$^1H(e,e'\pi^+)n$	N	> 20%
$^1H(e,e'K^+)\Lambda$	Λ	50%
$^1H(e,e'K^+)\Sigma$	Σ	17%

Off-shellness considerations



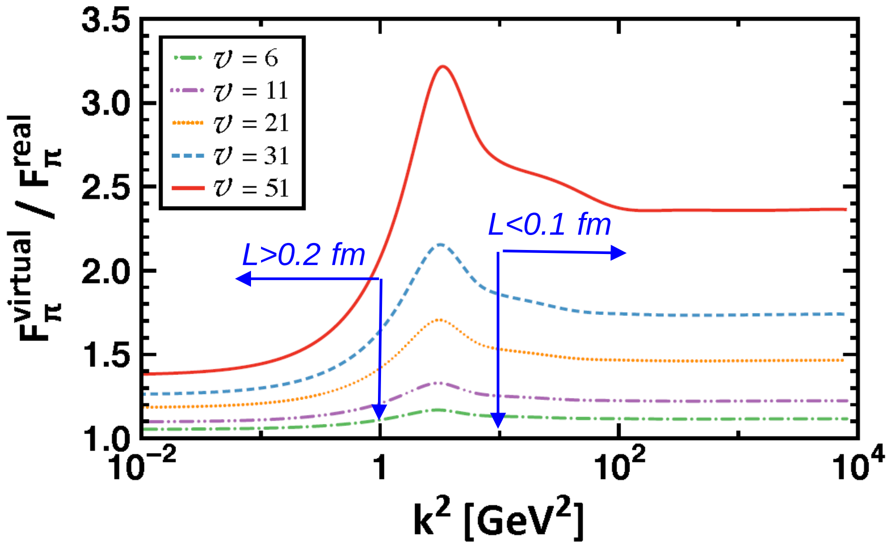
S-X Qin, C.Chen, C. Mezrag, C.D. Roberts, arXiv:1702.06100 (2017)



- 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

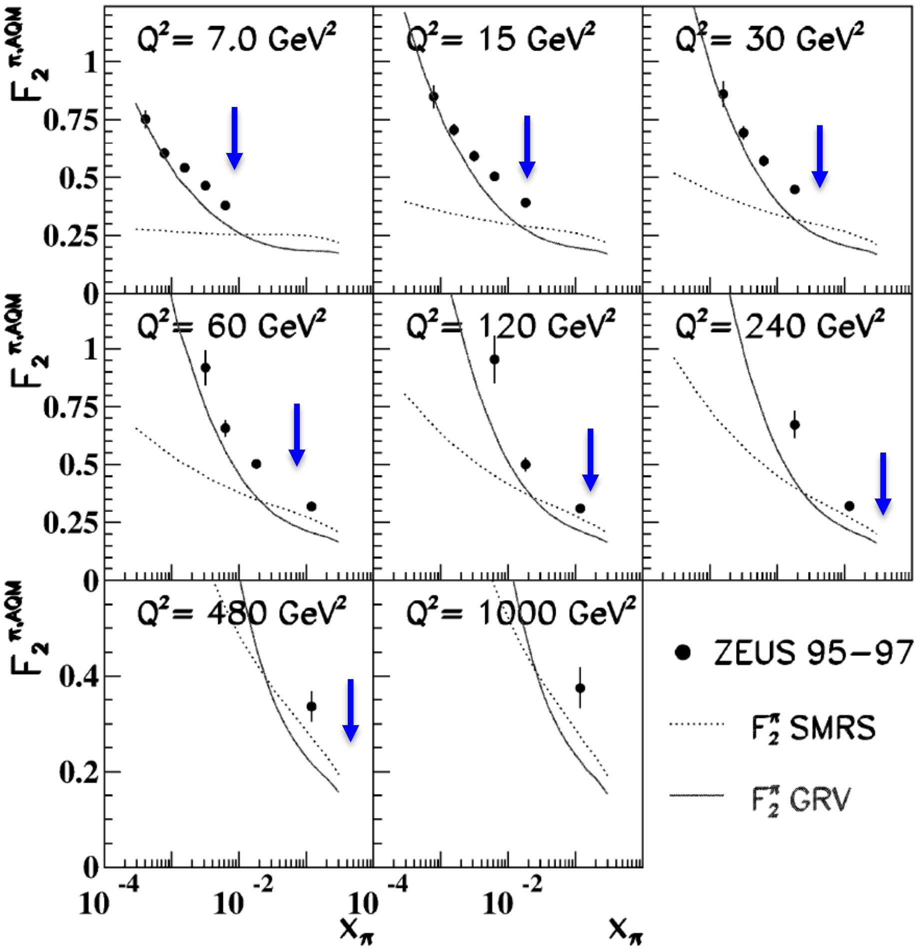
- *Off-shell meson = On-shell meson* for $t<0.6$ GeV^2 (ν =31) for pions and $t<0.9$ GeV^2(ν_s~3) for kaons



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

World Data on pion structure function F_2^{π}

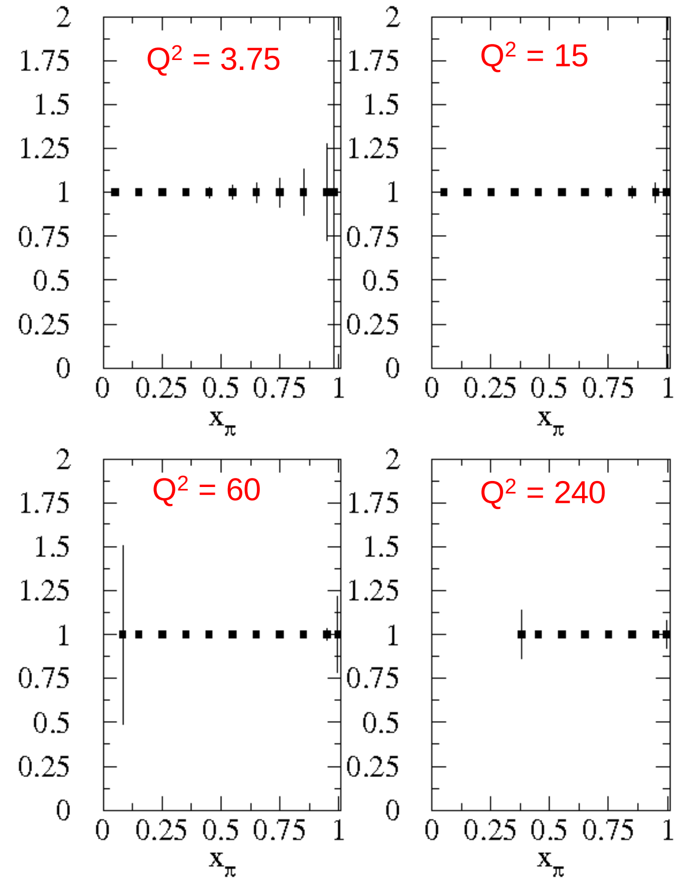
HERA



EIC

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

↓ roughly x_{min} for EIC projections



Assumes roughly a year of running (26 weeks at 50% efficiency) – need to multiply by geometric detection efficiency ~20%

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. A**47** (2011) 112:*

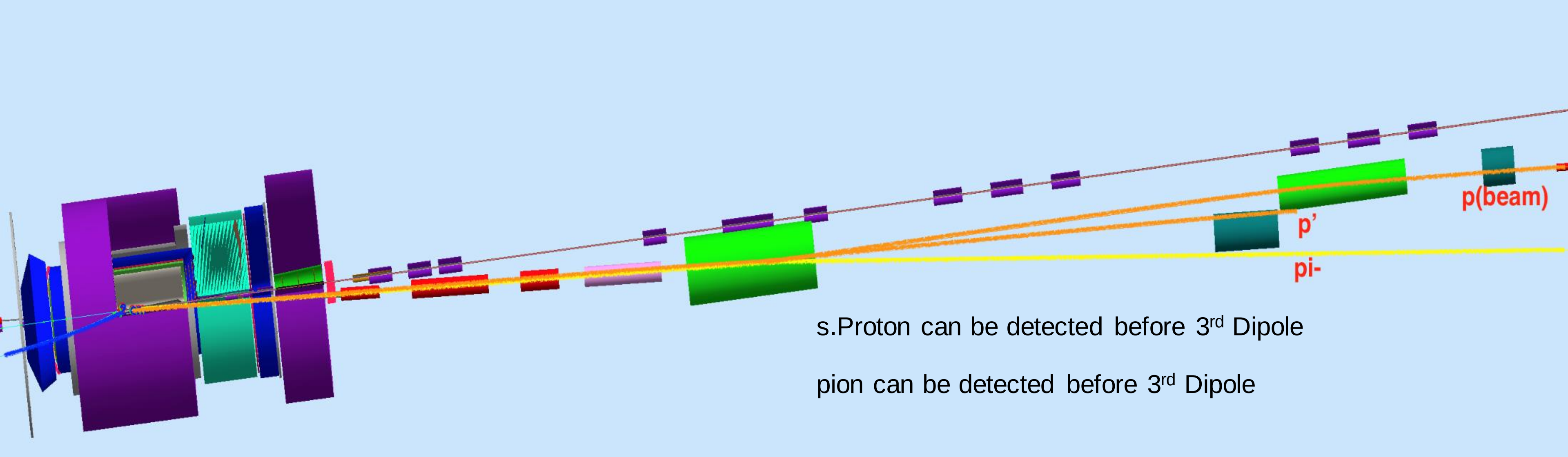
$g_{\pi NN}$=13.1 $g_{Kp\Lambda}$=-13.3 $g_{Kp\Sigma^0}$=-3.5

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

- 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.

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

Detection of ${}^{1}H(e,e'K^{+})\Lambda$



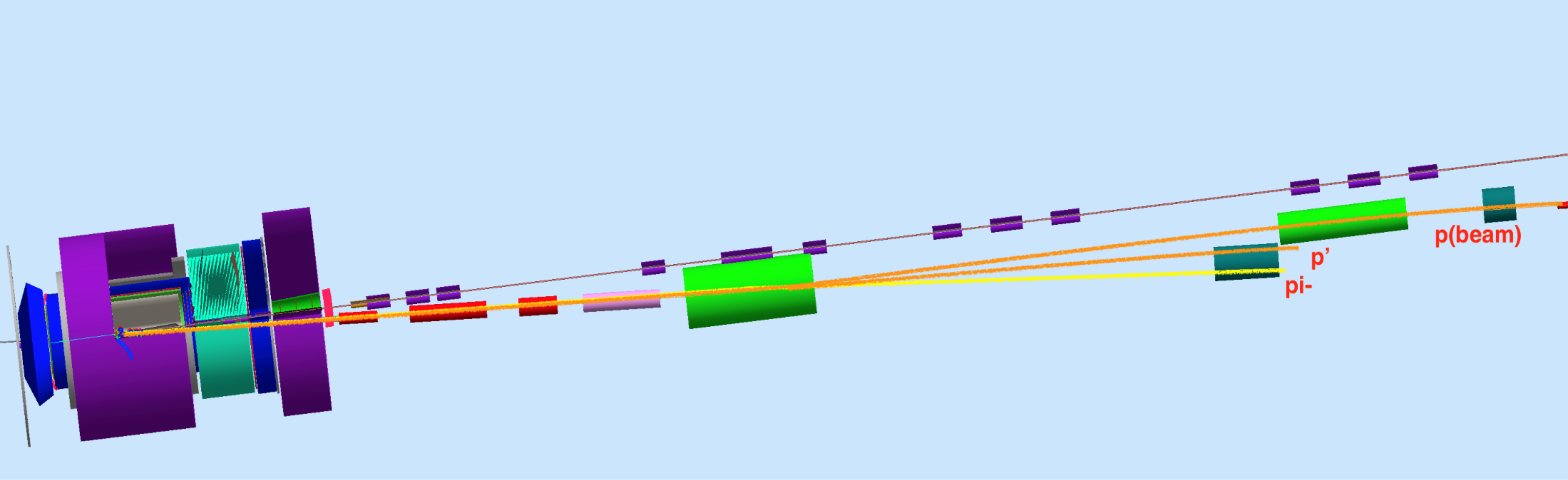
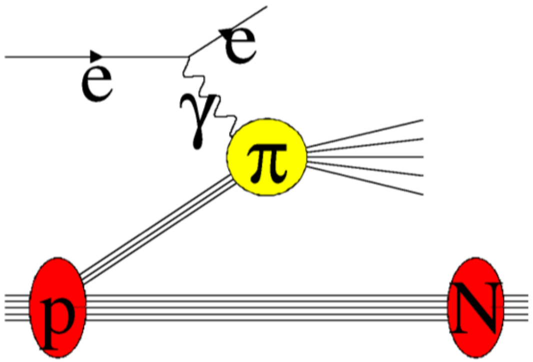


Figure from K.Park

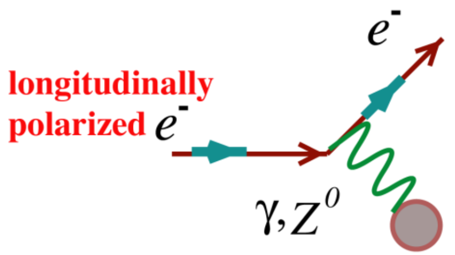
Electroweak Pion and Kaon Structure Functions



- The Sullivan Process will be sensitive to u and dbar for the pion, and likewise u and sbar 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 xF_3 through neutral/charged-current interactions



In the parton model:

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

$$F_2^{\gamma Z} = 2\sum_q e_q\, g_V^q\, x\,(q+\bar{q})$$ *Use different couplings/weights*

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

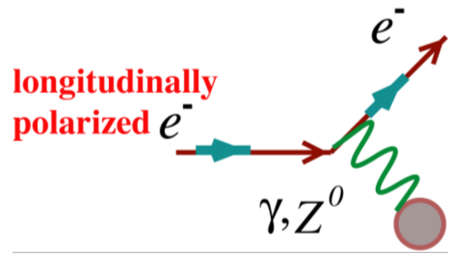
$$A = \frac{\sigma_R^{CC,e^+} \pm \sigma_L^{CC,e^-}}{\sigma_R^{NC} + \sigma_L^{NC}}$$

$$A = \frac{G_F^2\, Q^4}{32\,\pi^2\,\alpha_e^2}\left[\frac{F_2^{W^+} \pm F_2^{W^-}}{F_2^{\gamma}} - \frac{1-(1-y)^2}{1+(1-y)^2}\,\frac{xF_3^{W^+} \mp xF_3^{W^-}}{F_2^{\gamma}}\right]$$

Disentangling the Flavour-Dependence

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

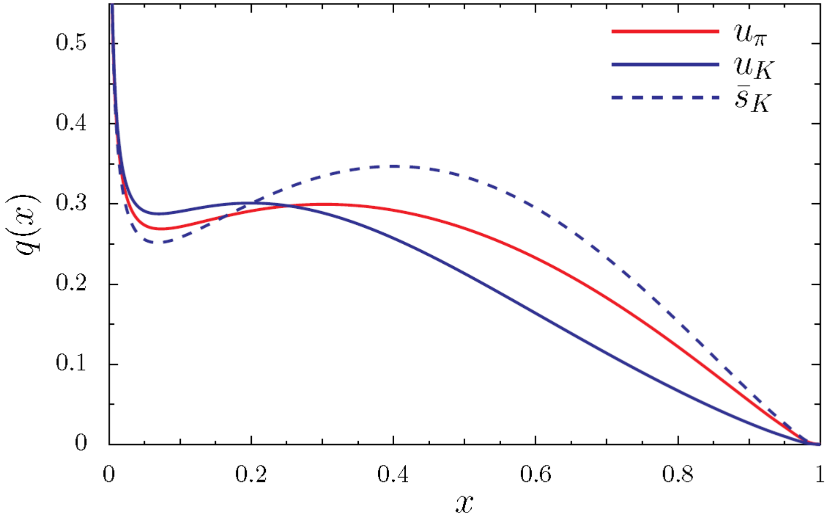
$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}$$



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

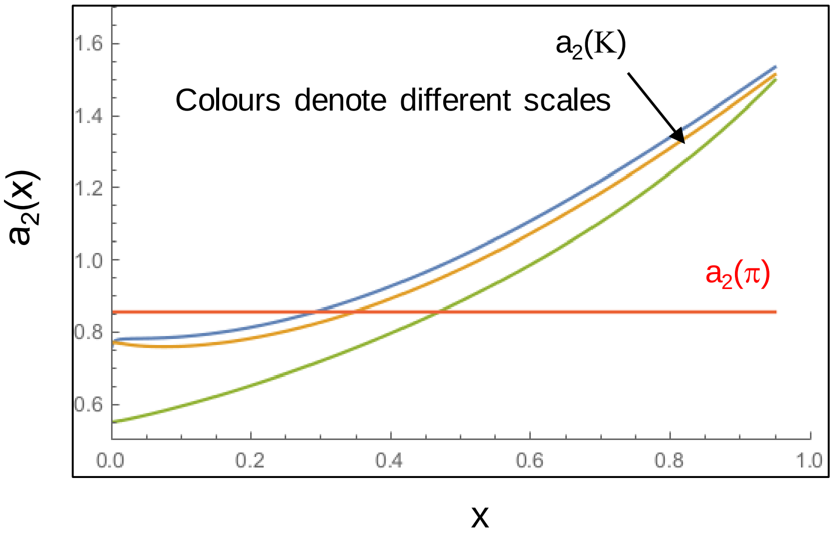
$$a_{2K}(x) = \frac{2\sum_q e_q g_V^q (q+\bar{q})}{\sum_q e_q^2 (q+\bar{q})} \simeq \frac{6\,u_K^+ + 3\,s_K^+}{4\,u_K^+ + s_K^+} - 4\sin^2\theta_W.$$

Figure from I. Cloet



DSE-based parton distributions in pion and kaon

Calculation by C.D. Roberts et al.



a_2 picks up different behaviour of u and sbar. Flavour decomposition in kaon possible?

Summary

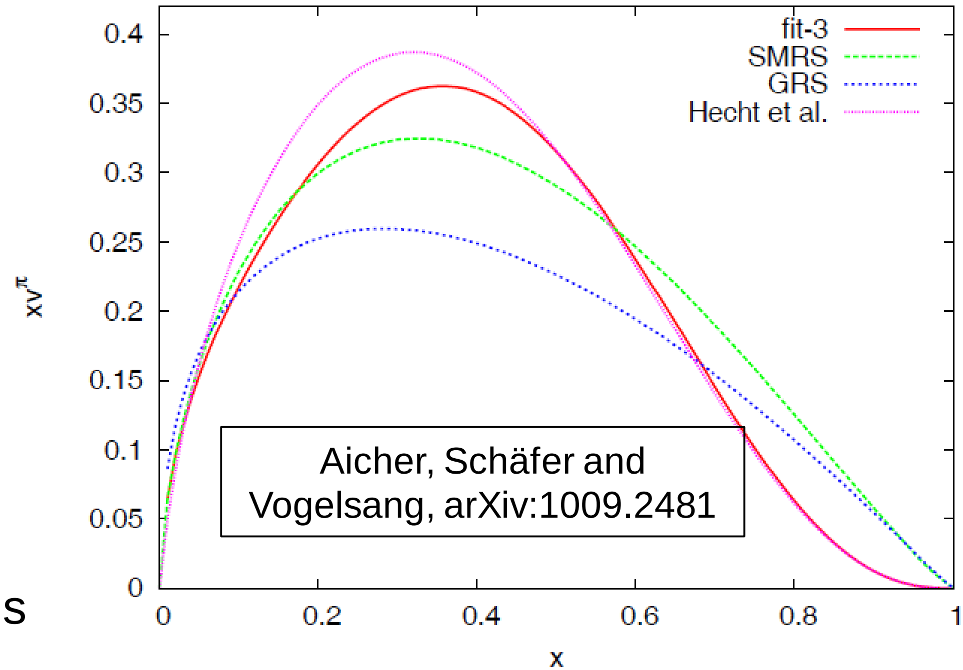
- Nucleons and the lightest mesons - pions and kaons, are the basic building blocks of nuclear matter. We should know their structure functions.
- The distributions of quarks and gluons in pions, kaons, and nucleons will be different.
- Is the origin of mass encoded in differences of gluons in pions, 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

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

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 (DχSB) that makes the pion and kaon masses light.

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

$$m_K^2 - m_\pi^2 = (m_s^\zeta - m_d^\zeta)\frac{\rho^\zeta}{f} = 0.225\,\text{GeV}^2 = (0.474\,\text{GeV})^2 \qquad m_s^\zeta = 0.095\,\text{GeV},\ m_d^\zeta = 0.005\,\text{GeV}$$

In good agreement with experimental values