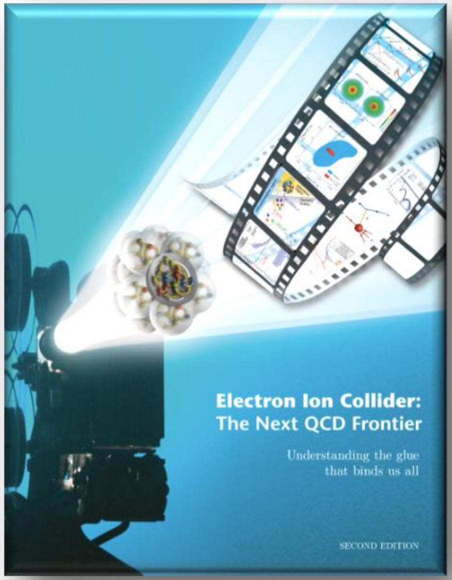
Pion and Kaon Structure Functions



… beyond the science of …

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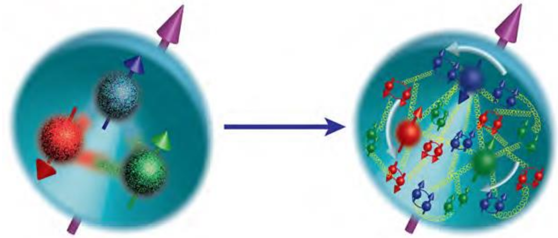
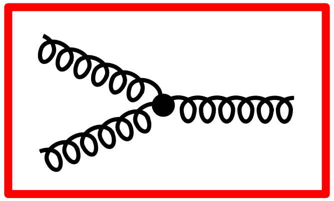
Collaboration with Roy Holt, Paul Reimer, Rolf Ent
Thanks to: Ian Cloet, Craig Roberts, Yulia Furletova and Steve Wood

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?

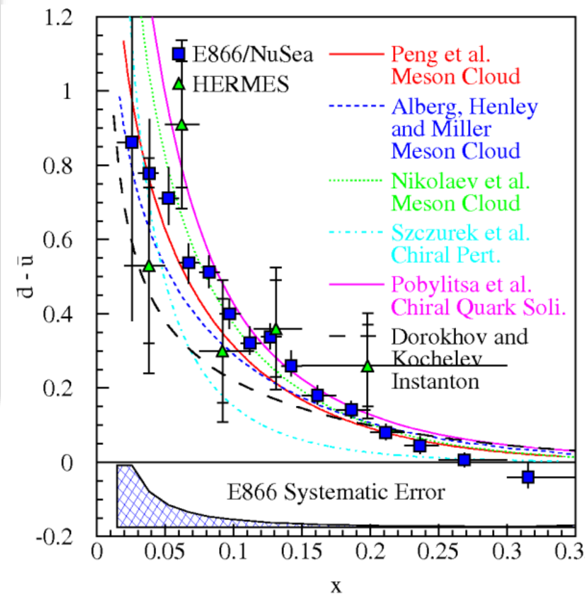


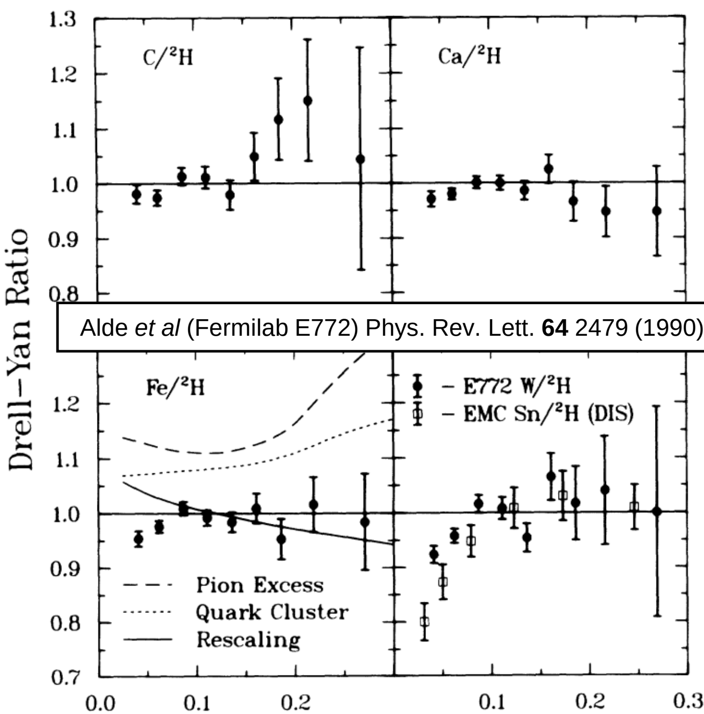
How about the distributions of quarks and gluons in the lightest mesons - pions and kaons?

Why should you be interested in pions and kaons?

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

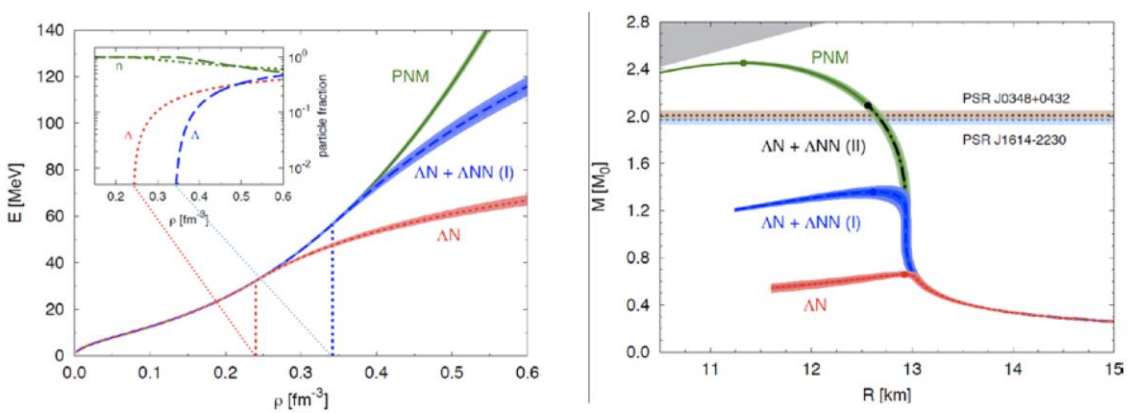
1) The pion, or a meson cloud, explains light-quark asymmetry in the nucleon sea
2) Pions are the Yukawa particles of the nuclear force – but no evidence for excess of nuclear pions or anti-quarks
3) Kaon exchange is similarly related to the ΛN interaction – correlated with the Equation of State and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





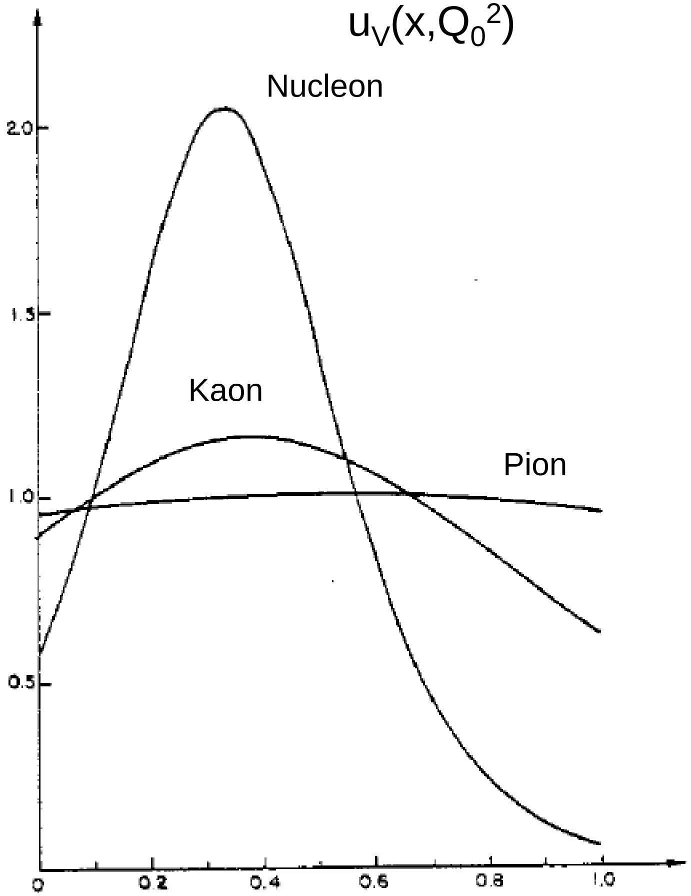
Alde *et al* (Fermilab E772) Phys. Rev. Lett. **64** 2479 (1990)

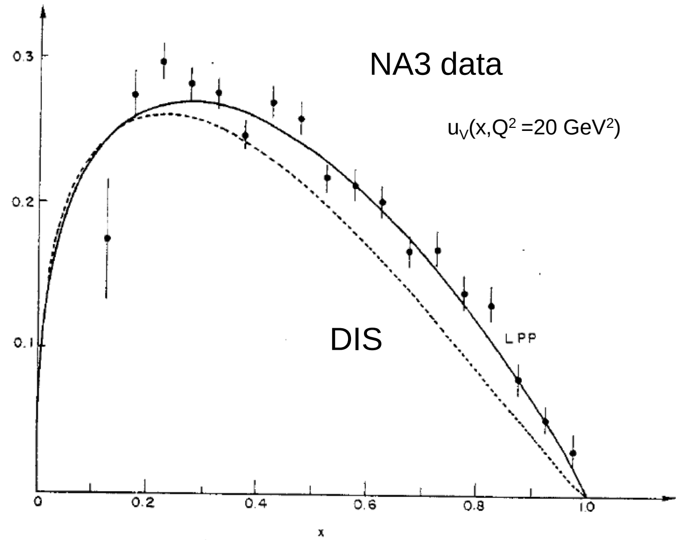
Equations of state and neutron star mass-radius relations



At some level an old story…

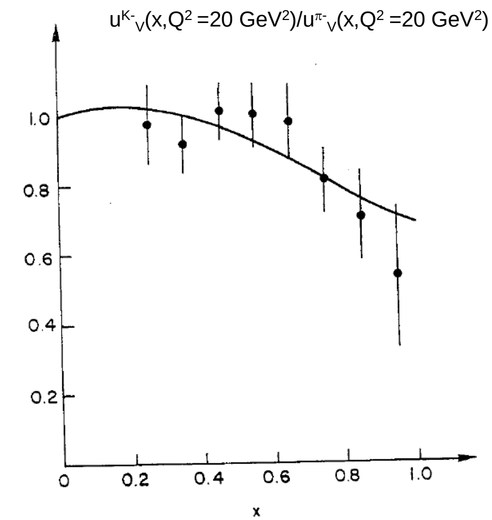
A model for nucleon, pion and kaon structure functions
F. Martin, CERN-TH 2845 (1980)



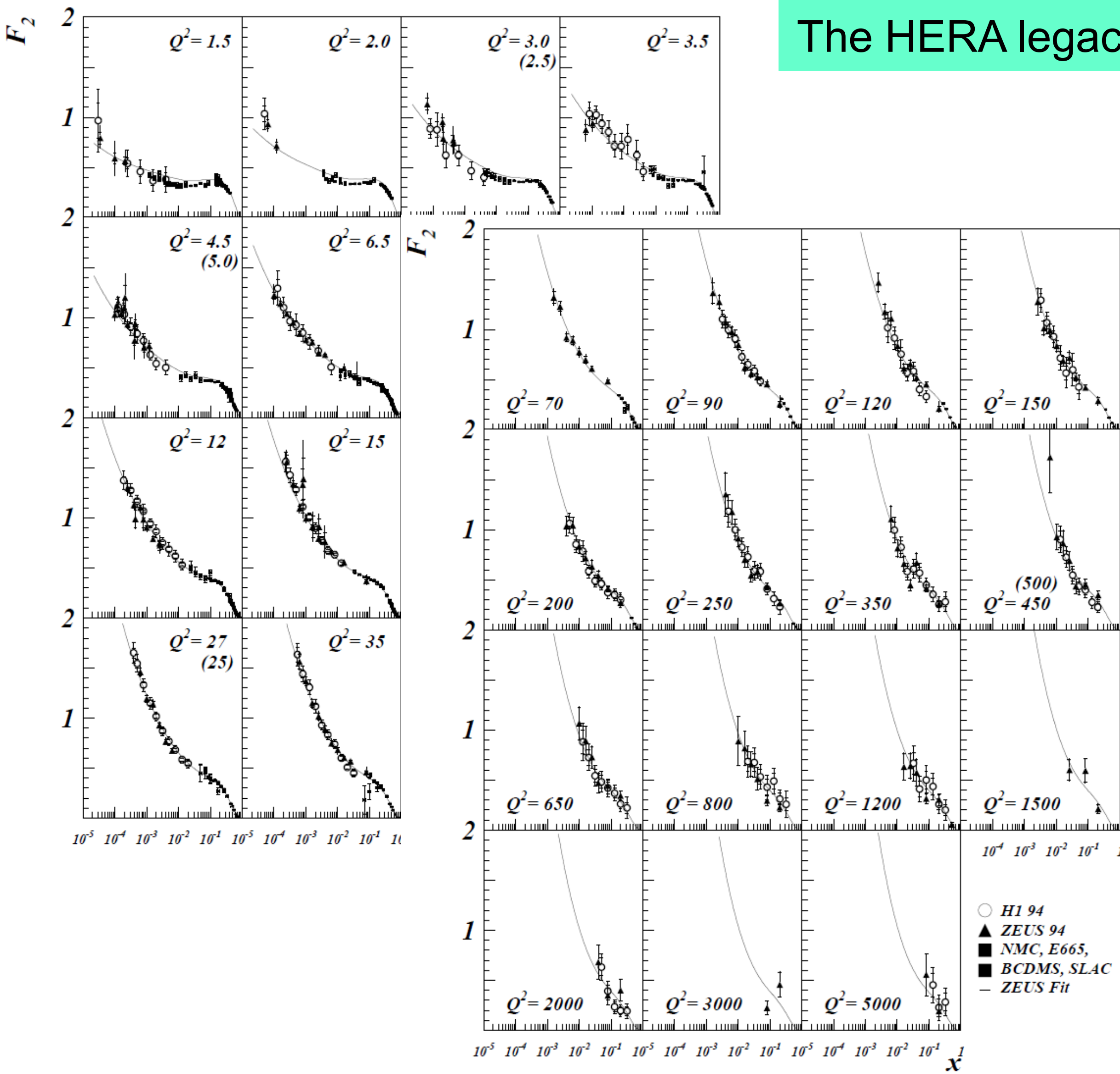


Predictions based on non-relativistic model with valence quarks only

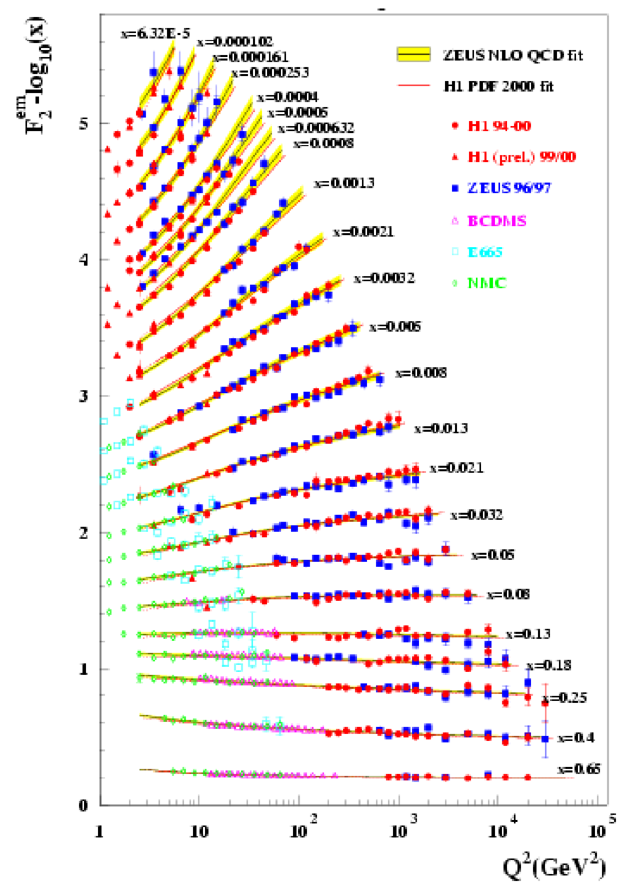
- pion/kaon differs from proton: 2- vs. 3- quark system
- kaon differs from pion owing to one heavy quark



World Data on proton structure function F_2^p

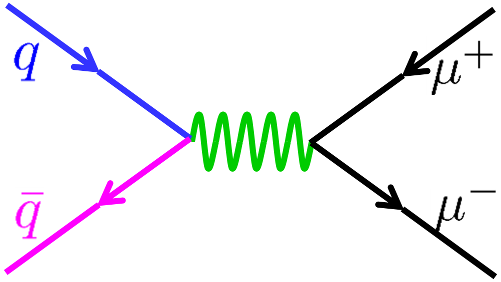


The HERA legacy, a textbook highlight…



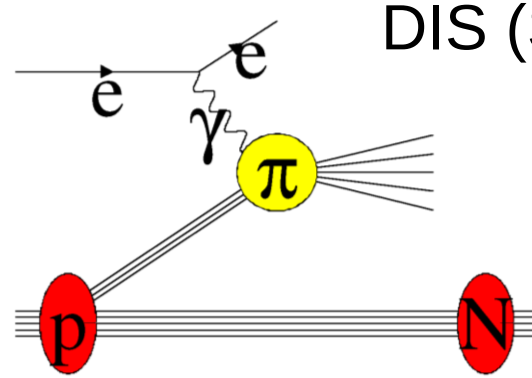
World Data on pion structure function F_2^{π}

Pion Drell-Yan

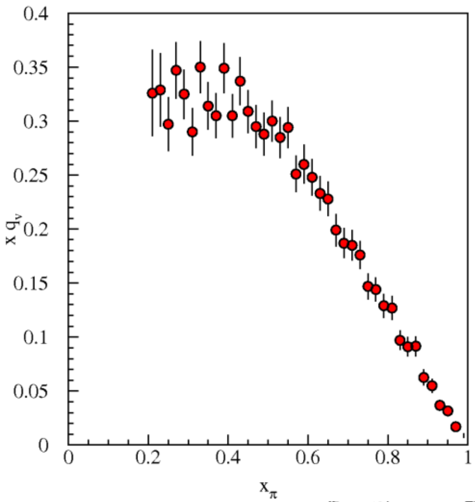


Data much more limited…

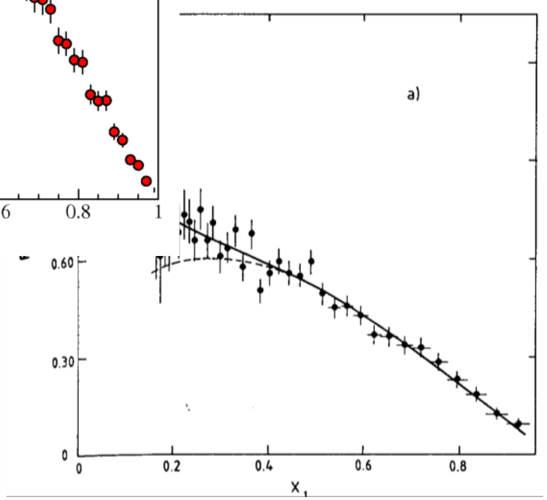
DIS (Sullivan Process)

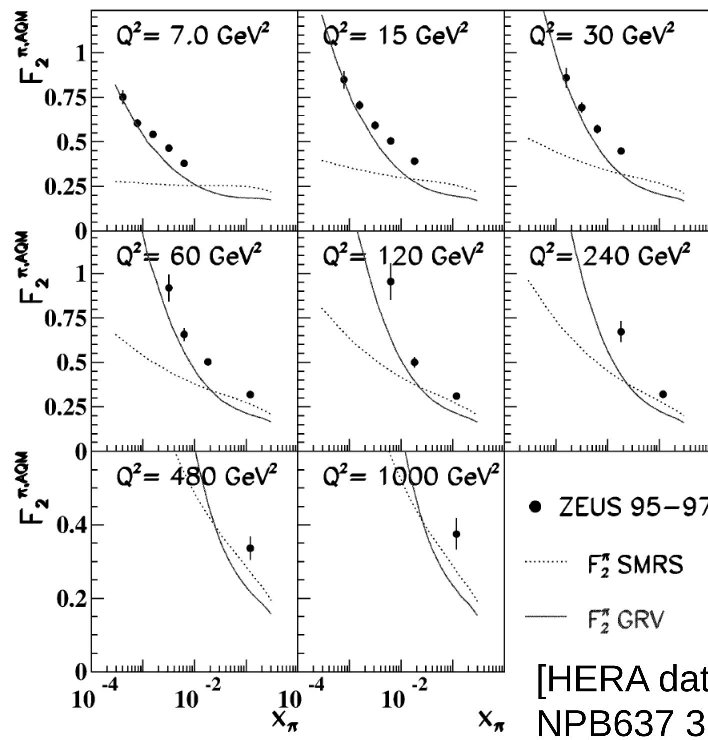


FNAL E615



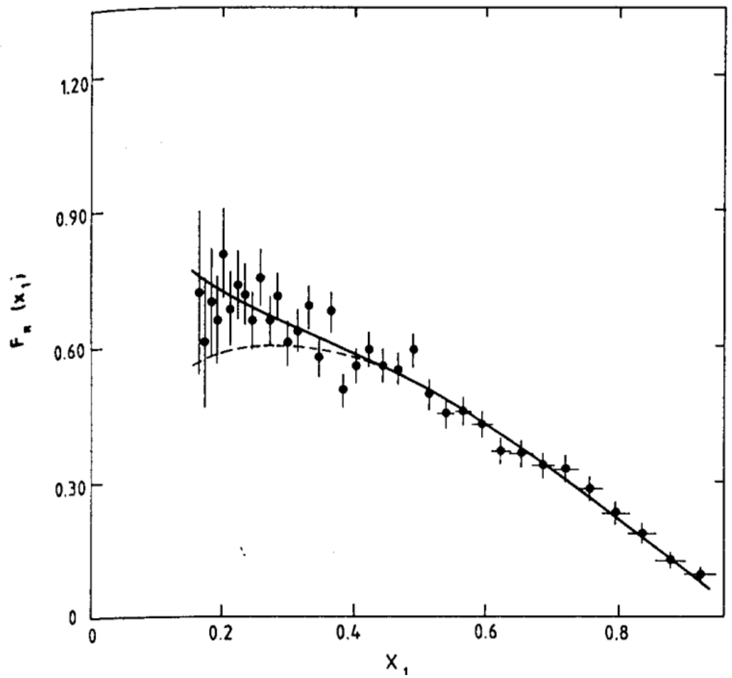
CERN NA3





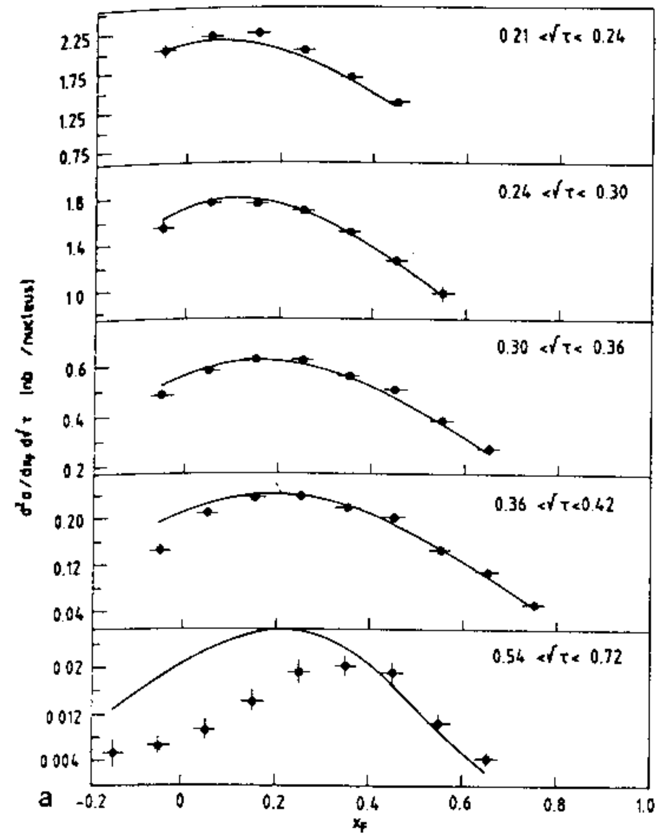
[HERA data [ZEUS, NPB637 3 (2002)]

Pion Drell-Yan Data: CERN NA3 ($\pi^{+/-}$) NA10 (π^{-})



NA3 200 GeV π^{-} data (also have 150 and 180 GeV π^{-} and 200 GeV π^{+} data). *Can determine pion sea*!

$$Q_{\pi}^{\text{sea}} \equiv \int_0^1 x q_{\pi}^{\text{sea}}(x) dx = 0.01$$



NA10 194 GeV π^{-} data

quark sea in pion is small – few %

Pion DIS: Musings about the pion structure function

The Structure of the Pion and Nucleon, and Leading Neutron Production at HERA

Gary Levman, Nucl.Phys. B642 (2002) 3-10

The ZEUS Collaboration has observed that the relative rate of neutron production in photo-production at HERA is *half* that of pp collisions. It follows from Eqn. 5 that $\sigma(\gamma\pi)/\sigma(\gamma p)$ is half $\sigma(\pi p)/\sigma(pp)$. Therefore, as ZEUS deduces directly,

$$\sigma(\gamma\pi) \simeq \sigma(\gamma p)/3$$

rather than two-thirds as expected from Regge factorization or the counting of valence quarks (the Additive Quark Model).

If accepted, some conjectures (per G. Levman article):

- the x dependence of F_2 for all hadrons is similar at low x and is determined mainly by the QCD evolution equations, only weakly by the valence structure.
- the number of partons at low x in the pion is 1/3 that of the proton; ~~since the charged radius of the pion is 2/3 the proton's~~, the volume density of partons in the pion is approximately *the same* as in the proton.
- the quark-antiquark sea of a hadron is generated mainly by valence-valence interactions (three for the proton and one for the pion), and not by self interactions.
- the number of partons at low x in the pion is 1/3 that of the proton - since the charge radius of the pion is only a little smaller than the proton's (R = 0.66 vs 0.84 or 0.88), the volume density of partons in the pion is *smaller* than in the proton.
    - Isn't this what we expect from the pion being the Goldstone boson???

The role of gluons in pions

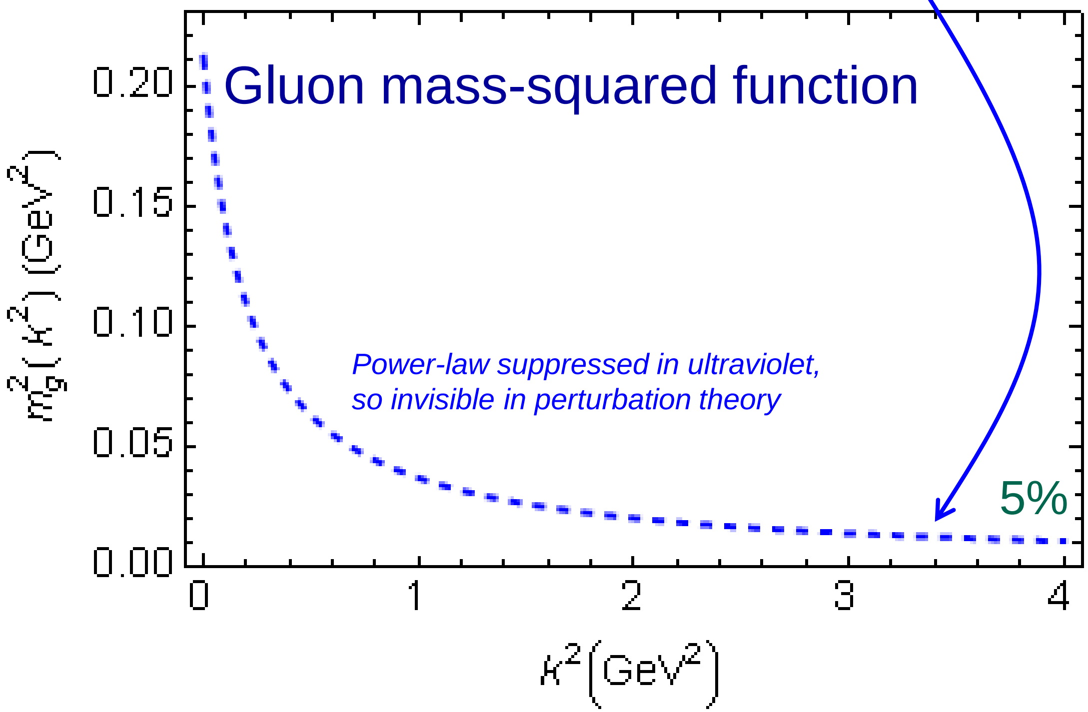
Pion mass is enigma – cannibalistic gluons vs massless Goldstone bosons

$$f_\pi E_\pi(p^2) = B(p^2)$$

$$m_g^2(k^2) = \frac{\mu_g^4}{\mu_g^2 + k^2}$$

Adapted from Craig Roberts:

- ❑ The most fundamental expression of Goldstone's Theorem and DCSB in the SM
- ❑ Pion exists if, and only if, mass is dynamically generated
- ❑ This is why $m_\pi = 0$ in the absence of a Higgs mechanism



What is the impact of this for gluon parton distributions in pions vs nucleons?
One would anticipate a different mass budget for the pion and the proton

Quarks and gluons in pions and kaons

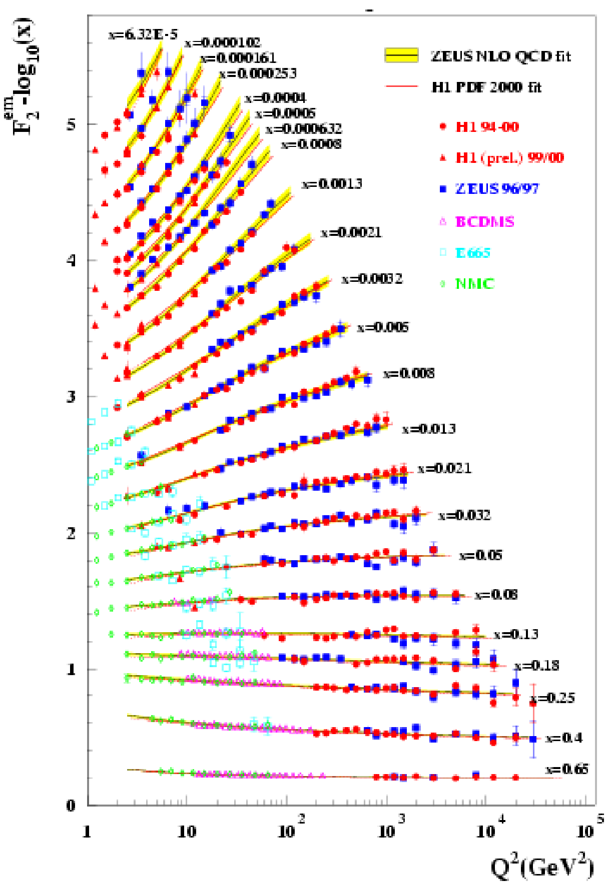
- At low x to moderate x, both the quark sea and the gluons are very interesting.
  - Are the sea in pions and kaons the same in magnitude and shape?
  - Is the origin of mass encoded in differences of gluons in pions, kaons and protons, or do they in the end all become universal?
- At moderate x, compare 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.

At high x, a long-standing issue has been the shape of the pion structure function as given by Drell-Yan data versus QCD expectations. However, this may be a solved case based on gluon resummation, and this may be confirmed with 12-GeV Jefferson Lab data. Nonetheless, soft gluon resummation is a sizable effect for Drell Yan, but expected to be a small effect for DIS, so additional data are welcome.

Landscape for p, π, K structure function after EIC

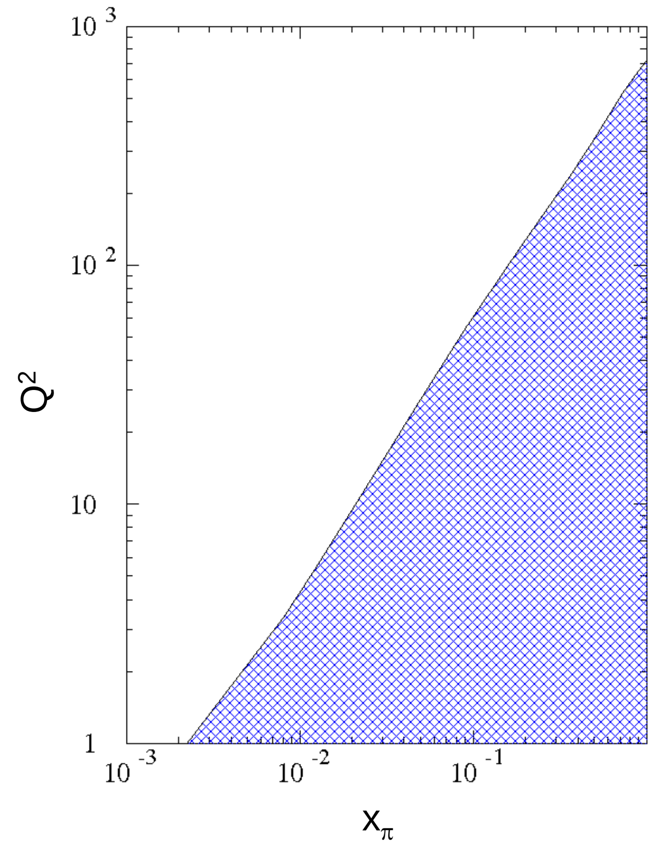
Proton: much existing from HERA

EIC will add:
- Better constraints at large-x
- Precise F_2^n neutron SF data



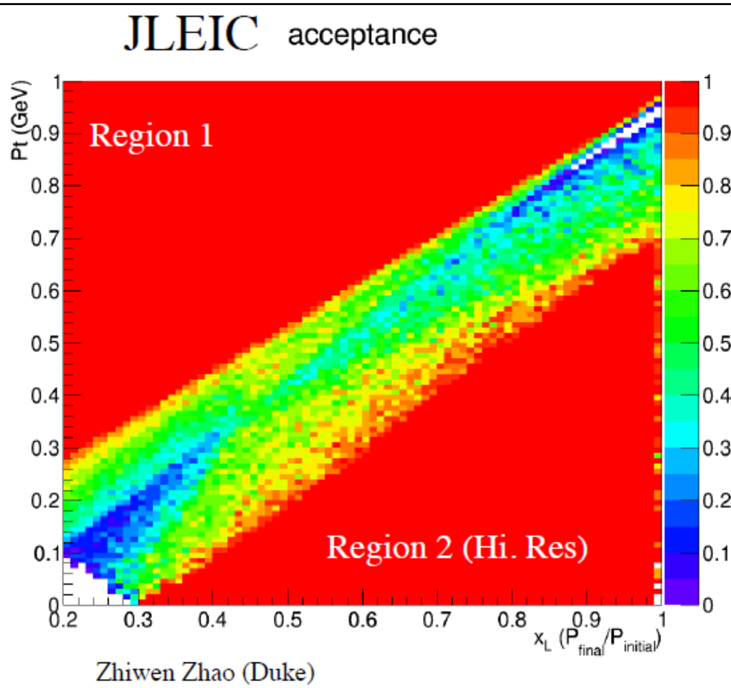
Pion and kaon: only limited data from:
- Pion and kaon Drell-Yan experiments
- Some pion SF data from HERA

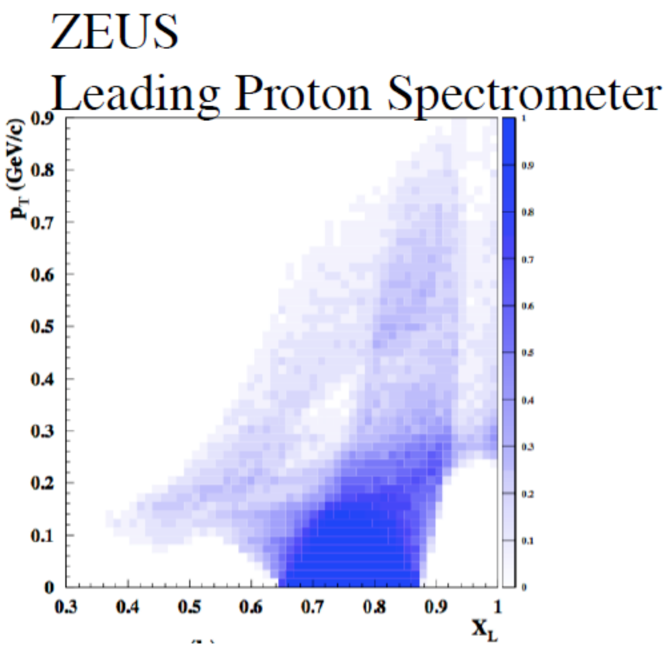
EIC will add large (x,Q^2) landscape for both pion and kaon!



EIC Needs Good Acceptance for Forward Physics!

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





Acceptance in diffractive peak (X_L>~.98)

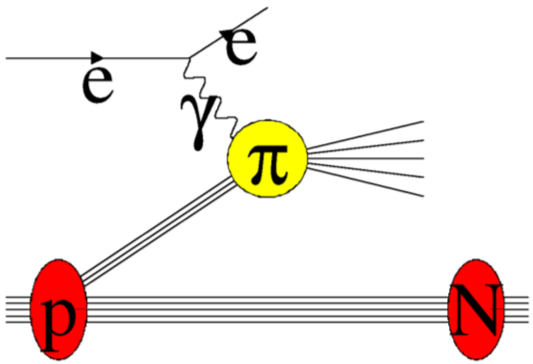
ZEUS: ~2%

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

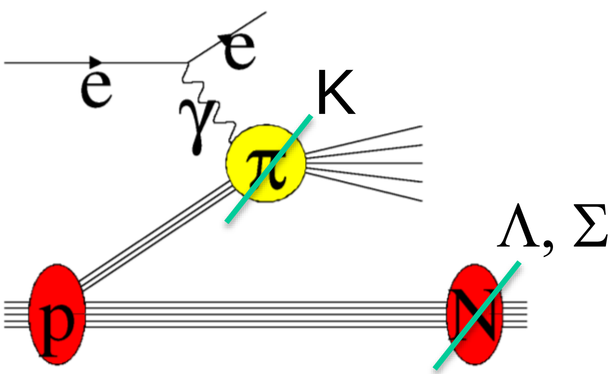
Huge gain in acceptance for forward tagging to measure F_2^n and diffractive physics!!!

Good Acceptance for n, Λ, Σ detection

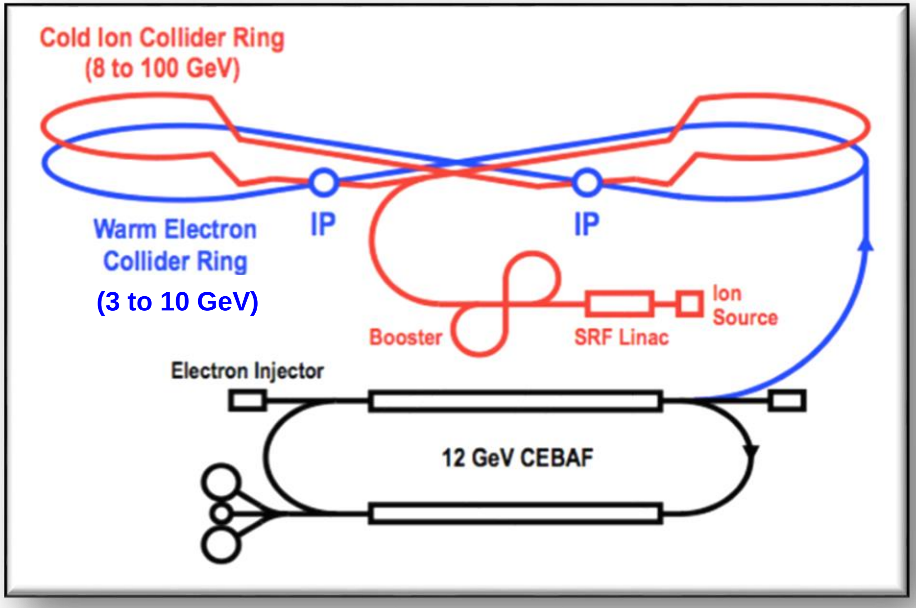
Sullivan process for pion SF



And similar process for kaon SF



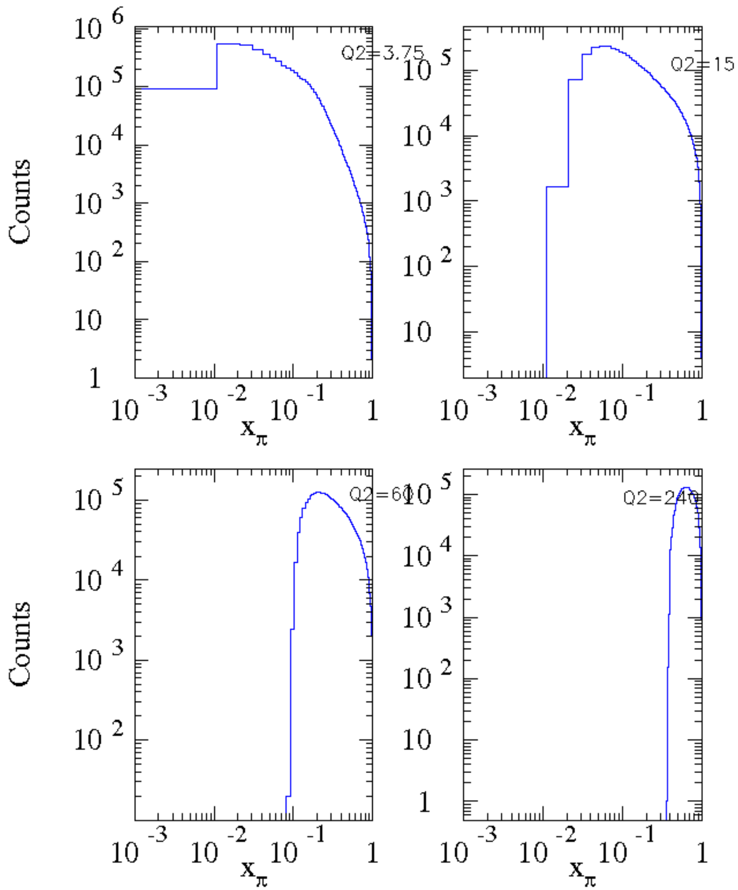
Simulations assume: 5 GeV electrons and 50 GeV protons @ luminosity of 10^{34} $s^{-1}cm^{-2}$

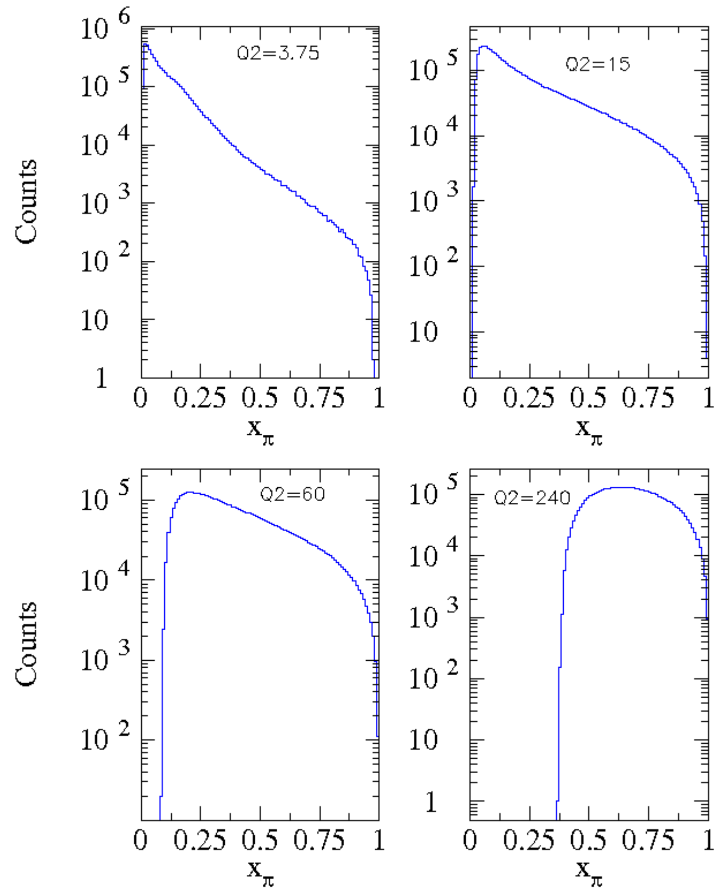


Process	Forward Particle	Geometric Detection Efficiency (at small –t)
$^{1}H(e,e'\pi^{+})n$	N	> 20%
$^{1}H(e,e'K^{+})\Lambda$	Λ	50%
$^{1}H(e,e'K^{+})\Sigma$	Σ	17%

Pion Structure Function Projections

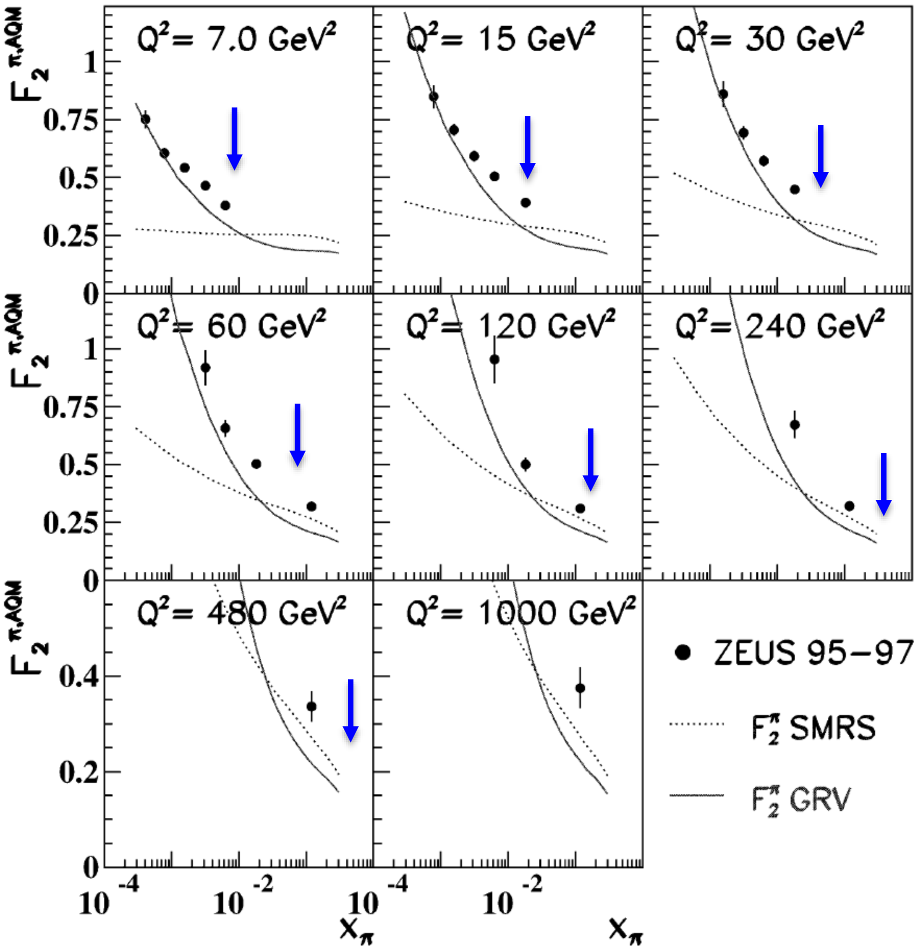
- Counts assume roughly one year of running (26 weeks at 50% efficiency) with 5 GeV electrons and 50 GeV protons at luminosity of $10^{34}\ s^{-1}cm^{-2}$.
- Counts here still need to be multiplied with geometric detection efficiency ~ 20%.





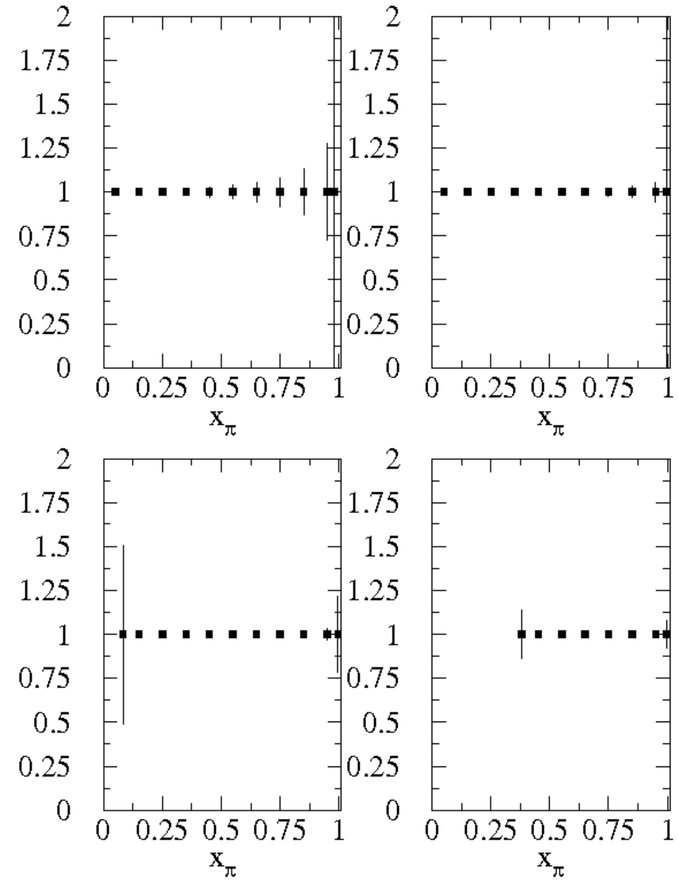
World Data on pion structure function F_2^{π}

HERA



EIC

roughly x_{min} for EIC projections

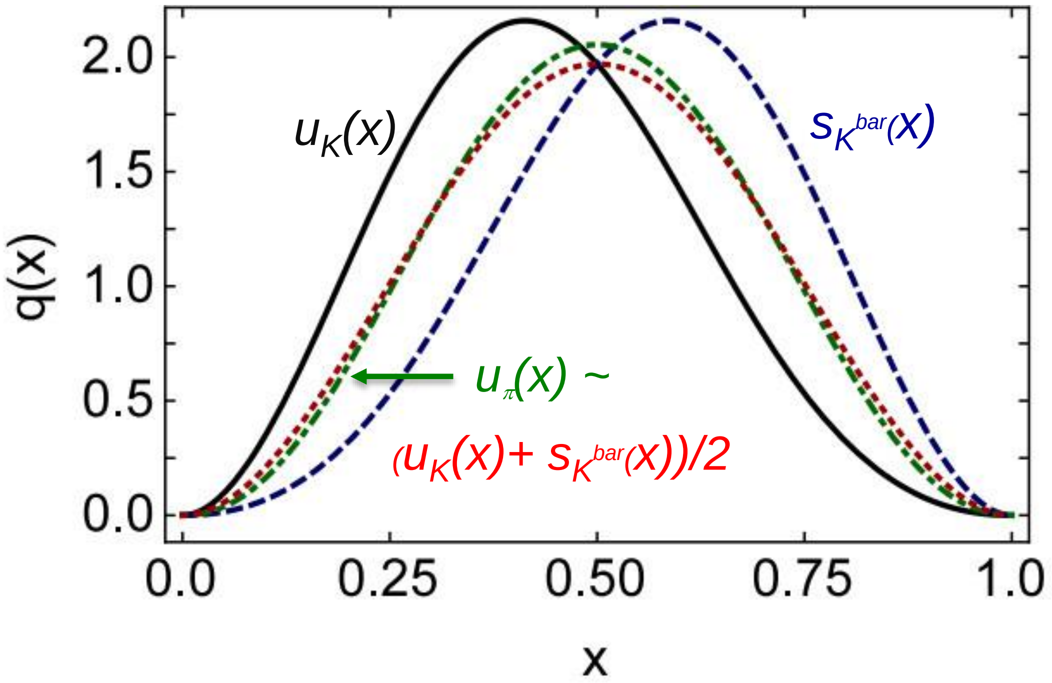


Kaon structure function - valence quarks

C.D. Roberts et al, arXiv:1602.01502 [nucl-th]

- Pointwise results obtained via reconstruction from (arbitrarily many) computed PDF moments.
- Peak in kaon PDFs shifted 17% away from x=½, *i.e.* the scale of flavor symmetry breaking is set by DCSB (M_s/M_u=1.2).
- $[u_K(x)+s_K^{bar}(x)]/2$ must be symmetric, owing to momentum sum rule. Similar, but not identical to $u_\pi(x)$

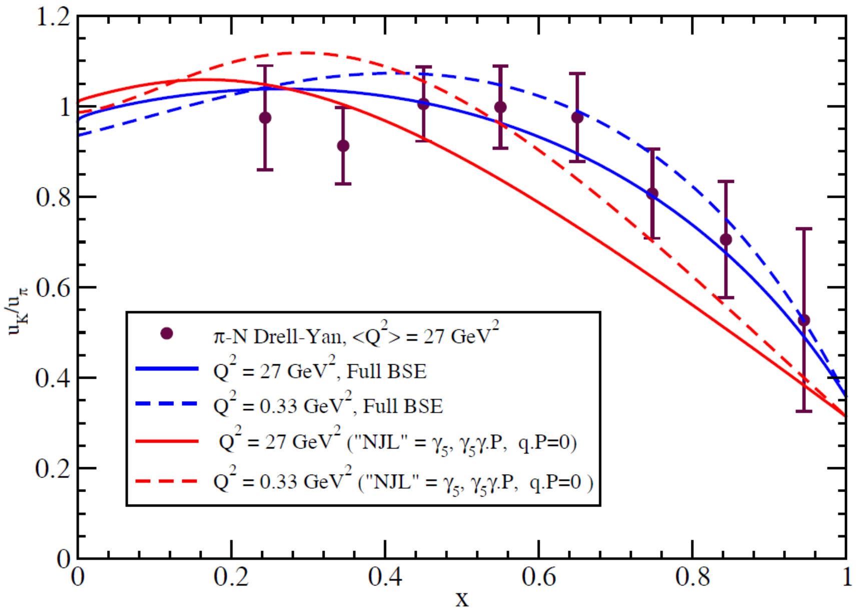
Valence quark pdfs



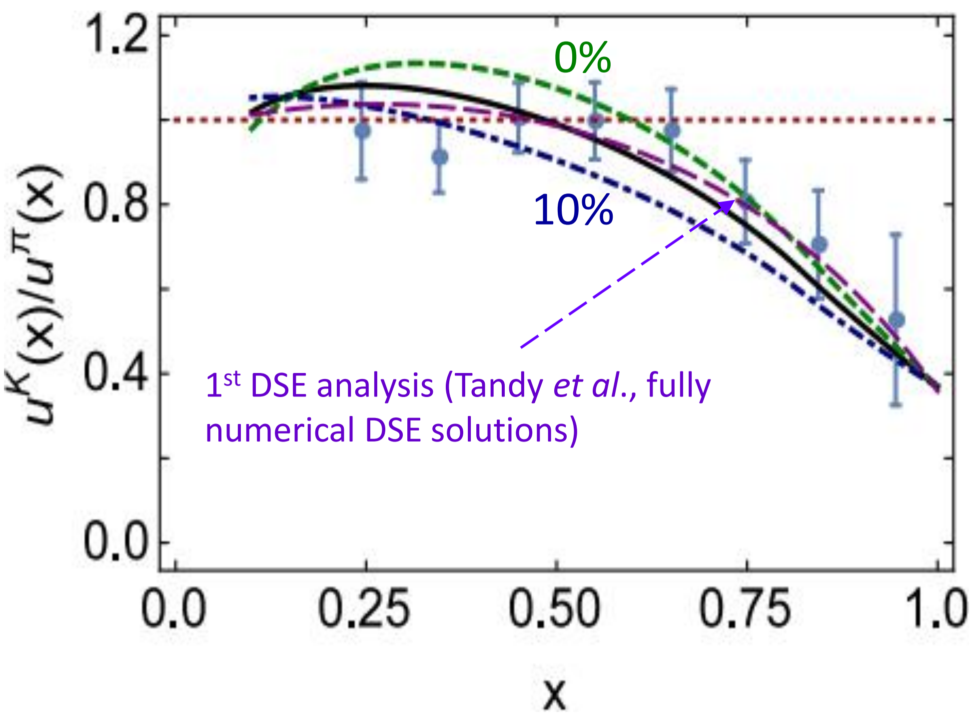
The bulk of this effect may be somewhat trivial and expected since the massive s quark carries most of the momentum of the kaon. *Nevertheless, the effects of gluons will make changes to this effect (see next slide).* This may turn this ratio into an excellent example for textbooks.

u_K/u_π ratios from K/π Drell-Yan Ratios

Predictions of the K/π Drell-Yan ratio based on Bethe-Salpeter Equations (BSE) work well – 1st fully numerical DSE analysis



Gluon content of the kaon



T. Nguyen, A. Bashir, C.D. Roberts and P.C. Tandy, Phys. Rev. C**83** (2011) 062201
Data: Badier *et al.* Phys. Lett. **B93** 354 (1980)

Kaon structure functions – gluon pdfs

Based on Lattice QCD calculations and DSE calculations:

- ❑ Valence quarks carry 52% of the pion's momentum at the light front, at the scale used for Lattice QCD calculations, or roughly 65% at the perturbative hadronic scale

- ❑ At the same scale, valence-quarks carry ⅔ of the kaon's light-front momentum, or roughly 95% at the perturbative hadronic scale

Thus, at a given scale, there is far less glue in the kaon than in the pion:

- ➢ heavier quarks radiate less readily than lighter quarks
- ➢ heavier quarks radiate softer gluons than do lighter quarks
- ➢ Landau-Pomeranchuk effect: softer gluons have longer wavelength and multiple scatterings are suppressed by interference.
- ➢ Momentum conservation communicates these effects to the kaon's u-quark.

Calculable Limits for Parton Distributions

- Calculable limits for ratios of PDFs at x = 1, same as predictive power of x → 1 limits for spin-averaged and spin-dependent proton structure functions (asymmetries)

$$\left.\frac{u_V^K(x)}{u_V^\pi(x)}\right|_{x\to 1} = 0.37\,, \quad \left.\frac{u_V^\pi(x)}{\bar{s}_V^K(x)}\right|_{x\to 1} = 0.29$$

- On the other hand, inexorable growth in both pions' and kaons' gluon and sea-quark content at asymptotic Q^2 should only be driven by pQCD splitting mechanisms. Hence, also calculable limits for ratios of PDFs at x = 0, *e.g.*,

$$\lim_{x\to 0} \frac{u^K(x;\zeta)}{u^\pi(x;\zeta)} \overset{\Lambda_{QCD}/\zeta\simeq 0}{\to} 1$$

The inexorable growth in both pions' and kaons' gluon content at asymptotic Q^2 provides connection to gluon saturation.

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

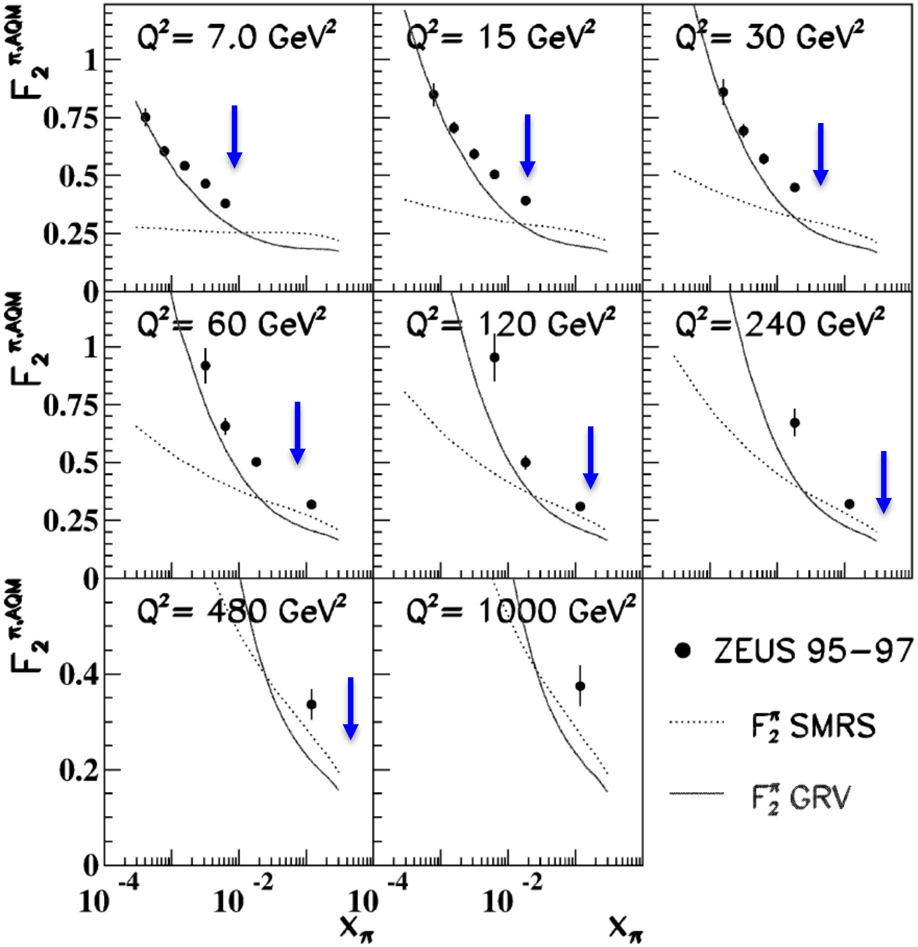
(these values can vary depending on what model one uses, so sometimes a range is used, *e.g.*, 13.1-13.5 for $g_{\pi NN}$)

- 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%

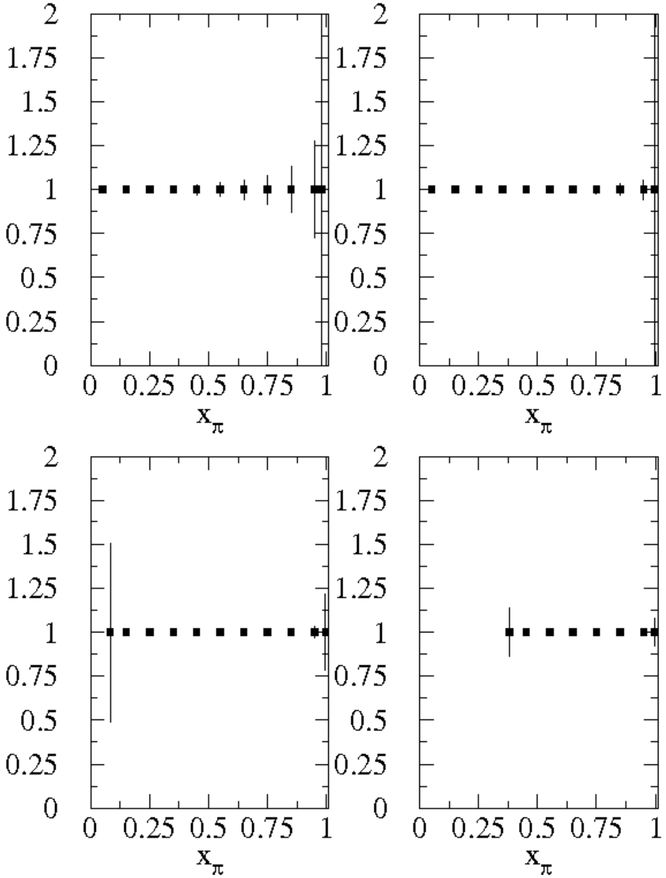
World Data on pion structure function F_2^π

HERA



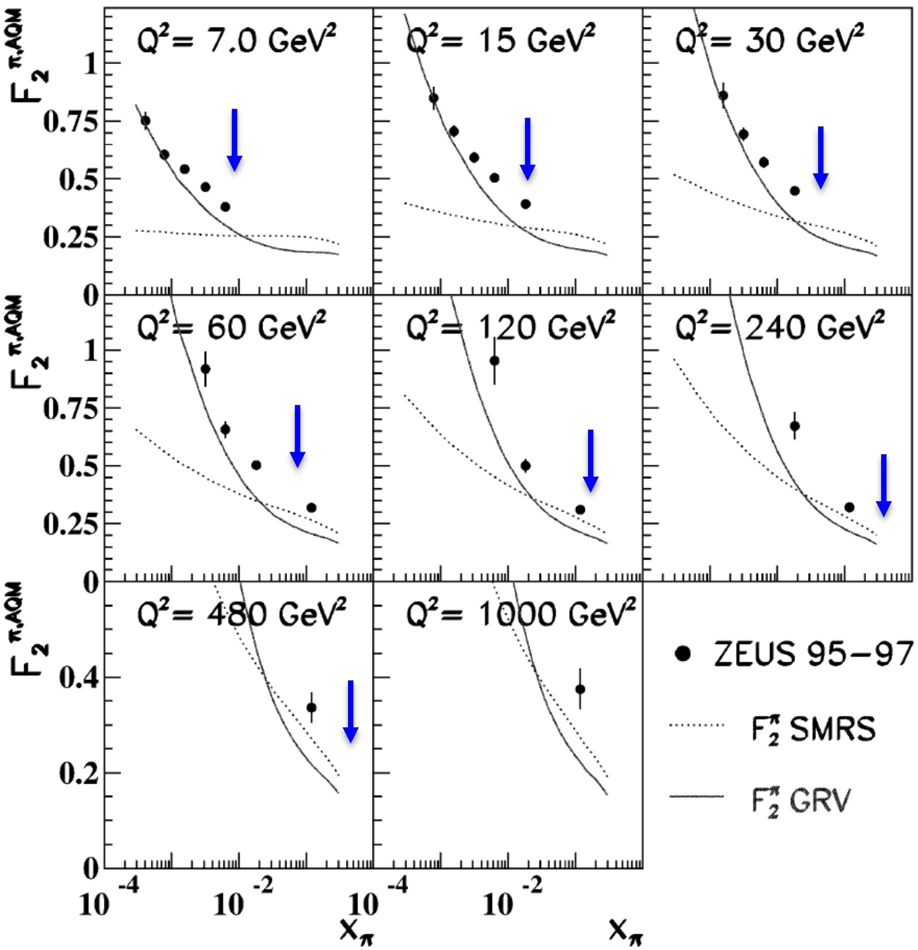
EIC

roughly x_{min} for EIC projections



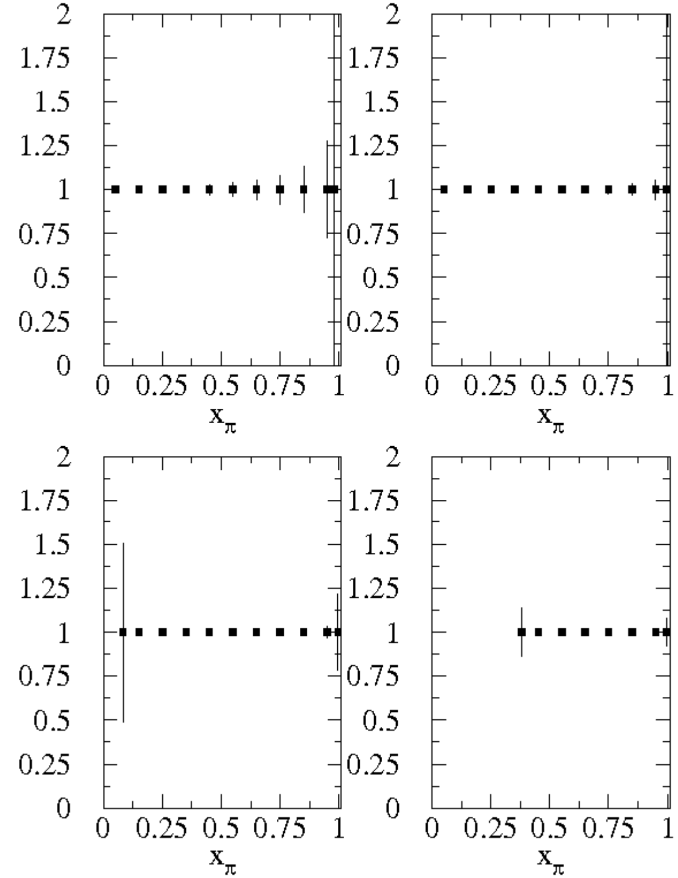
World Data on kaon structure function F_2^K

HERA



EIC

roughly x_{min} for EIC projections



Pion vs. Kaon parton distributions

- Flavor-dependence of DCSB modulates the strength of SU(3)-flavor symmetry breaking in meson PDFs

From: Craig Roberts et al.

- At perturbative hadronic scale ζ_H:
  - valence dressed-quarks carry roughly two-thirds of pion's light-front carried by glue … sea-quarks carry roughly 5%
  - valence dressed-quarks carry approximately 95% of the kaon's light-front momentum, with the remainder lying in the gluon distribution … sea-quarks carry $\simeq$ 0 %
  - heavier s-quarks radiate soft gluons less readily than lighter quarks and momentum conservation subsequently constrains gluons associated with the kaon's u-quark

- Evolving distributions to scale characteristic of meson-nucleon Drell-Yan experiments, ζ=5.2 GeV
  - ratio $u_K(x)/u_\pi(x)$ explained by vastly different gluon content of π & K

- Distributions evolved the distributions to ζ_2 = 2 GeV, which is typically used in numerical simulations of lattice-regularised QCD:
  - Valence-quarks carry roughly half the pion's light-front momentum but two-thirds of the kaon's momentum

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.