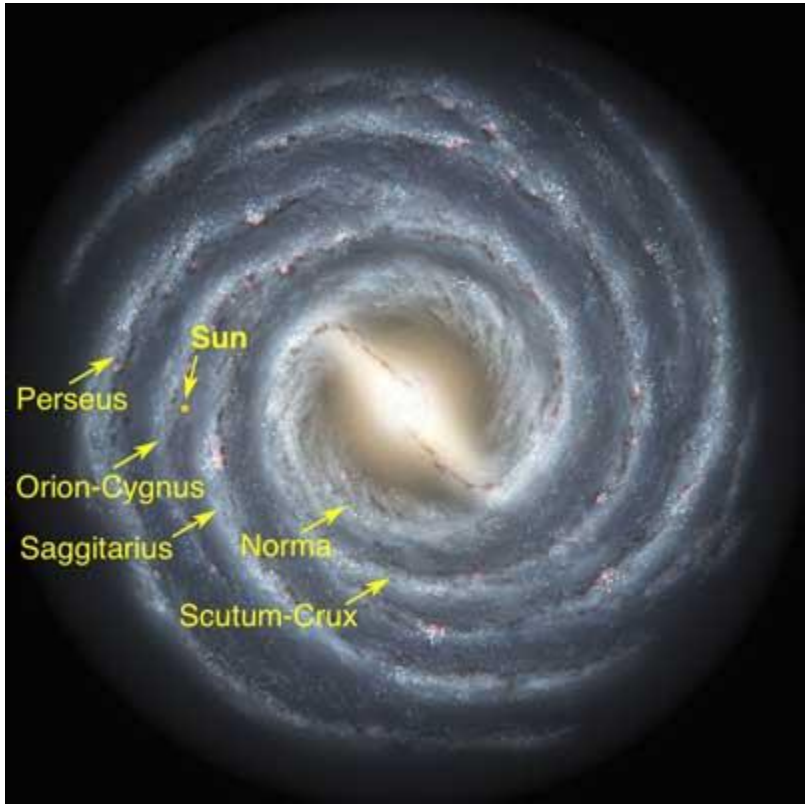
Emergent Phenomena in the Standard Model

Existence of the Universe as we know it depends critically on the following empirical facts:

- Proton is massive, *i.e.* the mass-scale for strong interactions is vastly different to that of electromagnetism
- Proton is absolutely stable, despite being a composite object constituted from three valence quarks
- Pion is unnaturally light (but not massless), despite being a strongly interacting composite object built from a valence-quark and valence antiquark

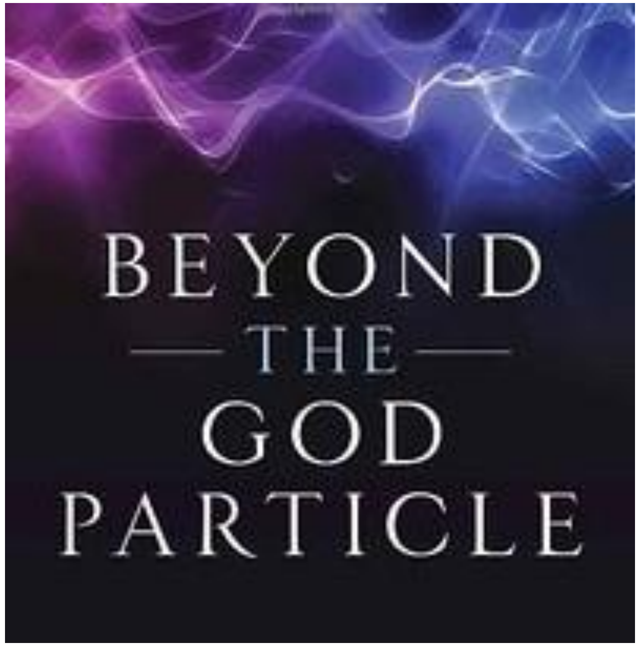


Emergence: low-level rules producing high-level phenomena, with enormous apparent complexity

Overture

- LHC has NOT found the "God Particle"
  because the Higgs boson is NOT the origin of mass
  - Higgs-boson only produces a little bit of mass
  - Higgs-generated mass-scales explain neither the proton's mass nor the pion's (*near*-)masslessness
  - Hence LHC has, as yet, taught us very little about
    - Origin   Nature   Structure

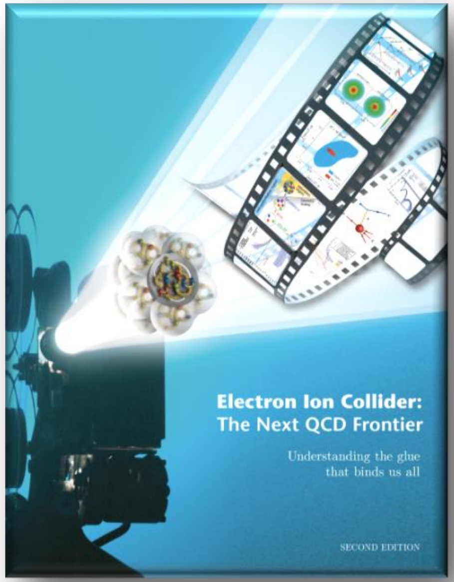
    of the nuclei whose existence support the Cosmos
- Strong interaction sector of the Standard Model,
  i.e. QCD, is the key to understanding the
  origin, existence and properties
  of (almost) all known matter



➢ Answers are in sight
  – Theoretical tools are reaching point where sound QCD predictions can be made
  – New facilities – in operation or being planned – can validate those predictions

What & where is mass?

Pion and Kaon Structure Functions at an EIC



… beyond the science of …

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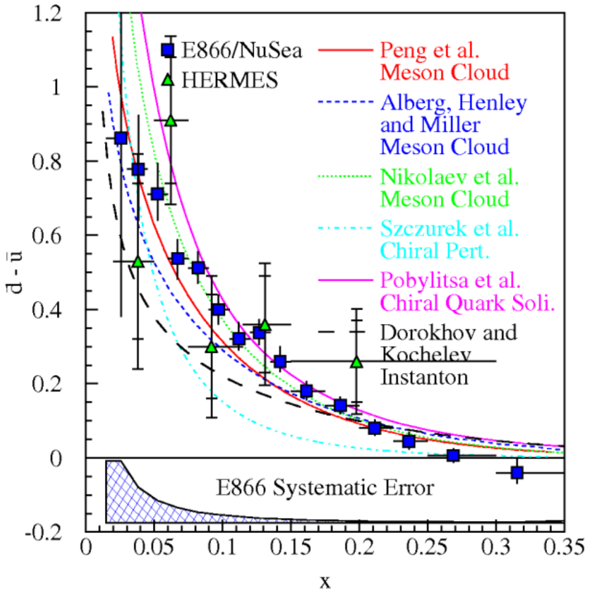
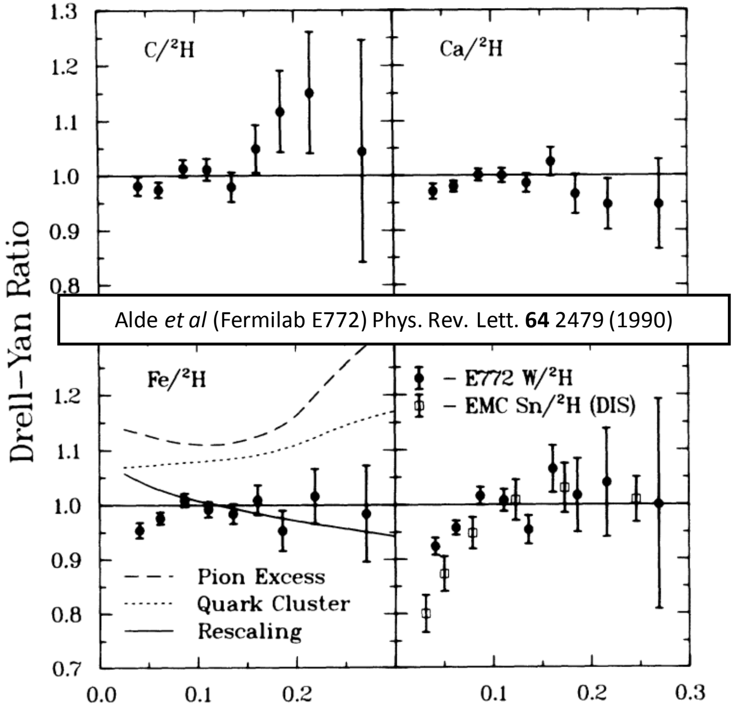
Collaboration with Ian Cloet, Rolf Ent, Roy Holt, Thia Keppel, Kijun Park, Paul Reimer, Craig Roberts, Richard Trotta, Andres Vargas
Thanks to: Yulia Furletova, Elke Aschenauer and Steve Wood

Why should you be interested in pions and kaons?

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

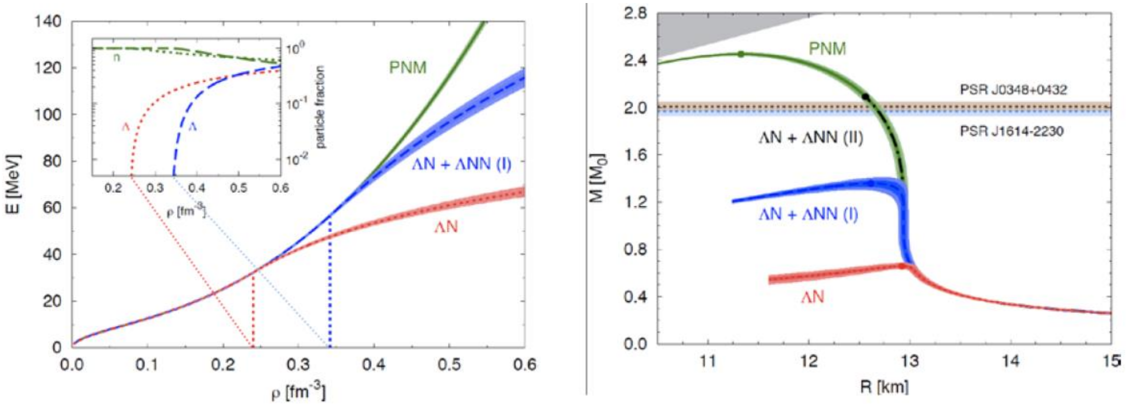
1) The pion, or a meson cloud, explains light-quark asymmetry in the nucleon sea
2) Pions are the Yukawa particles of the nuclear force – but no evidence for excess of nuclear pions or anti-quarks
3) Kaon exchange is similarly related to the ΛN interaction – correlated with the Equation of State and 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



Quarks and gluons in pions and kaons

See also talk by C. Roberts

- **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.

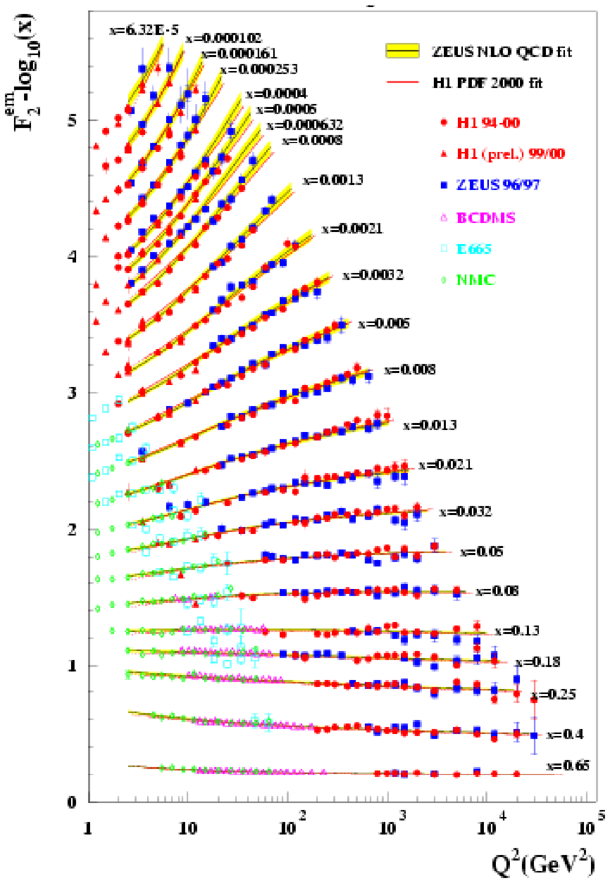
- **At high x,** the shapes of valence u quark distributions in pion, kaon and proton are different, and so are their asymptotic x → 1 limits
  - Some of these effects are due to the comparison of a two- versus three-quark system, and a meson with a heavier s quark embedded versus a lighter quark
  - However, effects of gluons come in as well. To measure these differences would be fantastic.

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

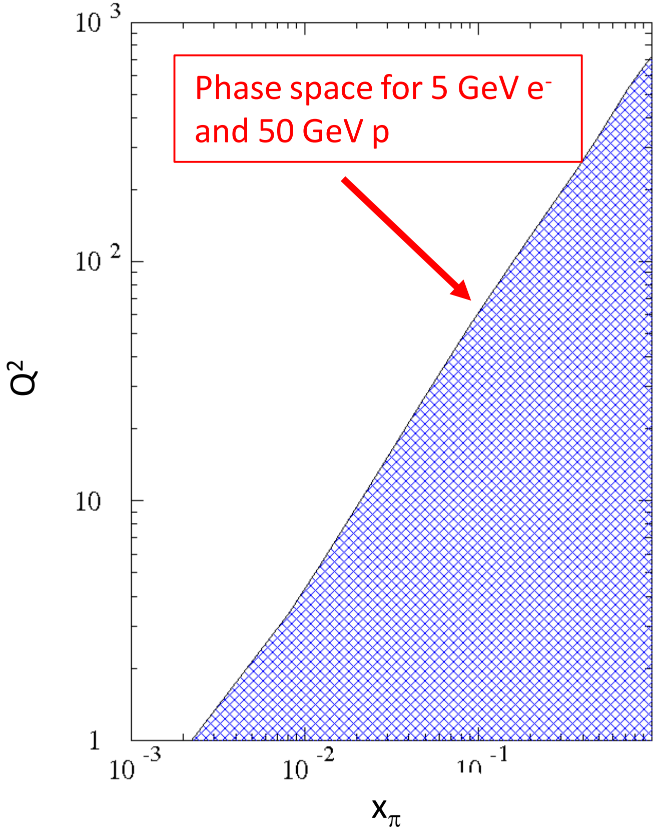


Pion and kaon: only limited data from:

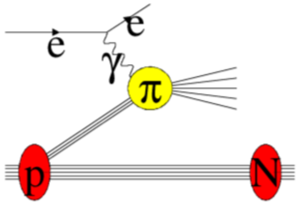
- Pion and kaon Drell-Yan experiments
- Some pion SF data from HERA

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

R. Trotta, A. Vargas, TH

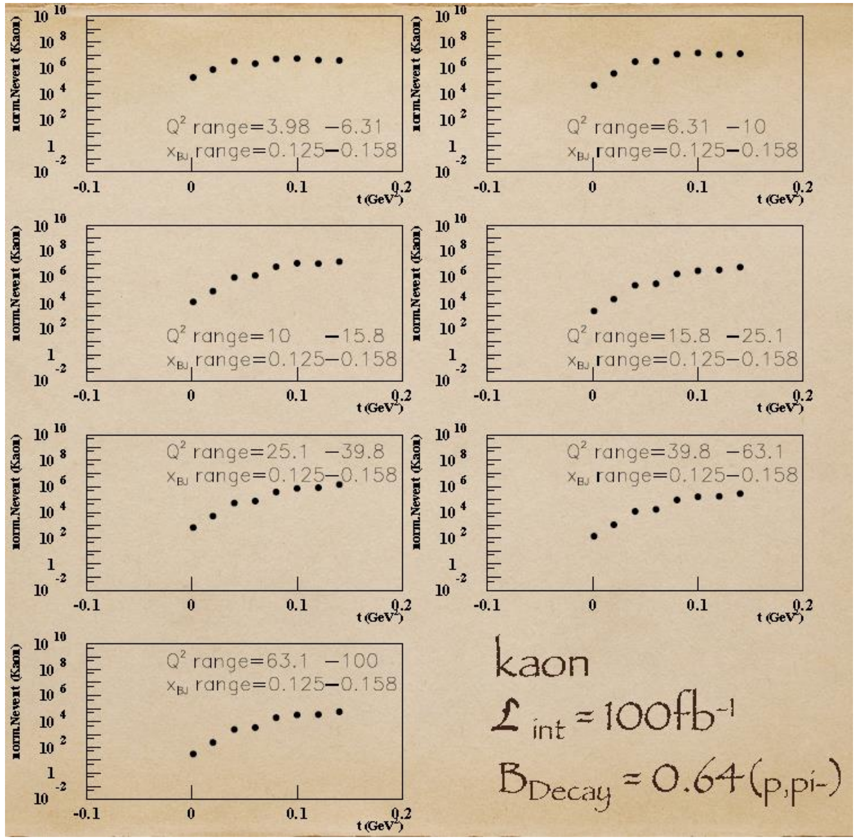


Sullivan process off-shellness corrections



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

Figure from K. Park



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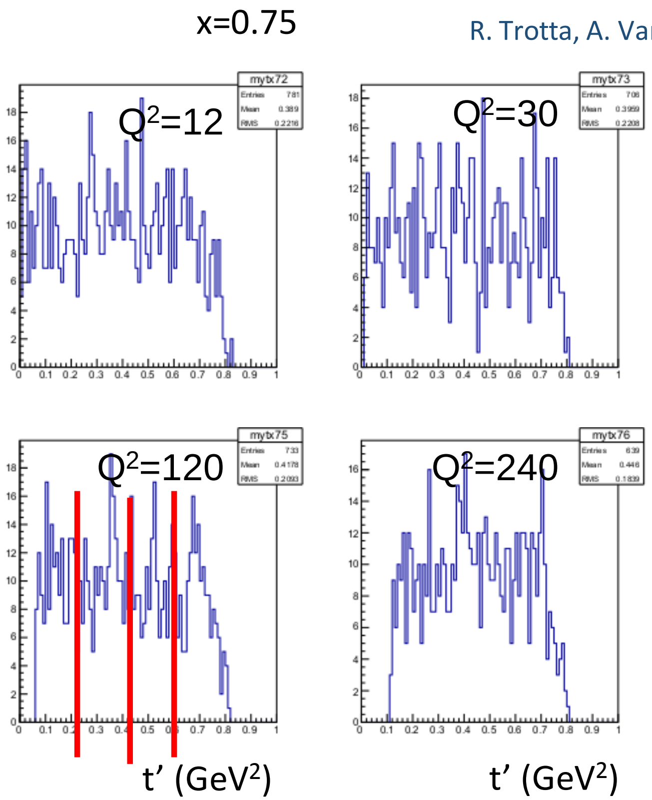
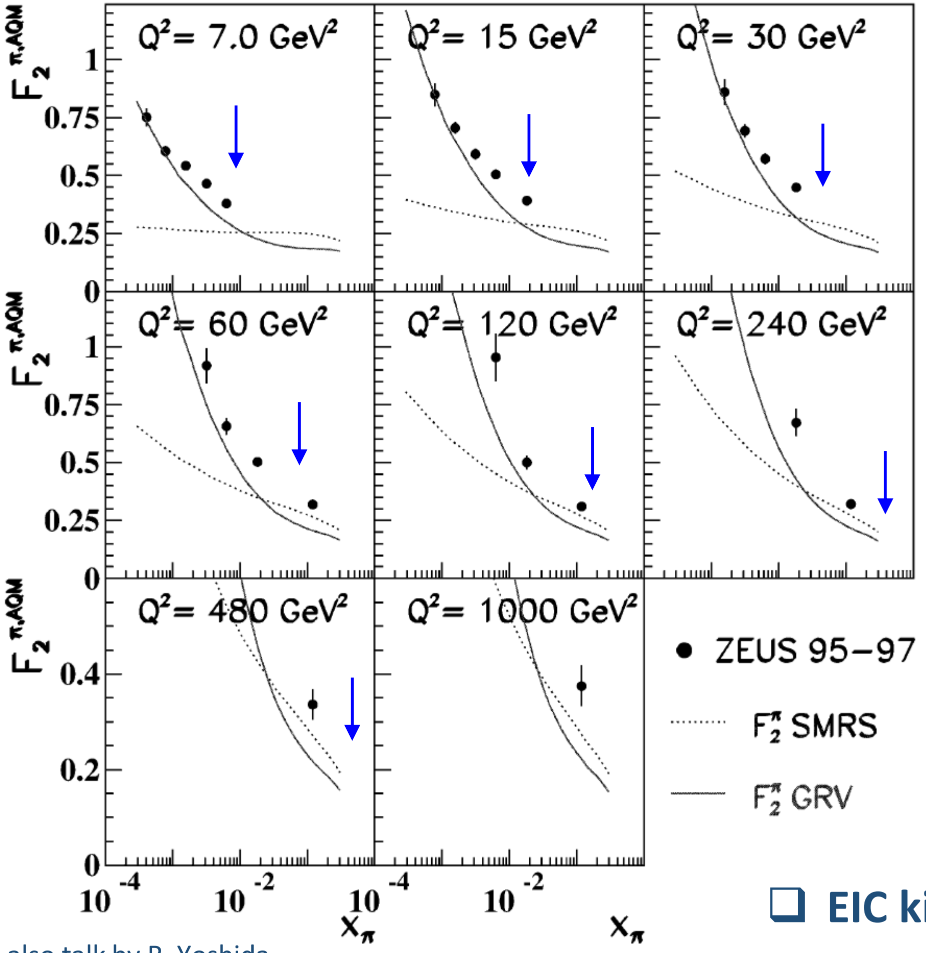


World Data on pion structure function F_2^{π}

HERA



See also talk by R. Yoshida

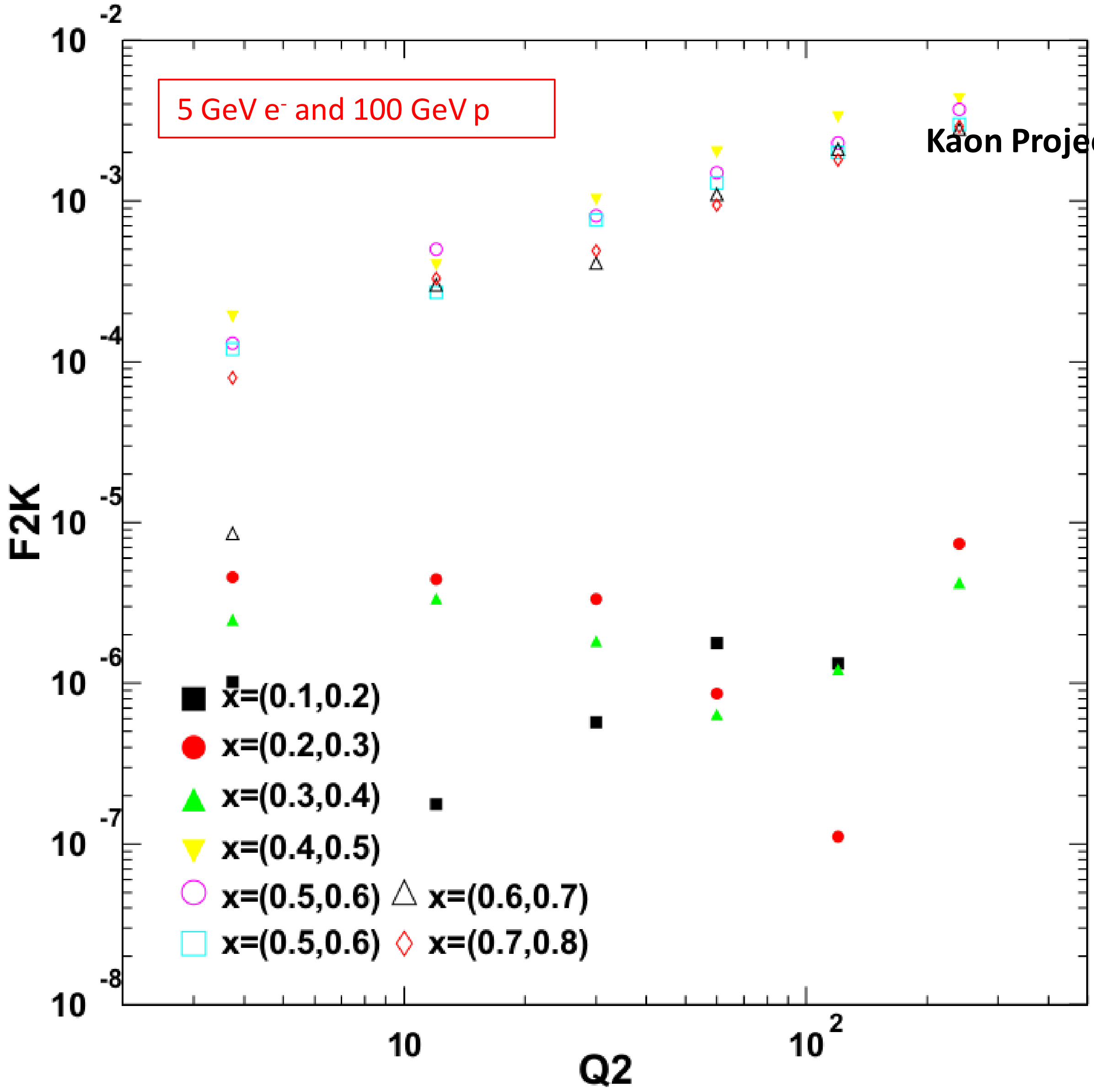
EIC

↓ roughly x_{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



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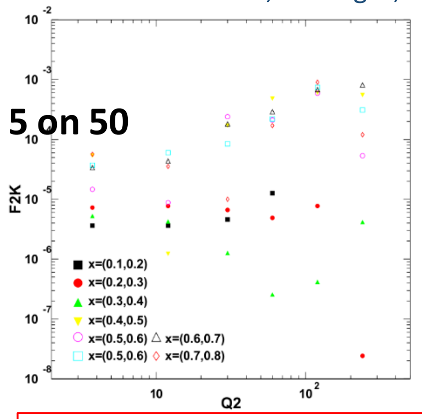
Kaon Projections 5 on 50



5 GeV e^- and 50 GeV p

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

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 $m_Q \sim ⅓m_N \sim 310$ MeV, in the pion $m_Q \sim ½m_\pi \sim 70$ 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