Pion and Kaon Structure Functions at EIC

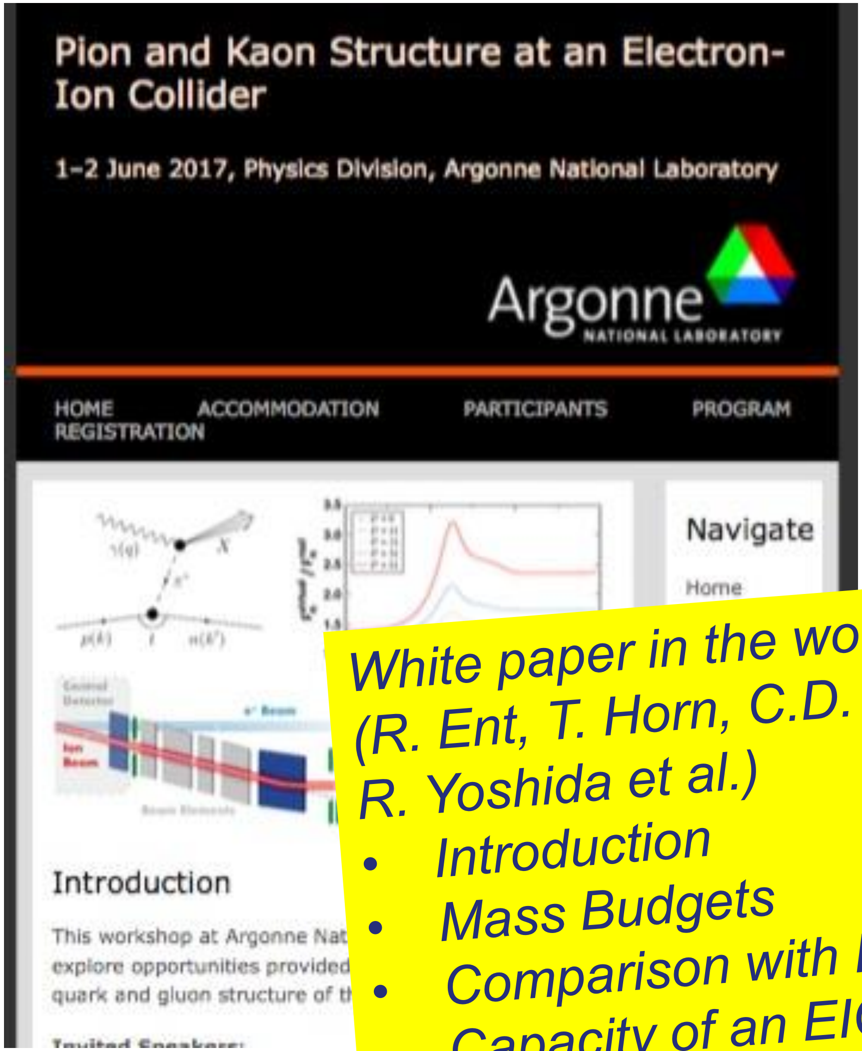
Collaboration with Ian Cloet, Tanja Horn, Thia Keppel, Wally Melnitchouk, Kijun Park, Paul Reimer, Craig Roberts, Nobuo Sato, Richard Trotta, Rik Yoshida

Thanks to: Roy Holt, Yulia Furletova, Elke Aschenauer and Steve Wood

Rolf Ent (Jefferson Lab)

Emergent Mass and its Consequences in the SM
ECT*, Trento, September 17, 2018

Much based on White Paper in Production



Pion and Kaon Structure at an Electron-Ion Collider

1-2 June 2017, Physics Division, Argonne National Laboratory

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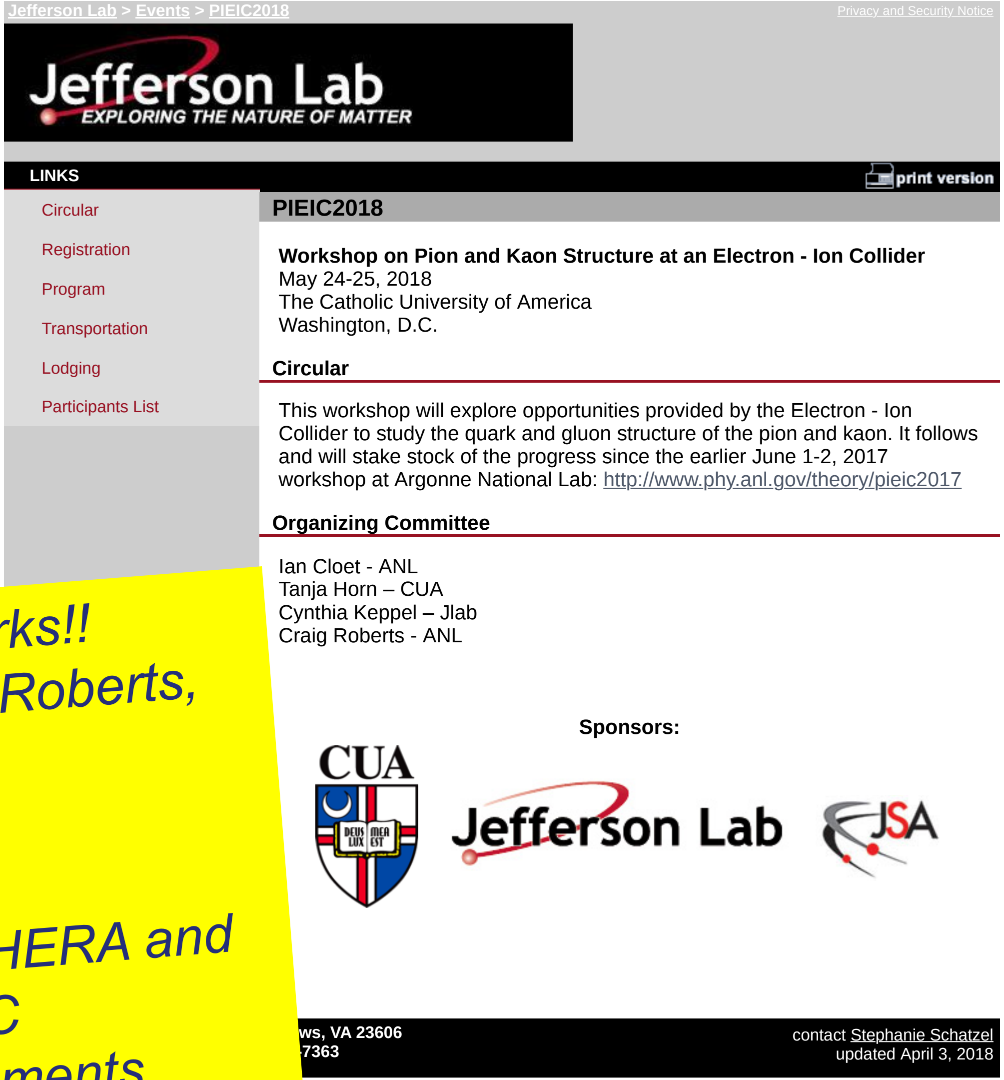
Introduction

This workshop at Argonne Nat
explore opportunities provided
quark and gluon structure of th

Invited Speakers:



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PIEIC2018

Workshop on Pion and Kaon Structure at an Electron - Ion Collider
May 24-25, 2018
The Catholic University of America
Washington, D.C.

Circular

This workshop will explore opportunities provided by the Electron - Ion Collider to study the quark and gluon structure of the pion and kaon. It follows and will stake stock of the progress since the earlier June 1-2, 2017 workshop at Argonne National Lab: http://www.phy.anl.gov/theory/pieic2017

Organizing Committee

Ian Cloet - ANL
Tanja Horn – CUA
Cynthia Keppel – Jlab
Craig Roberts - ANL

Sponsors:

ws, VA 23606
7363

contact Stephanie Schatzel
updated April 3, 2018

White paper in the works!!
(R. Ent, T. Horn, C.D. Roberts, R. Yoshida et al.)

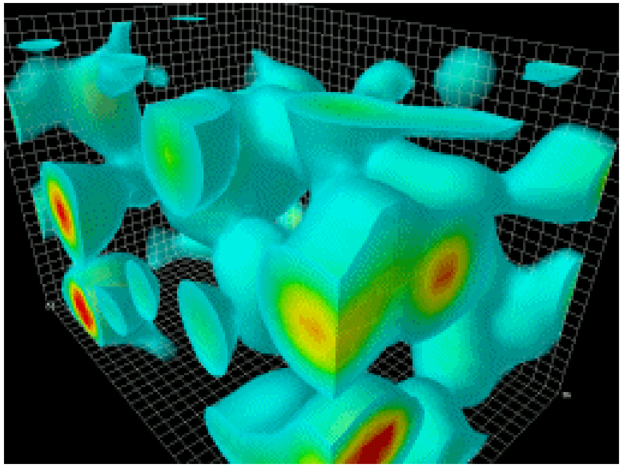
- *Introduction*
- *Mass Budgets*
- *Comparison with HERA and Capacity of an EIC*
- *Key EIC Measurements*

Outline

- The Emergence of Mass
- J/Ψ and Upsilon Threshold Production at an EIC
- Pion and Kaon PDFs – History
- Versatility and Detection Capabilities at an EIC
- Off-Shellness Considerations
- First Check of Impact of EIC on Pion PDFs
- Prospects for Kaon PDFs at an EIC
- EIC Measurement of Pion Form Factor at High Q^2

Gluons and QCD

- QCD is the fundamental theory that describes structure and interactions in nuclear matter.
- Without gluons there are no protons, no neutrons, and no atomic nuclei
- Gluons dominate the structure of the QCD vacuum



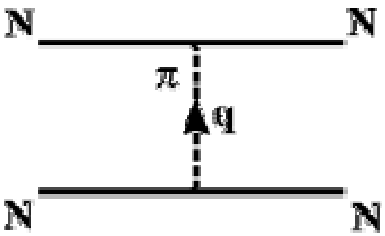
$$L_{QCD} = \sum_{j=u,d,s,\ldots} \bar{q}_j \left[i\gamma^\mu D_\mu - m_j \right] q_j - \frac{1}{4} G^a_{\mu\nu} G^{a\mu\nu}$$

$$D_\mu = \partial_\mu + ig\tfrac{1}{2}\lambda^a A^a_\mu, \, G^a_{\mu\nu} = \partial_\mu A_\nu + \partial_\nu A_\mu \boxed{+ igf^{abc} A^b_\mu A^c_\nu}$$

- Facts:
  - Unique aspect of QCD is the self interaction of the gluons
  - The essential features of QCD - asymptotic freedom and (the emergent features) dynamical chiral symmetry breaking and color confinement - are all driven by gluons!
  - Mass from massless gluons and nearly massless quarks
    - Most of the mass of the visible universe emerges from quark-gluon interactions
    - The Higgs mechanism has almost no role here

Origin of mass of QCD's pseudoscalar Goldstone modes

- The pion is responsible for the long-range part of the nuclear force, acting as the basis for meson exchange forces and playing a critical role as an elementary field in nuclear structure Hamiltonians



- The pion is both the lightest bound quark system with a valence $q\bar{q}$ structure and a Nambu-Goldstone boson

- There are 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**
  - The mass of bound states increases as √m with the constituent masses – $m_\pi^2 \sim \sqrt{m_q}$
  - 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.*, 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 one 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.

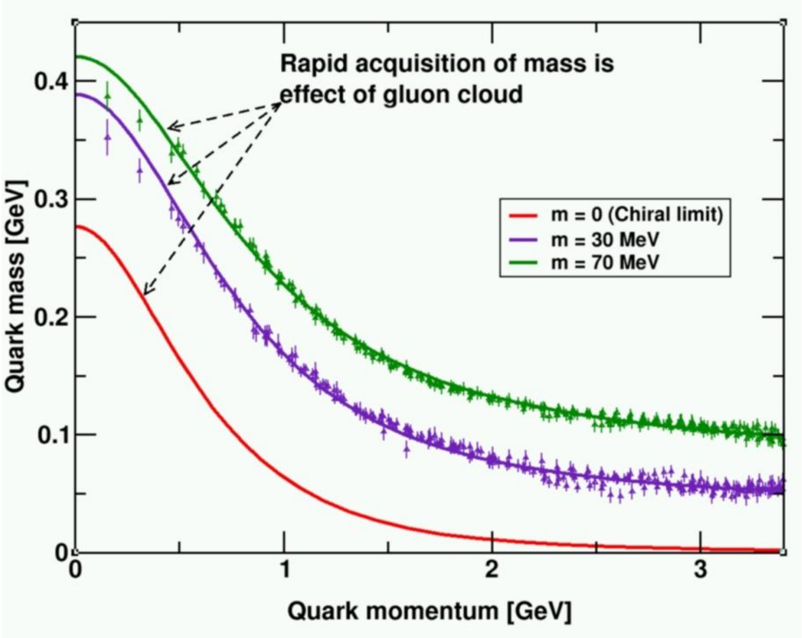
The role of gluons in pions

Pion mass is enigma – cannibalistic gluons vs massless Goldstone bosons

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

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 – "because of B, there is a pion"
- On the other hand, in absence of the Higgs mechanism, the pion mass $m_\pi = 0$ – the pion mass^2 is entirely driven by the current quark mass (for reference, for the ρ, only 6% of its mass^2 is driven by this).



Rapid acquisition of mass is effect of gluon interactions

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

The role of gluons in the chiral limit

In the chiral limit, using a parton model basis: *the entirety of the proton mass is produced by gluons and due to the trace anomaly*

$$\langle P(p)|\Theta_0|P(p)\rangle = -p_\mu p_\mu = m_N^2$$

In the chiral limit, for the pion ($m_\pi = 0$):

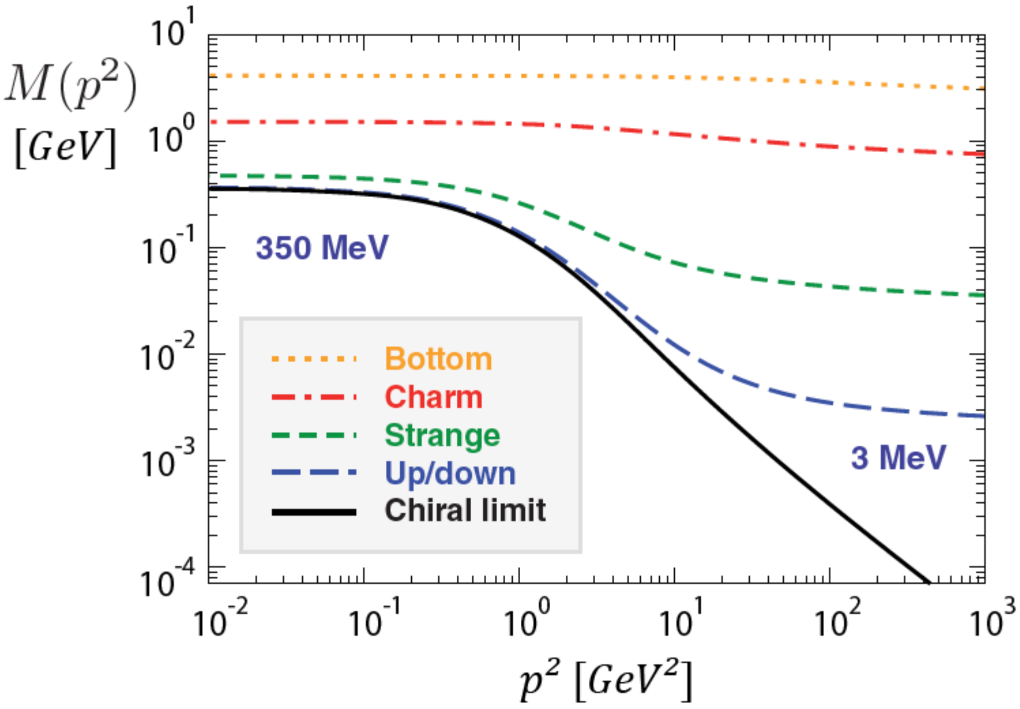
$$\langle \pi(q)|\Theta_0|\pi(q)\rangle = -q_\mu q_\mu = m_\pi^2 = 0$$

Sometimes interpreted as: *in the chiral limit the gluons disappear and thus contribute nothing to the pion mass*.

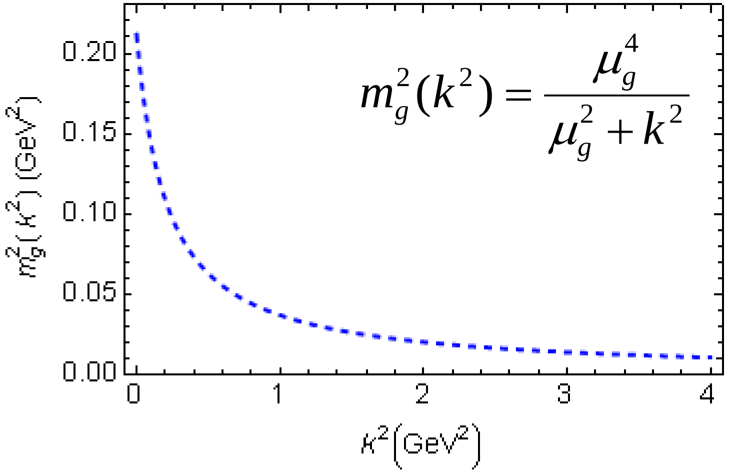
This is unlikely as quarks and gluons still dynamically acquire mass – this is a universal feature in hadrons – so more likely a cancellation of terms leads to "0"

Nonetheless: are there gluons at large Q^2 in the pion or not?

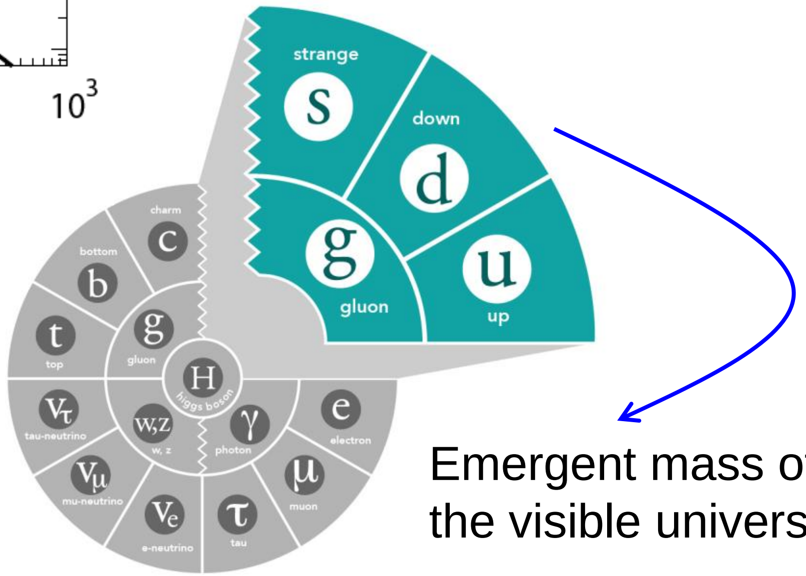
Mass of the Visible Universe



Gluon mass-squared function



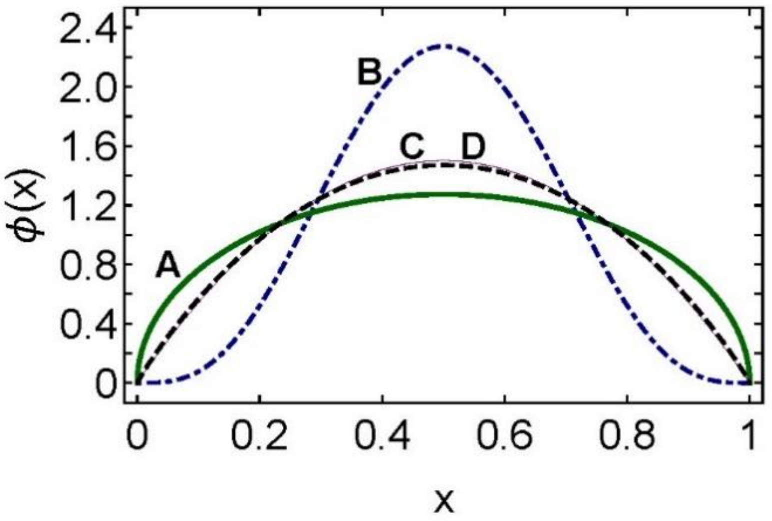
The strange quark is at the boundary - both emergent-mass and Higgs-mass generation mechanisms are important.



Emergent mass of the visible universe

Emergent- versus Higgs-Mass Generation

Twist-2 PDA at Scale ζ = 2 GeV



Unfortunately, experimental signatures of the exact PDA form are, in general, difficult.

A solid (green) curve – pion ⇐ emergent mass is dominant;

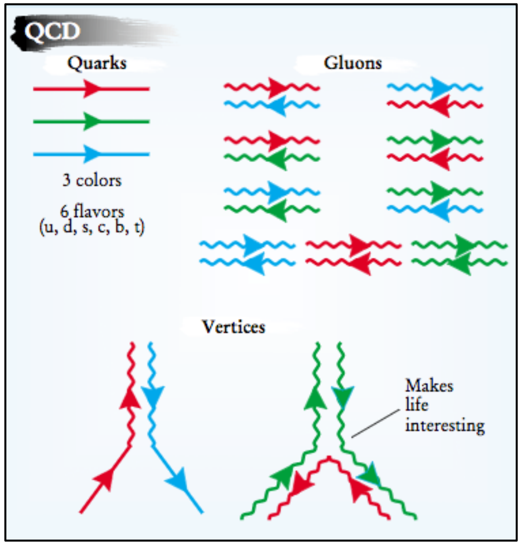
B dot-dashed (blue) curve – η_c ⇐ primarily, Higgs mass generation;

C solid (thin, purple) curve – conformal limit result, 6x(1 - x); and

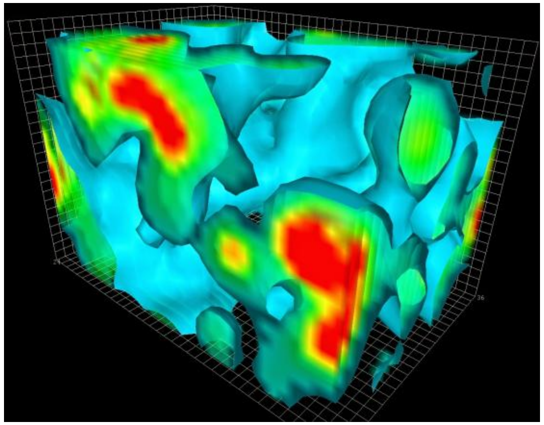
D dashed (black) curve – "heavy-pion", i.e., a pion-like pseudo-scalar meson ($\sim\eta_s$) in which the valence-quark current masses take values corresponding to a strange quark ⇐ the border, where emergent and Higgs mass generation are equally important.

- In the limit of infinitely-heavy quark masses, the Higgs mechanism overwhelms every other mass generating force, and the PDA becomes a δ-function at x = ½.
- The sufficiently heavy η_c meson (**B**), feels the Higgs mechanism strongly.
- The PDA for the light-quark pion (**A**) is a broad, concave function, a feature of emergent mass generation.

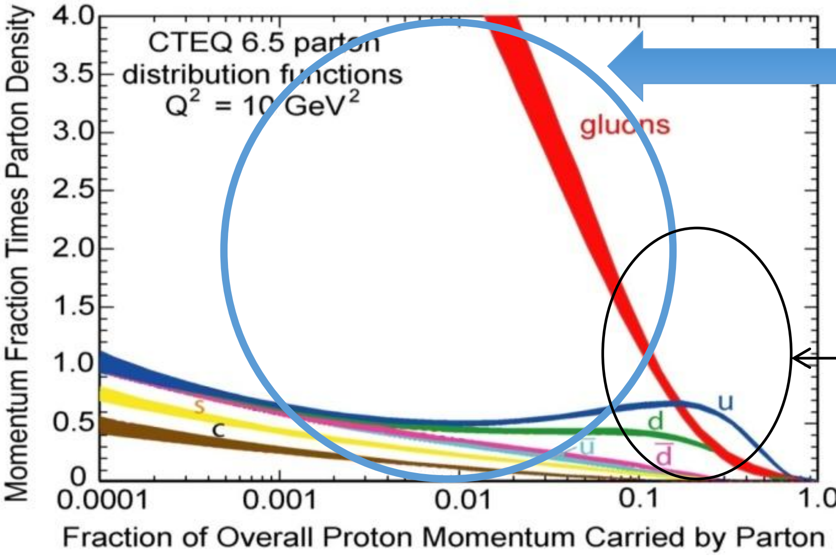
Cold Matter is Unique



Interactions and Structure are entangled because of gluon self-interaction.



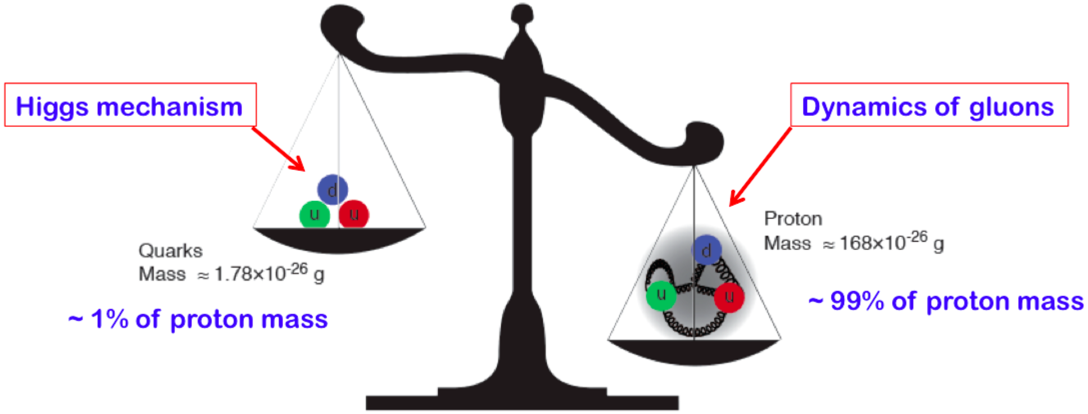
Observed properties such as mass and spin emerge from this complex system.

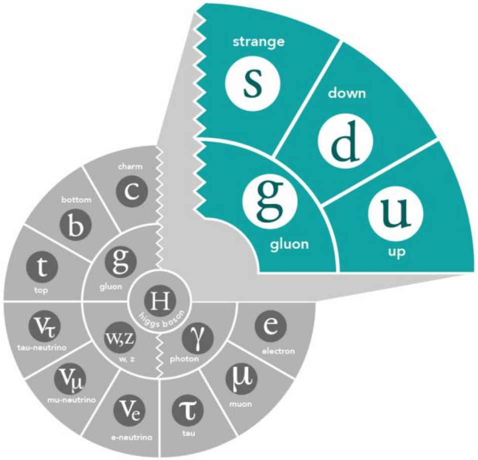


EIC needed to explore the gluon dominated region

JLAB 12 to explore the valence quark region

The Incomplete Nucleon: Mass Puzzle





"… The vast majority of the nucleon's mass is due to quantum fluctuations of quark-antiquark pairs, the gluons, and the energy associated with quarks moving around at close to the speed of light. …"

- ❑ Proton mass:

$$M = \overbrace{\underbrace{E_q}_{\text{Quark Energy}} + \underbrace{E_g}_{\text{Gluon Energy}}}^{\text{Relativistic motion}} + \overbrace{\underbrace{\chi_{m_q}}_{\text{Quark Mass}} + \underbrace{T_g}_{\text{Trace Anomaly}}}^{\text{Quantum fluctuation}}$$

Not unambiguous: Physical interpretation of the proton mass decomposition also has to be done with care, as one seemingly treats gluons in the trace anomaly and in kinetic and potential energy as separate entities (C. Lorcé, Eur. Phys. J. C 78 (2018) 120).

The Incomplete Nucleon: Mass Puzzle

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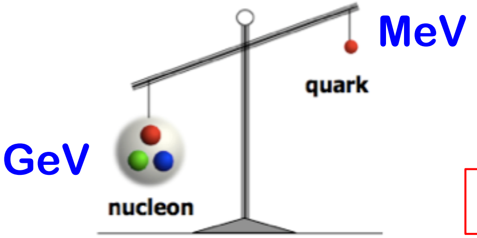
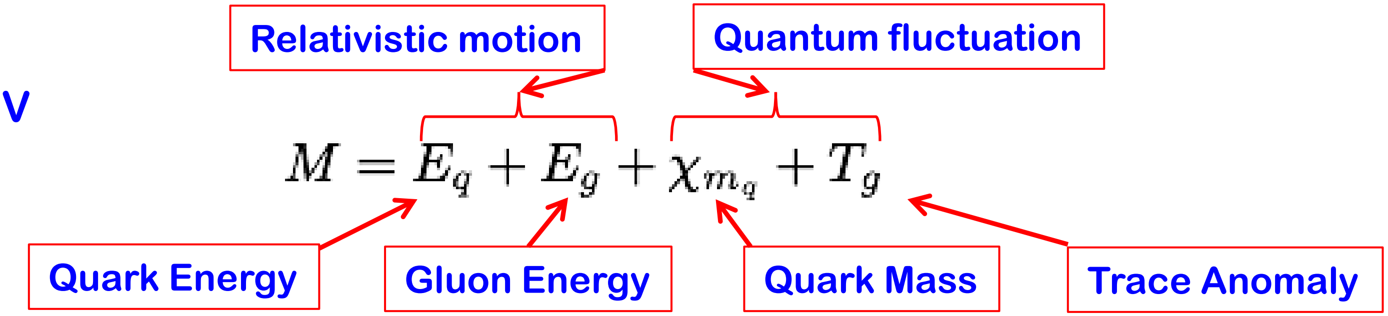




$$M = \overbrace{E_q + E_g}^{\text{Relativistic motion}} + \overbrace{\chi_{m_q} + T_g}^{\text{Quantum fluctuation}}$$

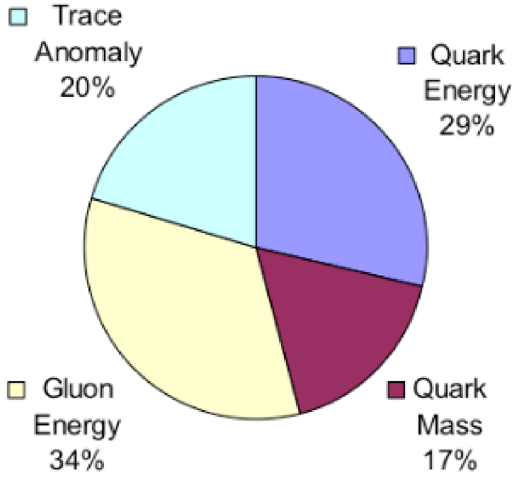
Quark Energy

Gluon Energy

Quark Mass

Trace Anomaly

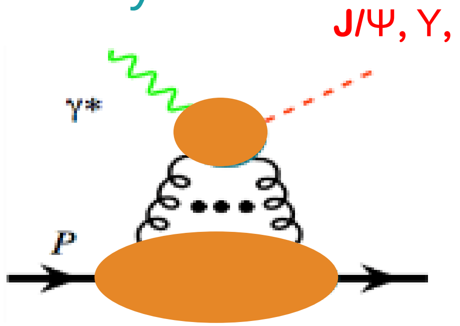
❑ Preliminary Lattice QCD results:



❑ EIC projected measurements:

✧ trace anomaly:

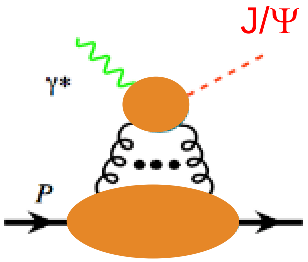
Upsilon production near the threshold



✧ Quark-gluon energy: SIDIS

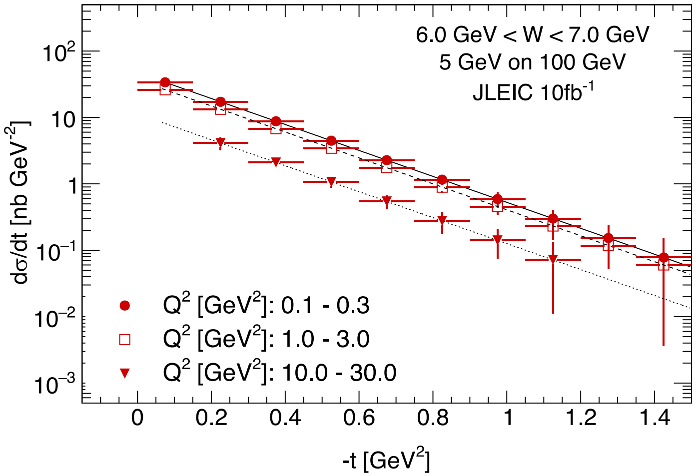
Elastic J/Ψ production near threshold at an EIC

At an EIC a study of the Q^2 dependence in the threshold region is possible

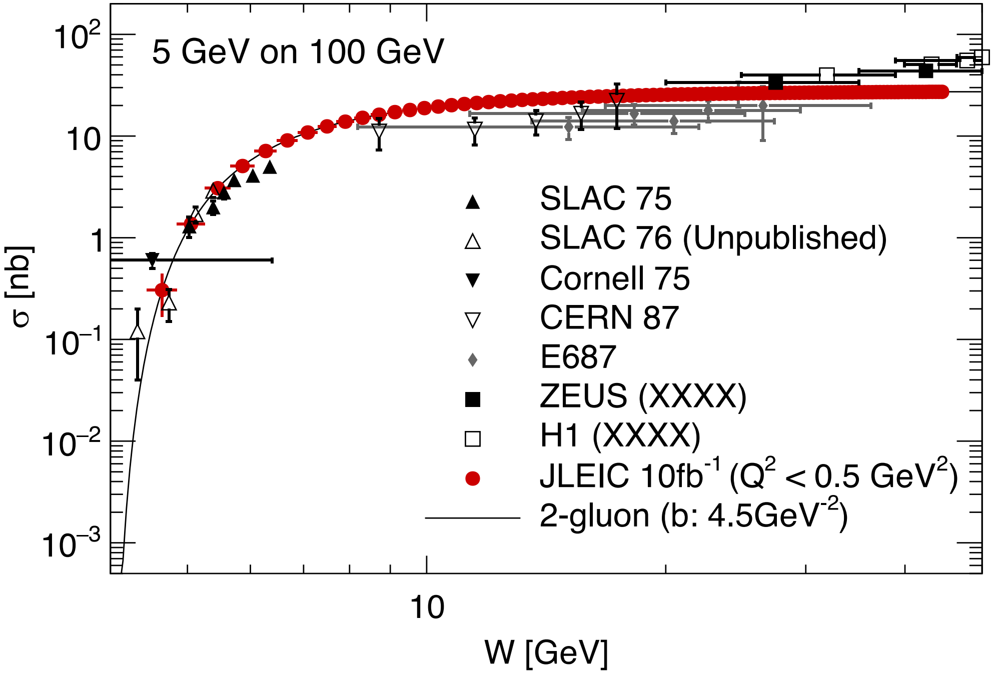


S. Joosten,
Z-E. Meziani

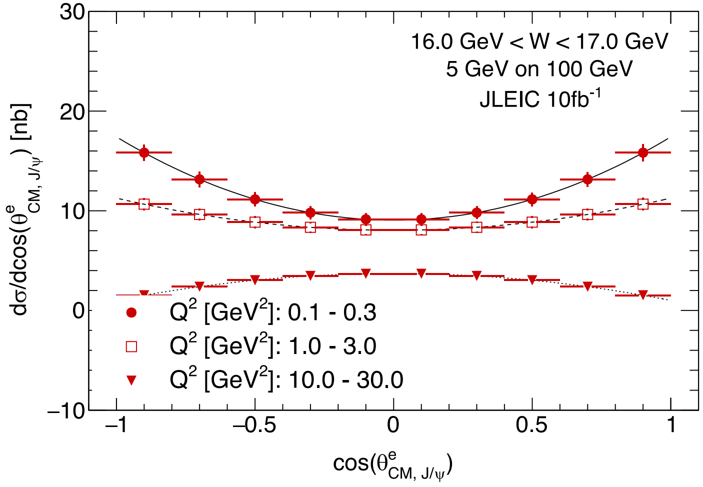
t distribution



Total electroproduction cross section

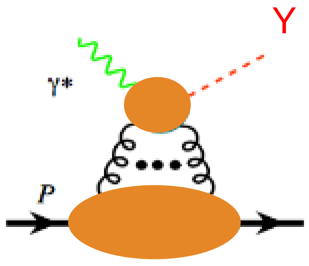


angular distribution of decay



Elastic Υ production near threshold at an EIC

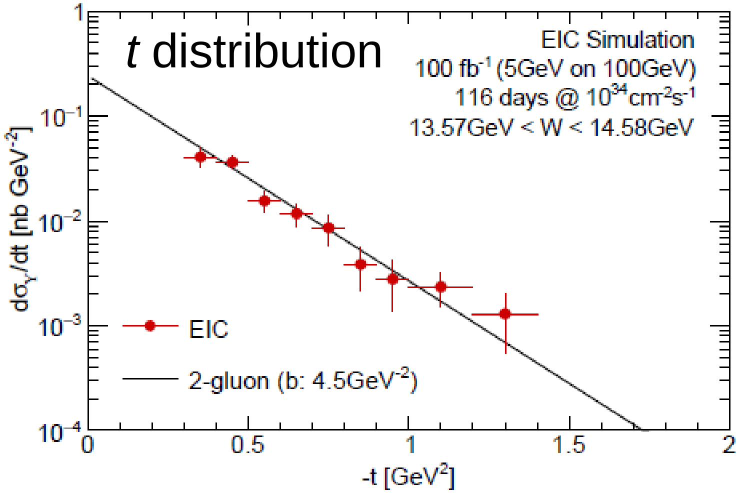
At an EIC a study of the Q^2 dependence in the threshold region is possible

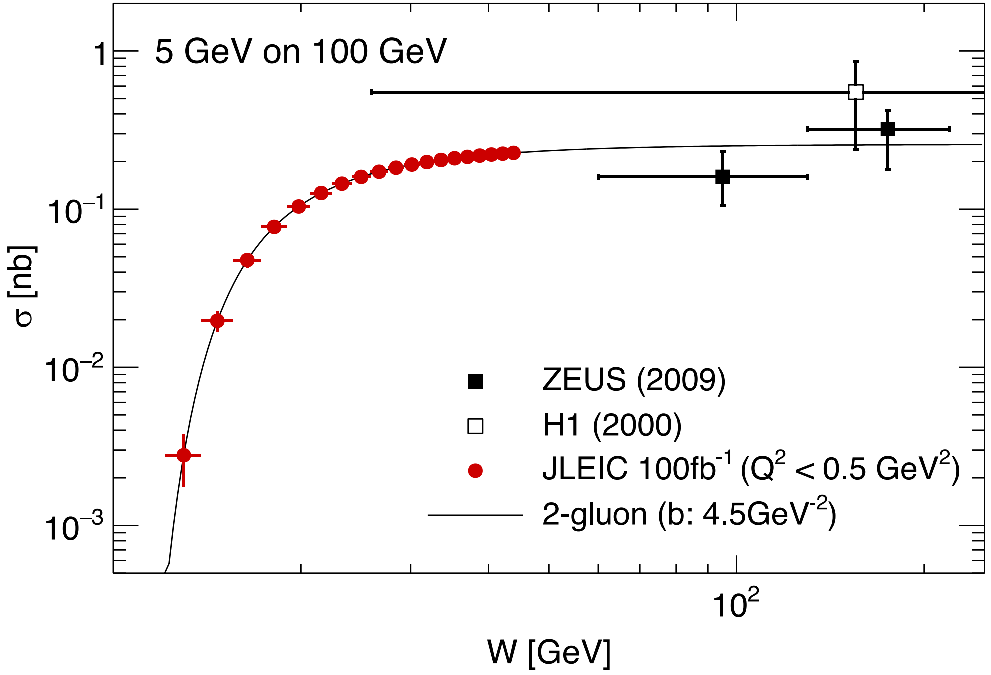


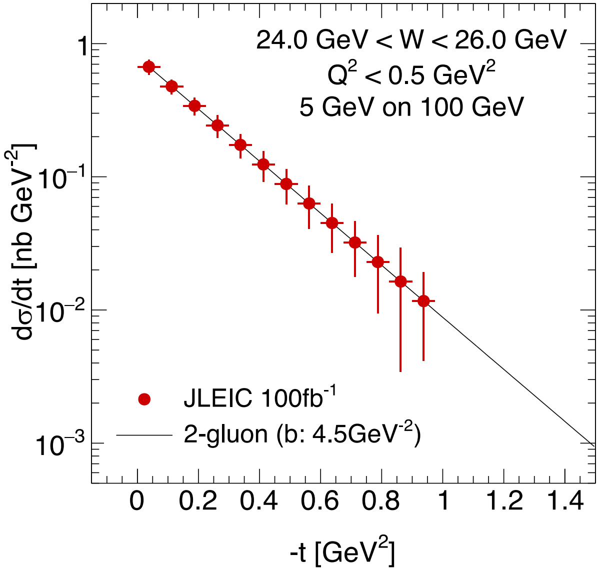
S. Joosten,
Z-E. Meziani

Low W → trace anomaly
Large W → Gluon GPDs

(see arXiv:1802.02616)



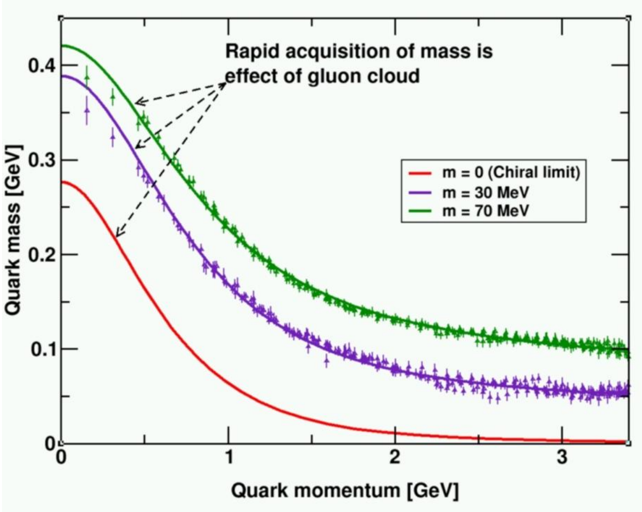




The Incomplete Hadron: Mass Puzzle

"Mass without mass!"

Bhagwat & Tandy/Roberts et al



Proton: Mass ~ 940 MeV
preliminary LQCD results on mass budget,
or view as mass acquisition by DχSB

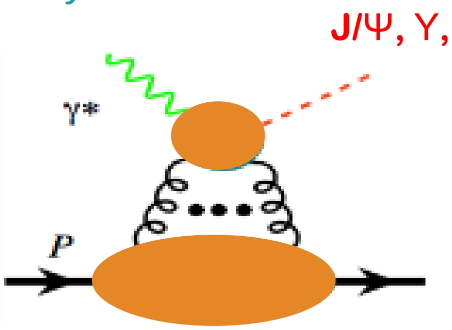
Kaon: Mass ~ 490 MeV
at a given scale, less gluons than in pion

Pion: Mass ~ 140 MeV
mass enigma – gluons vs Goldstone boson

☐ EIC expected contributions in:

✧ trace anomaly:

Upsilon production near the threshold

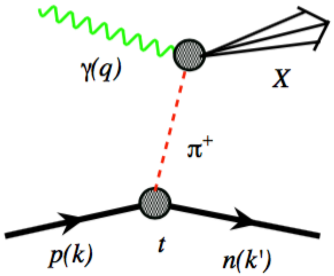


☐ EIC's expected contribution in:

✧ Quark-gluon energy:
∝ *quark-gluon momentum fractions*

In π, K and N with DIS and SIDIS

In π and K with Sullivan process



Why should you be interested in pions and kaons?

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

Why should you be interested in pions and kaons?

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

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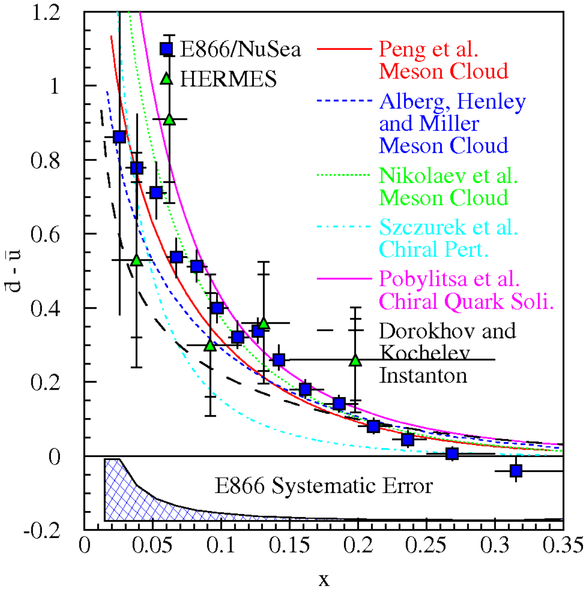
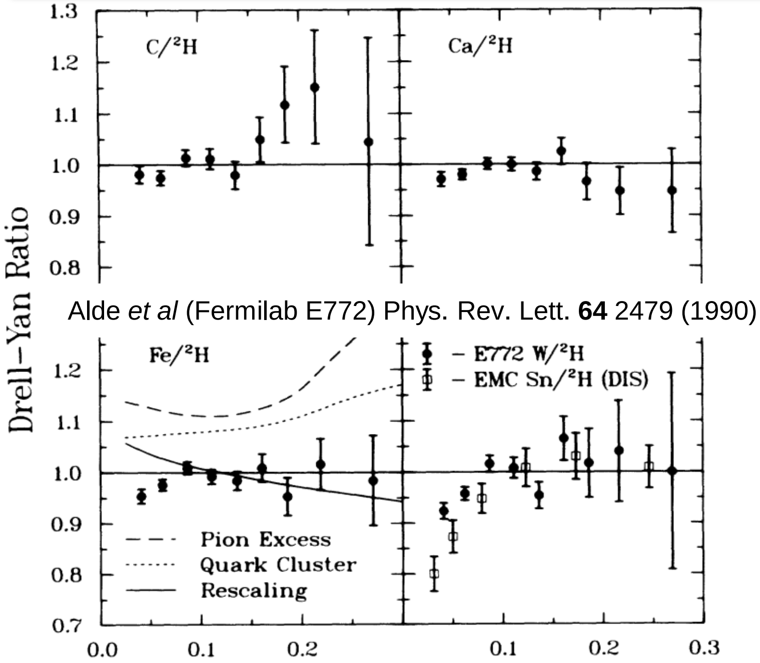
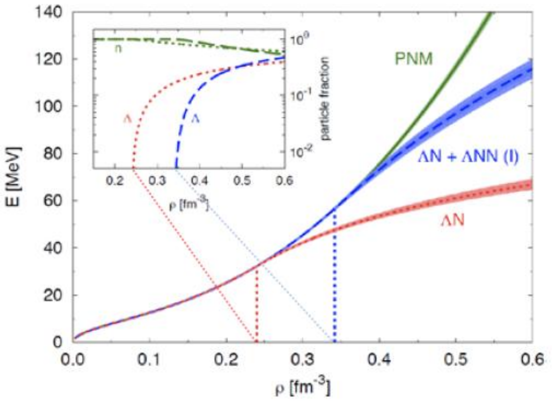
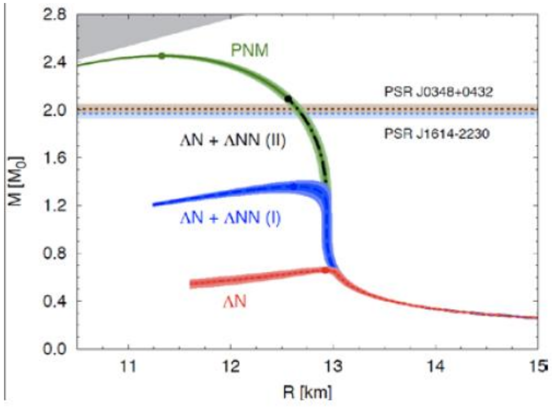




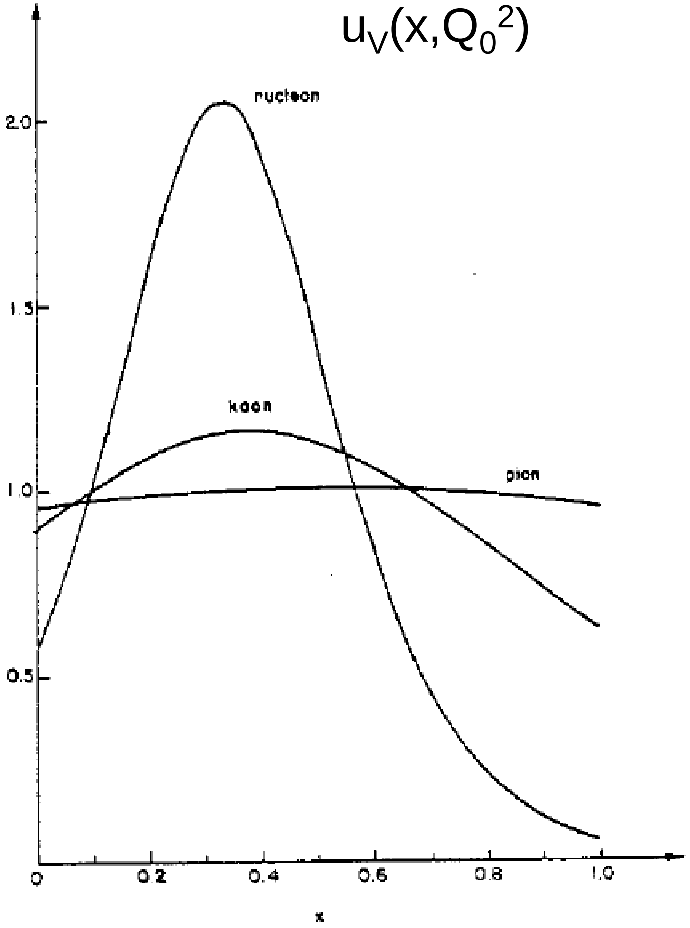
Alde *et al* (Fermilab E772) Phys. Rev. Lett. **64** 2479 (1990)



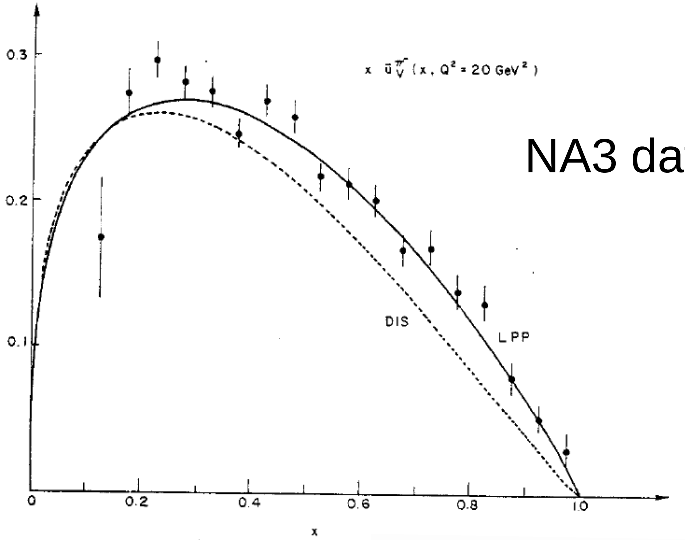


At some level an old story…

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



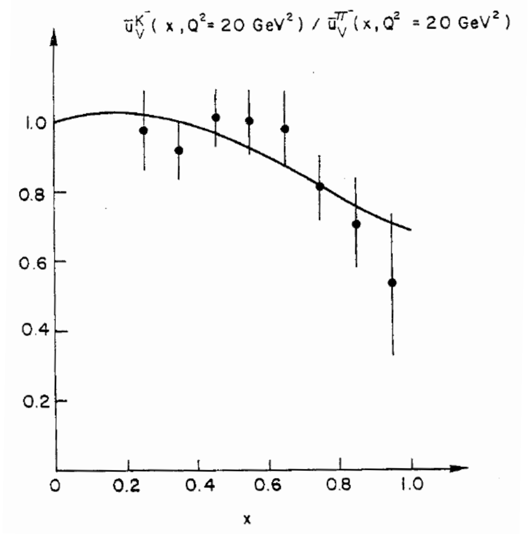
$u_V(x,Q_0^2)$



NA3 data

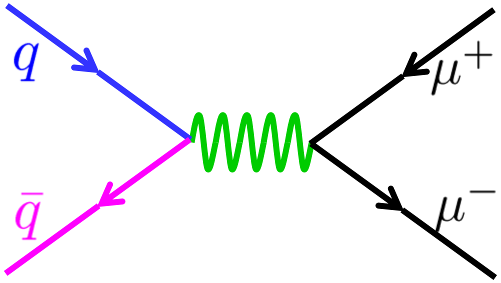
Predictions based on non-relativistic model with valence quarks only →

1) pion/kaon differs from proton: 2q vs. 3q system
2) kaon differs from pion as it owns one heavy quark



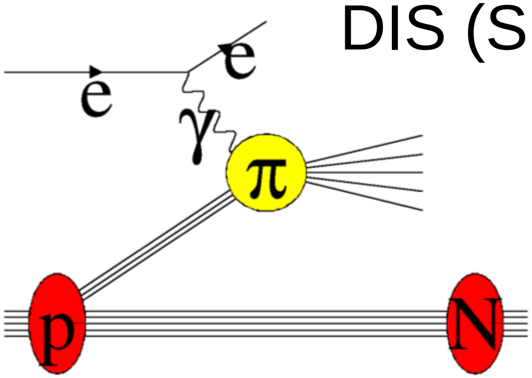
World Data on pion structure function F_2^π

Pion Drell-Yan

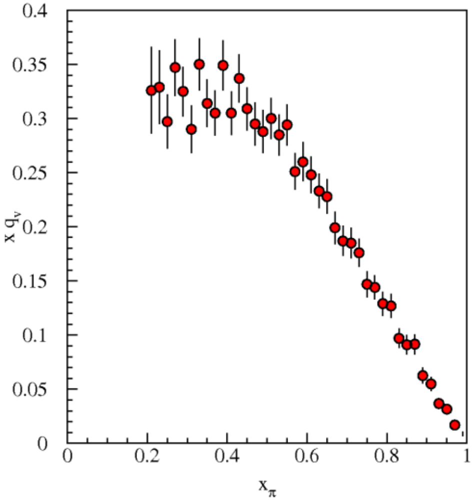


Data much more limited…

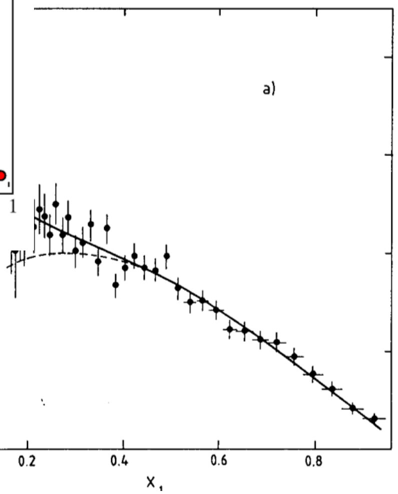
DIS (Sullivan Process)

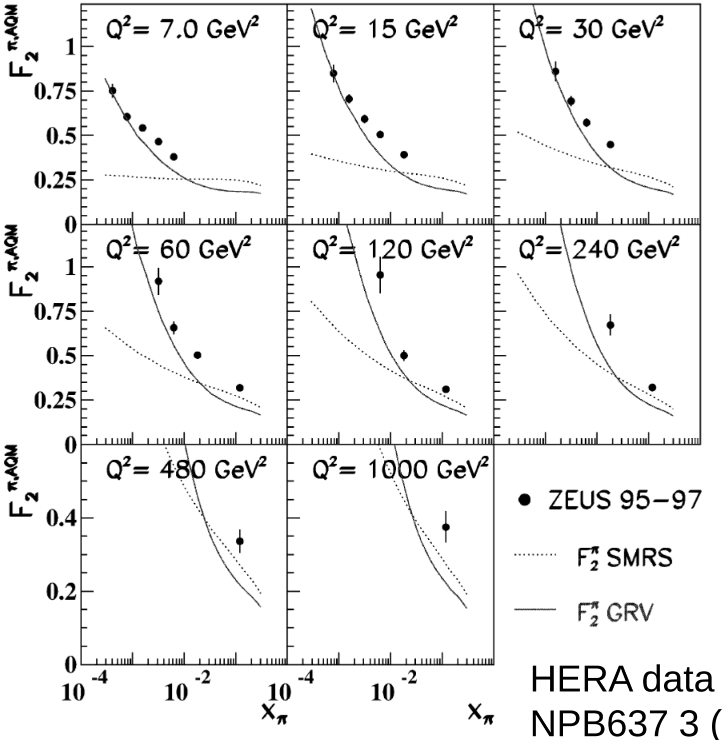


FNAL E615



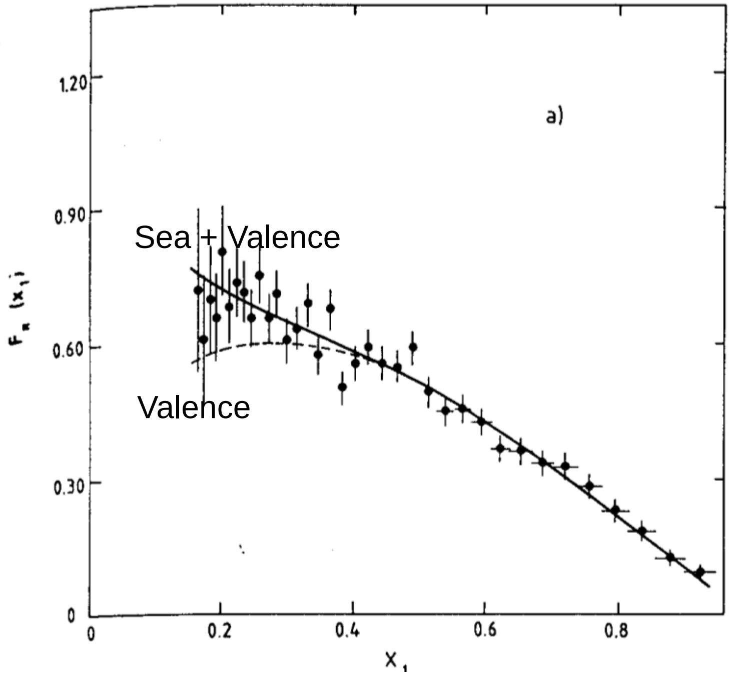
CERN NA3





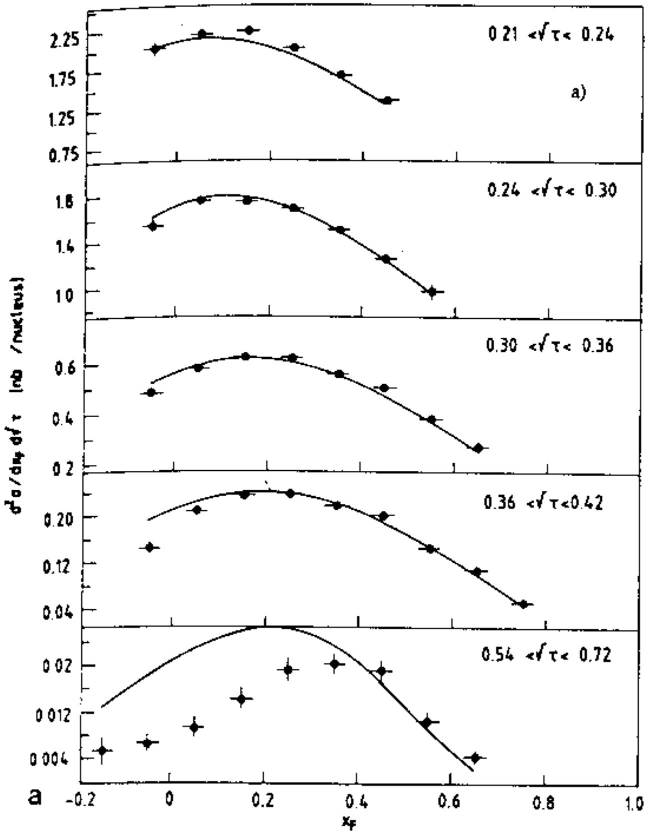
HERA data [ZEUS, NPB637 3 (2002)]

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*!

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



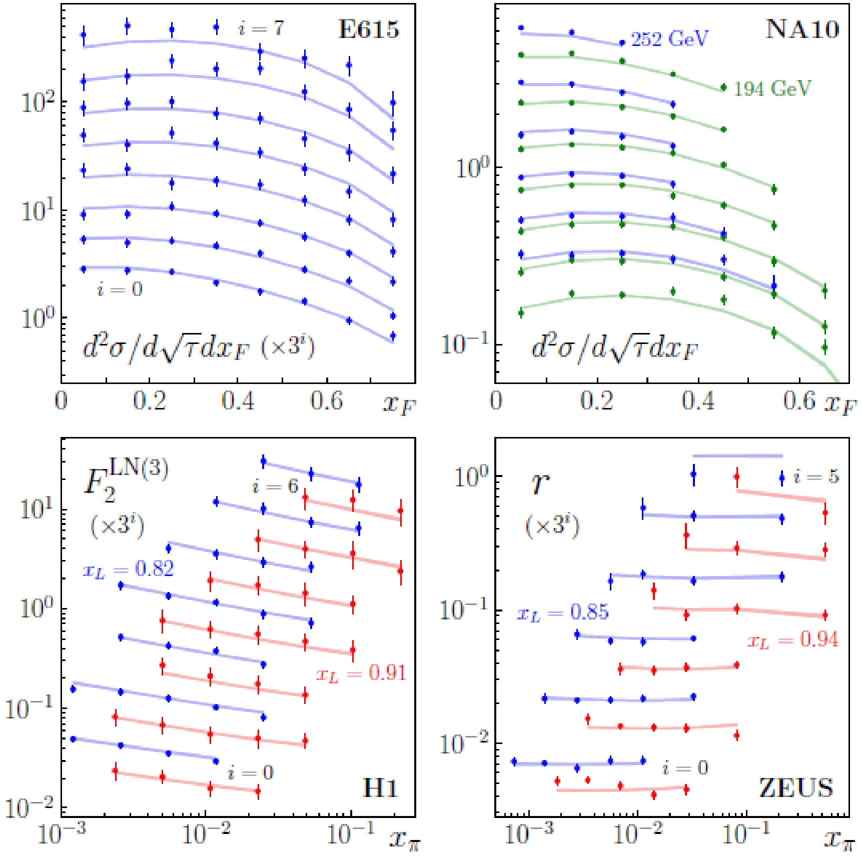
NA10 194 GeV π^- data

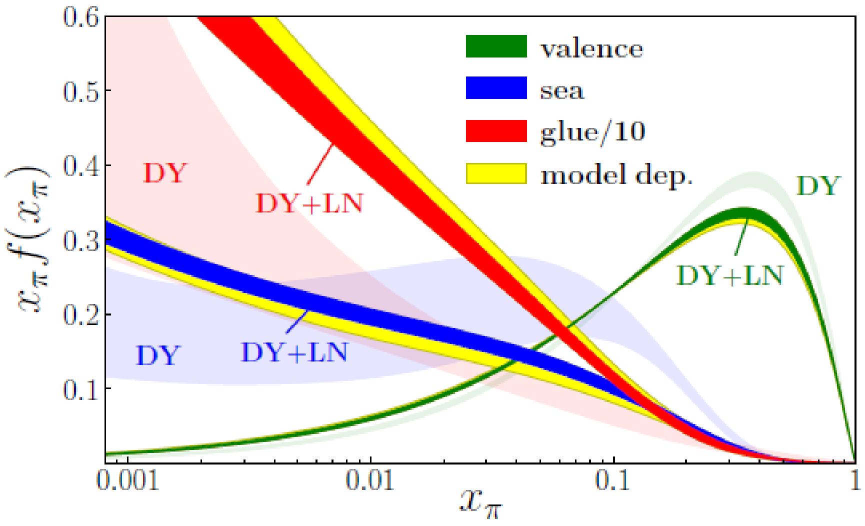
quark sea in pion is small – few %

First Monte Carlo global analysis of pion pdfs

arXiv:1804.01965v1 Barry, Sato, Melnitchouk and Ji

From combined Leading-Neutron (LN) and Drell-Yan (DY) analysis





quark and gluon pdfs 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?

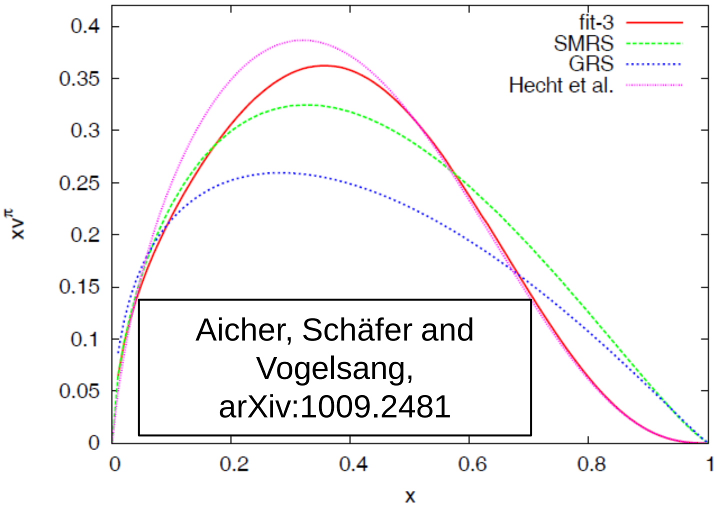
- At moderate x, compare pionic Drell-Yan to DIS from the pion cloud,
  - ❖ test of the assumptions used in the extraction of the structure function (and similar assumptions in the pion and kaon form factors).

- 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, also effects of gluons come in. To measure this 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.

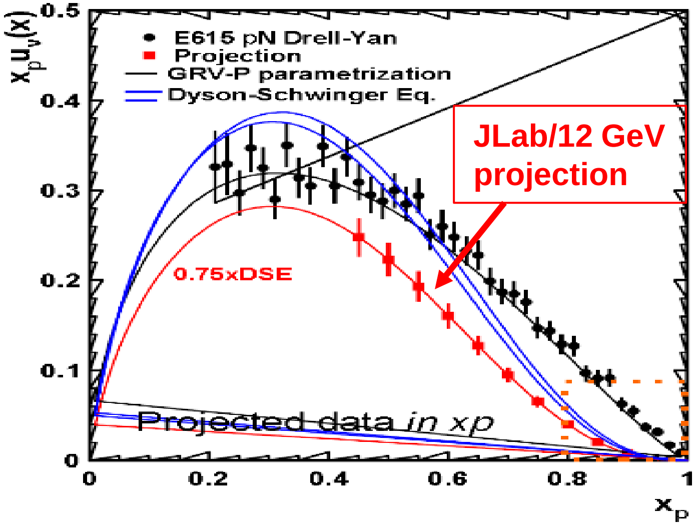
The issue at large-x: solved by resummation?

- ❑ 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

Pion SF: $(1-x)^{-1}$ or $(1-x)^{-2}$ dependence at large x?



- ❑ **Soft Gluon Resummation saves the day! (or ?)**
  - ➢ 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

Towards Pion Structure Functions

- ☐ Similar as process used to measure the pion elastic form factors, isolate the One Pion Exchange Contribution also to measure pion structure functions

In the Sullivan process, the mesons in the nucleon cloud are virtual (off-shell) particles

- ☐ Sullivan was the first to consider the “Drell” process, with π+X final states where m_X^2 grows linearly with Q^2

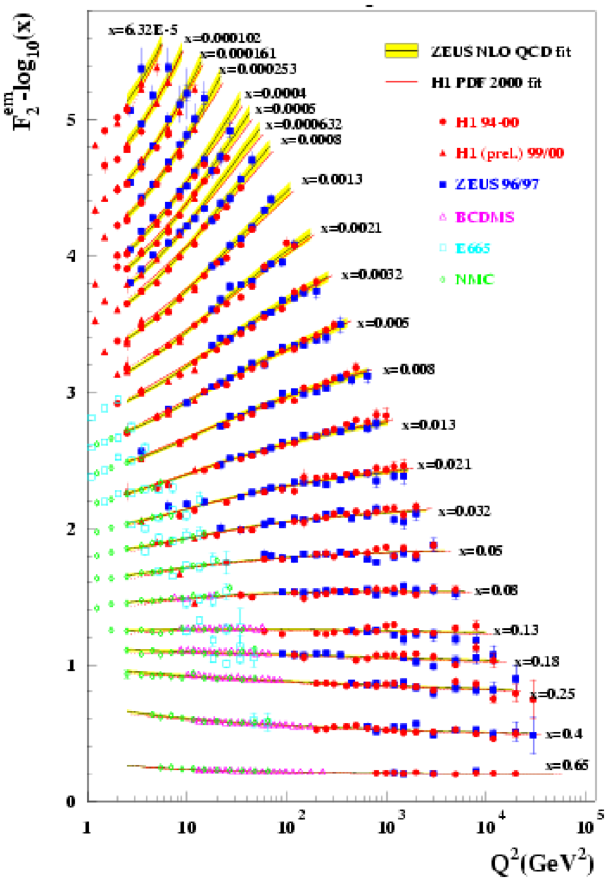
- ☐ A simple calculation gives the minimum momentum transfer squared $t_{min} = (q-k)^2_{min} \rightarrow \infty$ as $Q^2 \rightarrow \infty$
  - ➢ The requirement of being near the pion pole at $t = m_\pi^2$ can never be satisfied and processes of this type play no role in the scaling region

- ☐ Similar consideration for offshellness as for meson FF – a well-constrained experimental analysis should be reliable in regions of -t

Landscape for p, π, K structure function after EIC

Proton: much existing from HERA
EIC will add:

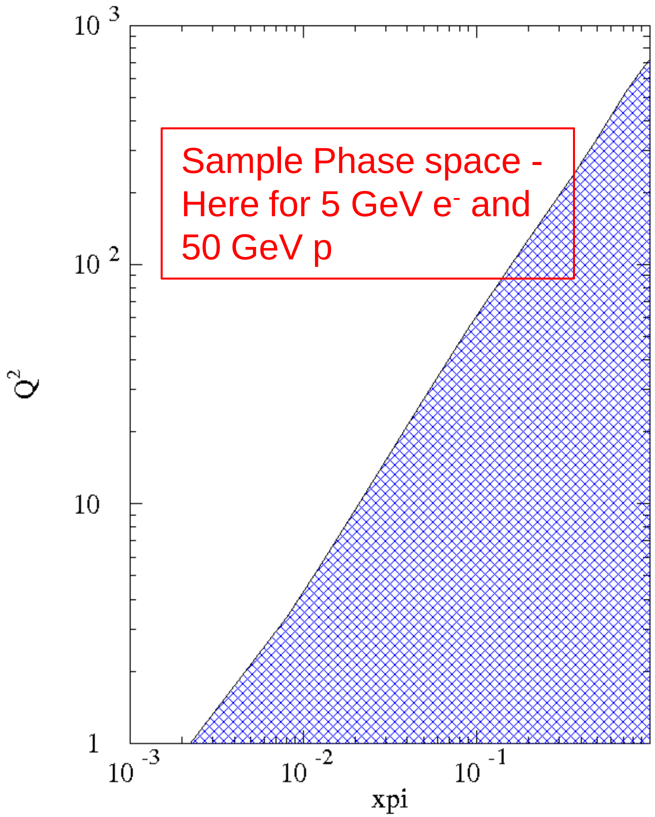
- Better constraints at large-x
- Precise F_2^n neutron SF data



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!

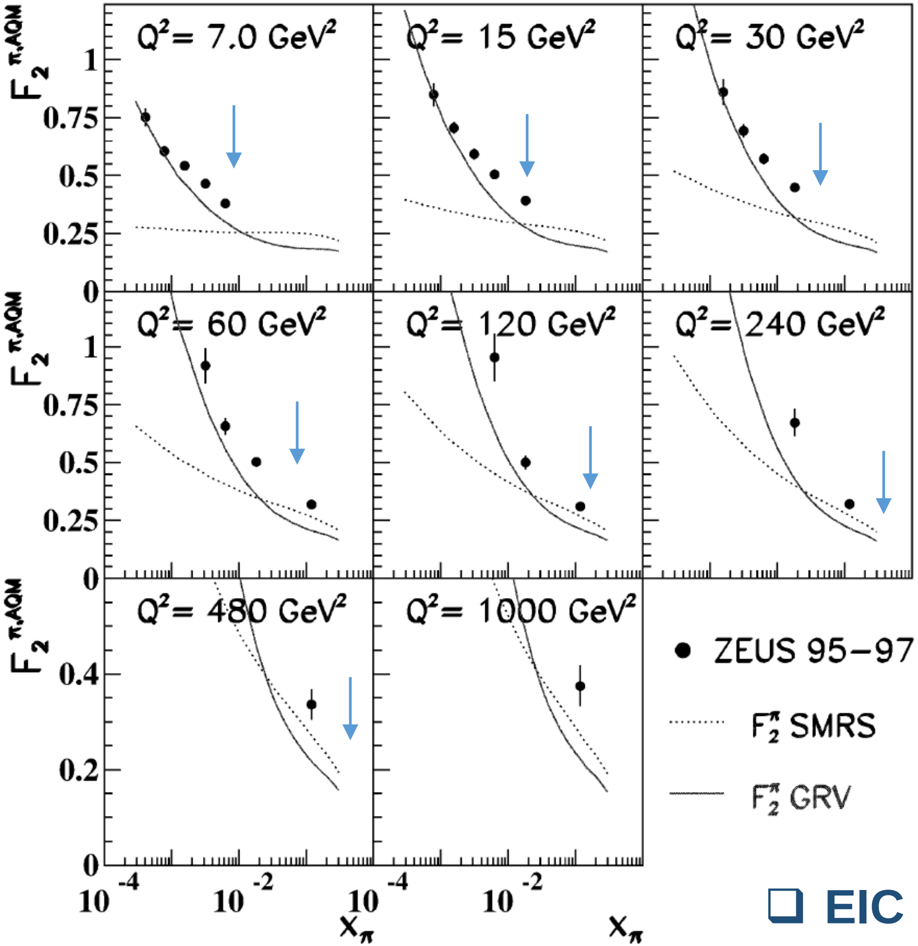


Sample Phase space - Here for 5 GeV e^- and 50 GeV p

World Data on pion structure function F_2^π

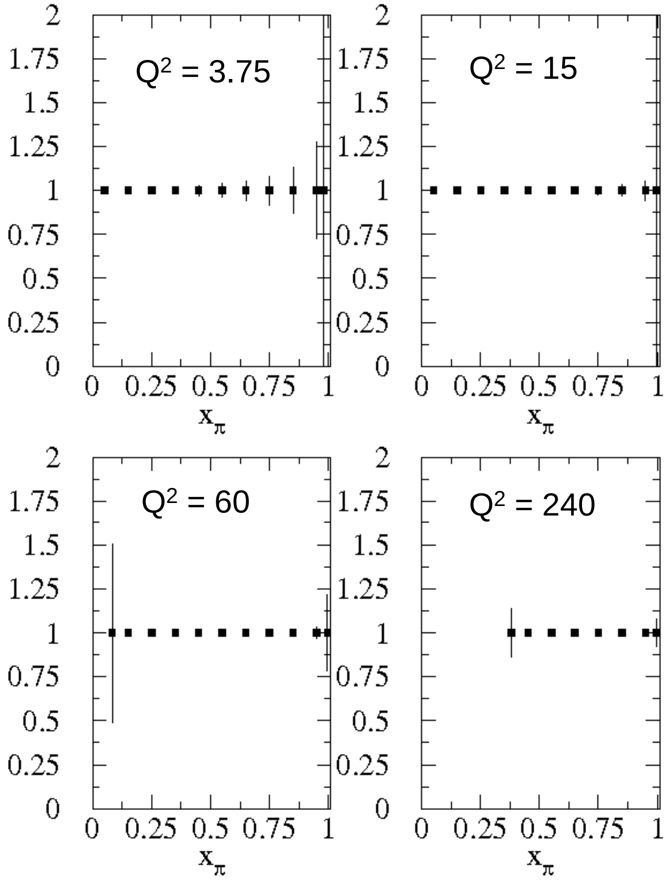
HERA

↓ ~x_{min} for EIC



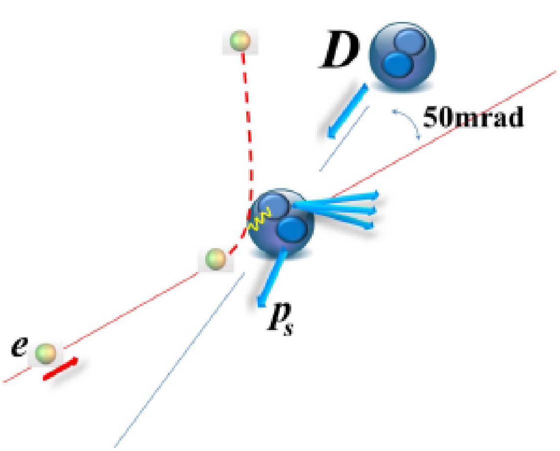
EIC

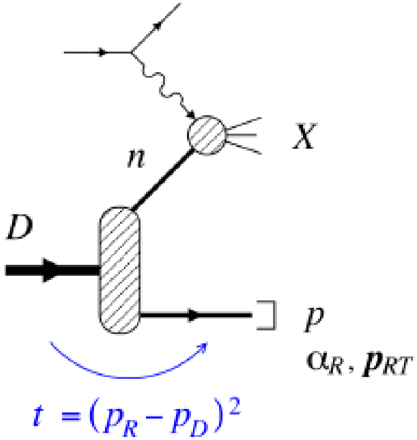
Here example for 5 GeV e⁻ and 50 GeV p

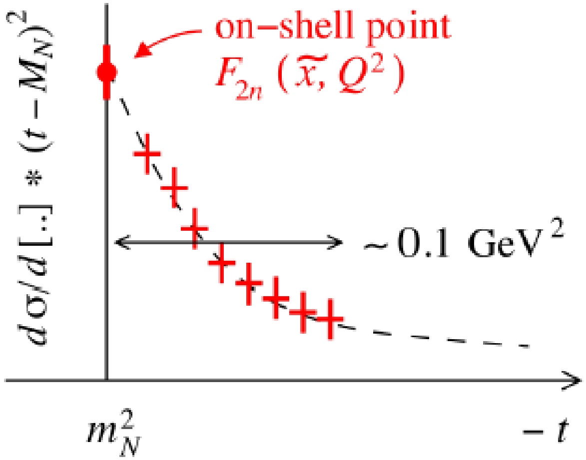


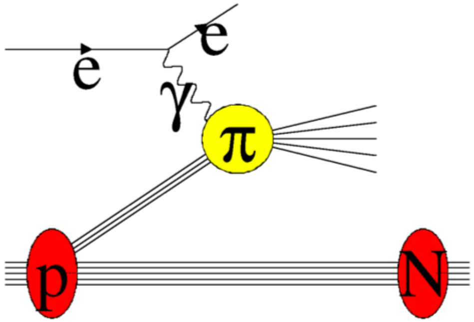
- ☐ **EIC kinematic reach down to a x = few 10^{-3}**
- ☐ **Lowest x constrained by HERA**

EIC – Versatility is Key







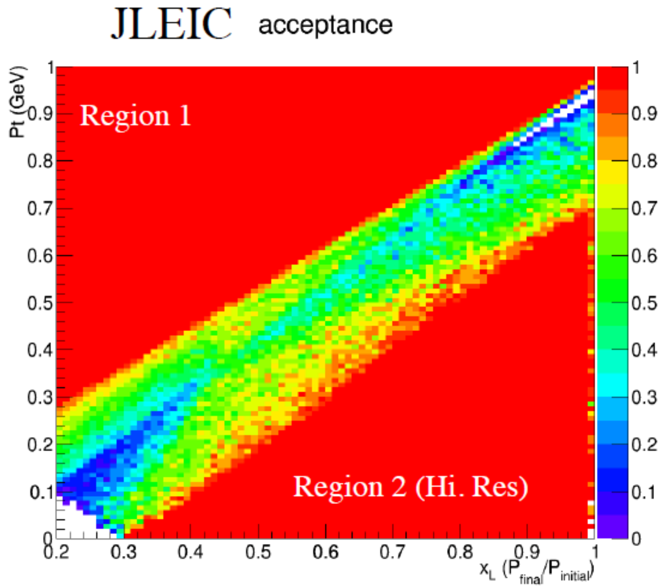


- Obtain F_2^n by tagging spectator proton from e-d, and extrapolate to on-shell neutron to correct for binding and motion effects.
- Obtain F_2^π and F_2^K by Sullivan process and extrapolate the measured t-dependence as compared to DSE-based models.

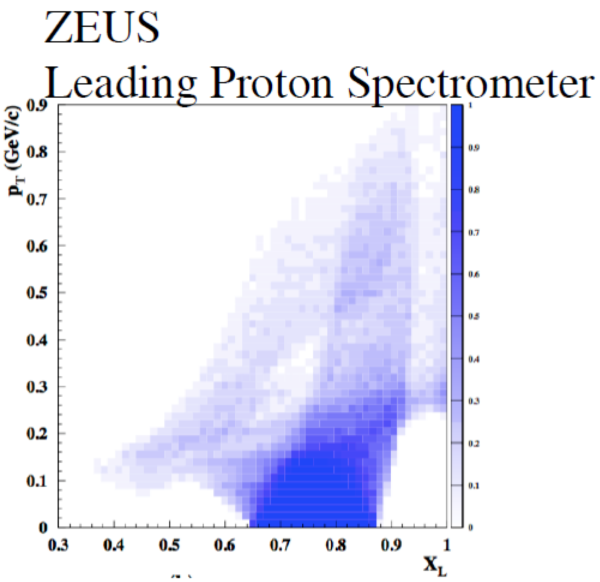
→ **Need excellent detection capabilities, and good resolution in –t**

Full Acceptance for Forward Physics!

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



Zhiwen Zhao (Duke)

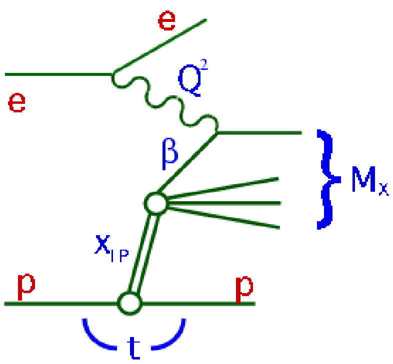


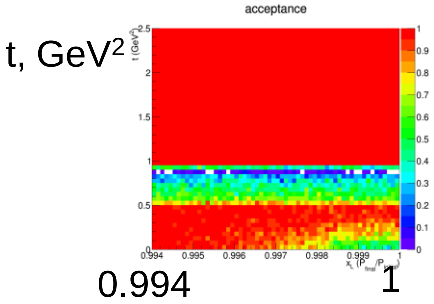
Acceptance in diffractive peak (X_L>~.98)

ZEUS: ~2%

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

Diffraction





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

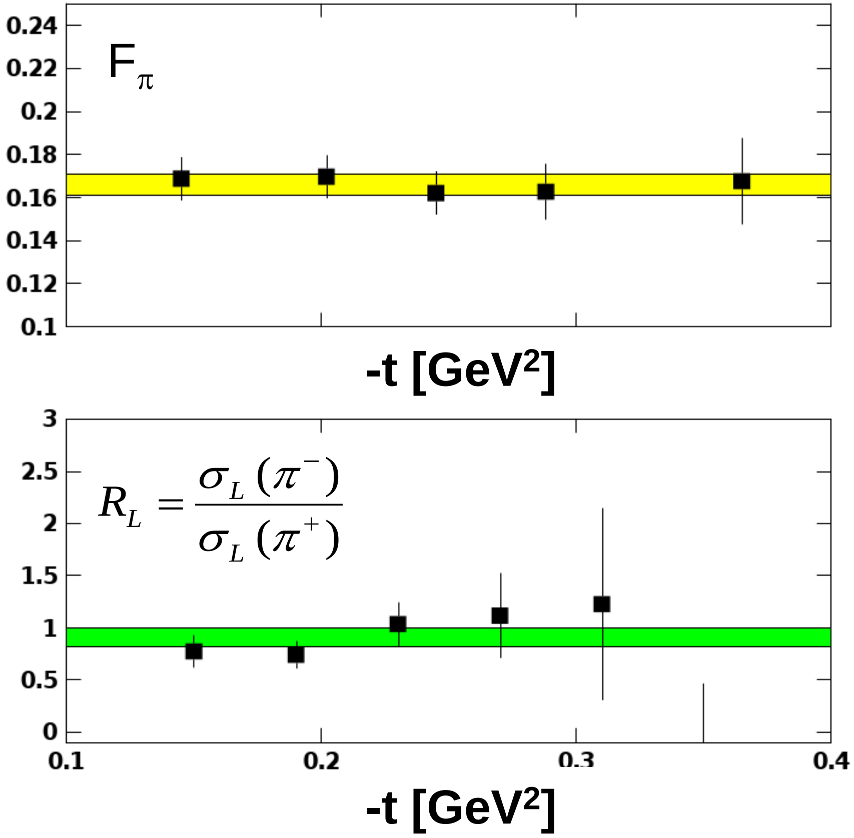
Experimental Validation (Pion Form Factor example)

Experimental studies over the last decade have given *confidence* in the electroproduction method yielding the physical pion form factor

Experimental studies include:

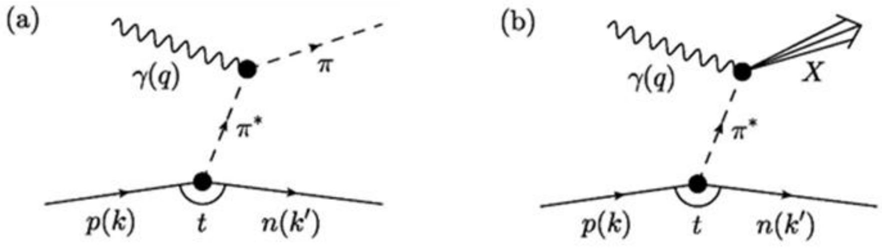
- ☐ Take data covering a range in –t and compare with theoretical expectation
  - ○ F_π values do not depend on -t – confidence in applicability of model to the kinematic regime of the data
- ☐ Verify that the pion pole diagram is the dominant contribution in the reaction mechanism
  - ○ R_L (= $\sigma_L(\pi^-)/\sigma_L(\pi^+)$) approaches the pion charge ratio, consistent with pion pole dominance

*[G. Huber et al, PRL**112** (**2014**)182501]*



*[T. Horn, C.D. Roberts, J. Phys. G**43** (**2016**) no.7, 073001]*

Theoretical Off-Shellness Considerations

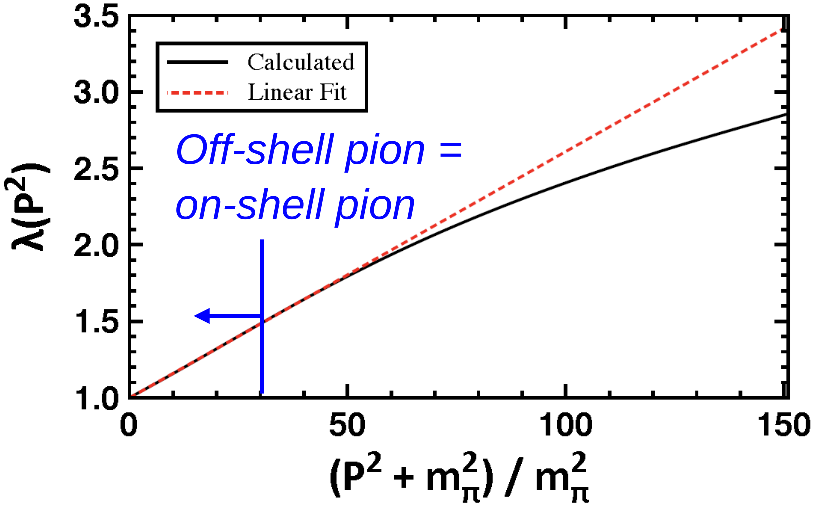


In the Sullivan process, the mesons in the nucleon cloud are virtual (off-shell) particles

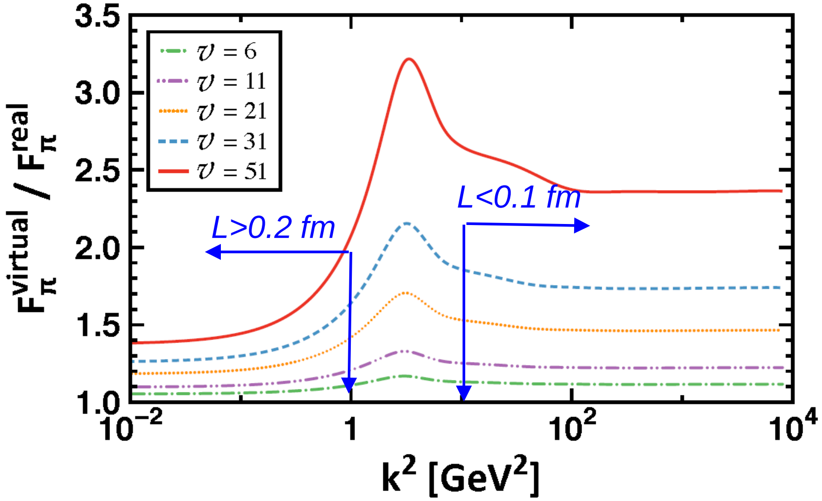
- Recent calculations estimate the effect in the BSE/DSE framework – as long as $\lambda(\nu)$ is linear in ν the meson pole dominates
    - Within the linearity domain, alterations of the meson internal structure can be analyzed through the amplitude ratio
- *Off-shell meson = On-shell meson* for t<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

S-X Qin, C. Chen, C. Mezrag, C.D. Roberts, Phys. Rev. C 97 (2017) 015203



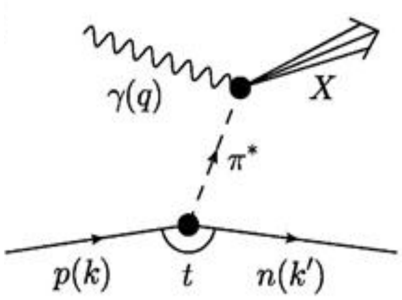
Off-shell pion = on-shell pion



L>0.2 fm

L<0.1 fm

Experimental Off-Shellness Considerations



- Like nuclear binding corrections (neutron in deuterium)
- Bin in t to determine the off-shellness correction
- Compare with pion/kaon D-Y (→ pion/kaon flux factor!)

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

T. Horn,
R. Trotta,
A. Vargas

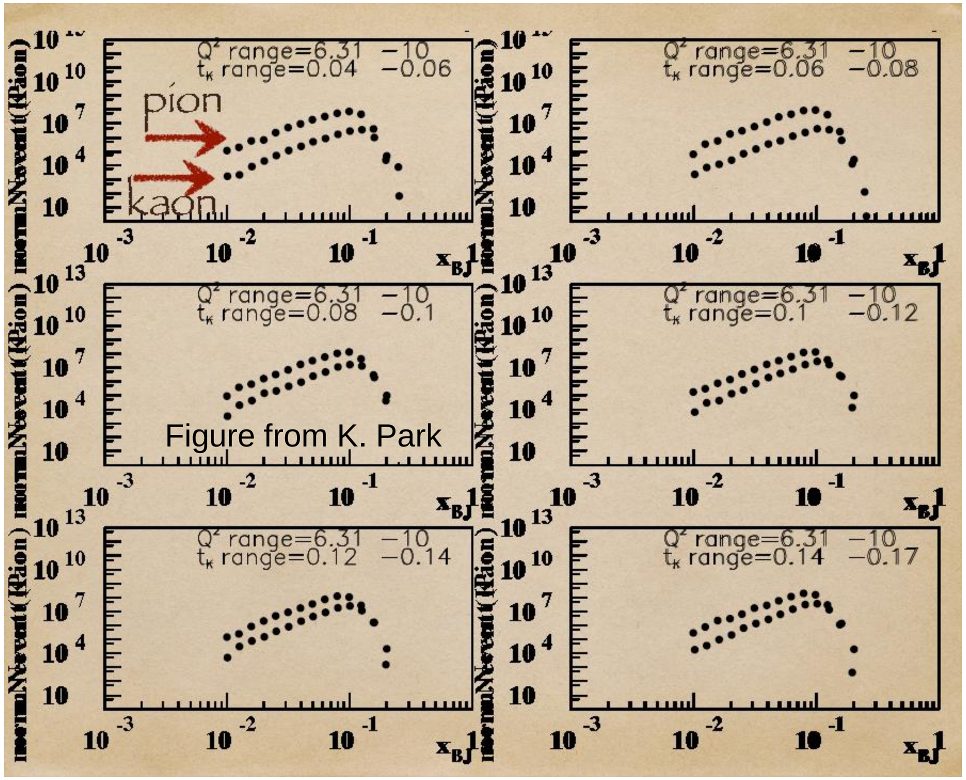
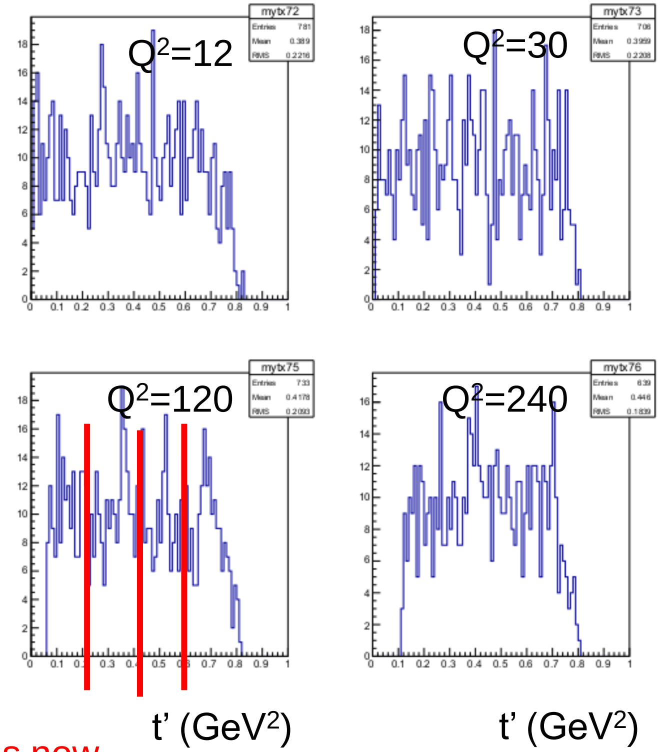


Figure from K. Park

x=0.75

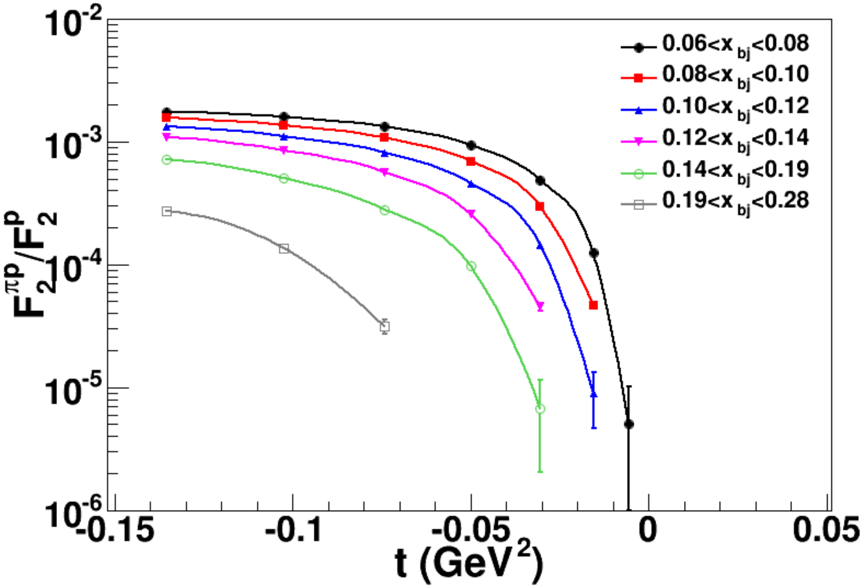


These are from initial trials and preliminary – we are redoing this now

EIC – Versatility **and Luminosity** is Key

Why would pion and kaon structure functions, and even measurements of pion structure beyond (pion GPDs and TMDs) be feasible at an EIC?

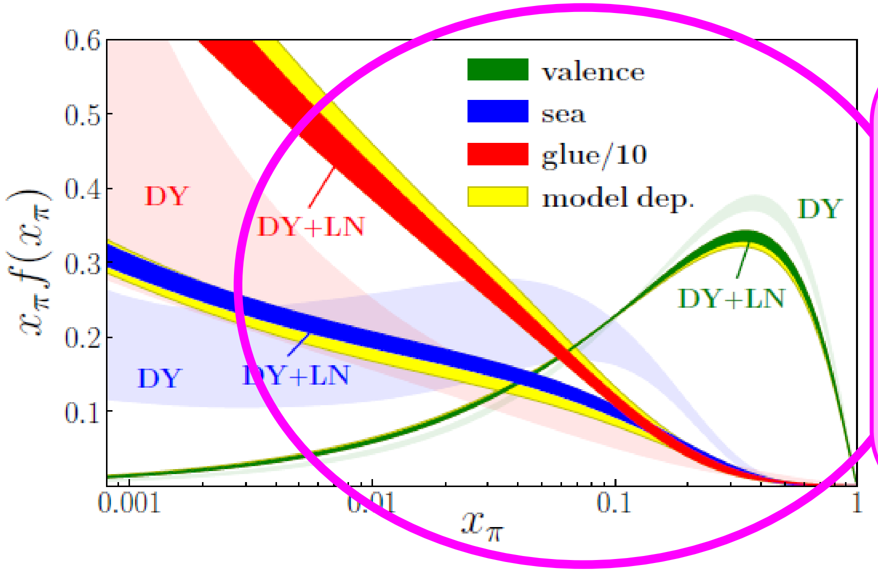
- $L_{EIC} = 10^{34} = 1000 \times L_{HERA}$
- Detection fraction @ EIC in general much higher than at HERA
- Fraction of proton wave function related to pion Sullivan process is roughly 10^{-3} for a small –t bin (0.02).
- Hence, pion data @ EIC should be comparable or better than the proton data @ HERA, or the 3D nucleon structure data @ COMPASS
- If we can convince ourselves we can map pion (kaon) structure for –t < 0.6 (0.9) GeV2, we gain at least a decade as compared to HERA/COMPASS.



Ratio of the F_2 structure function related to the pion Sullivan process as compared to the proton F_2 structure function in the low-t vicinity of the pion pole, as a function of Bjorken-x (for JLab kinematics)

Web-based Self-Serve Pion PDF

From combined Leading-Neutron (LN) and Drell-Yan (DY) analysis



- ☐ JLab 12 GeV: Tagged Pion and Kaon TDIS ($x_\pi > 0.5$)
- ☐ Also prospects for pion + kaon DY at COMPASS ($x_\pi > 0.2$), and for pion and kaon LN at EIC ($x_\pi > 0.001$)

Web-based self-server performs a combined Leading-Neutron, Drell-Yan and new data analysis

N. Sato

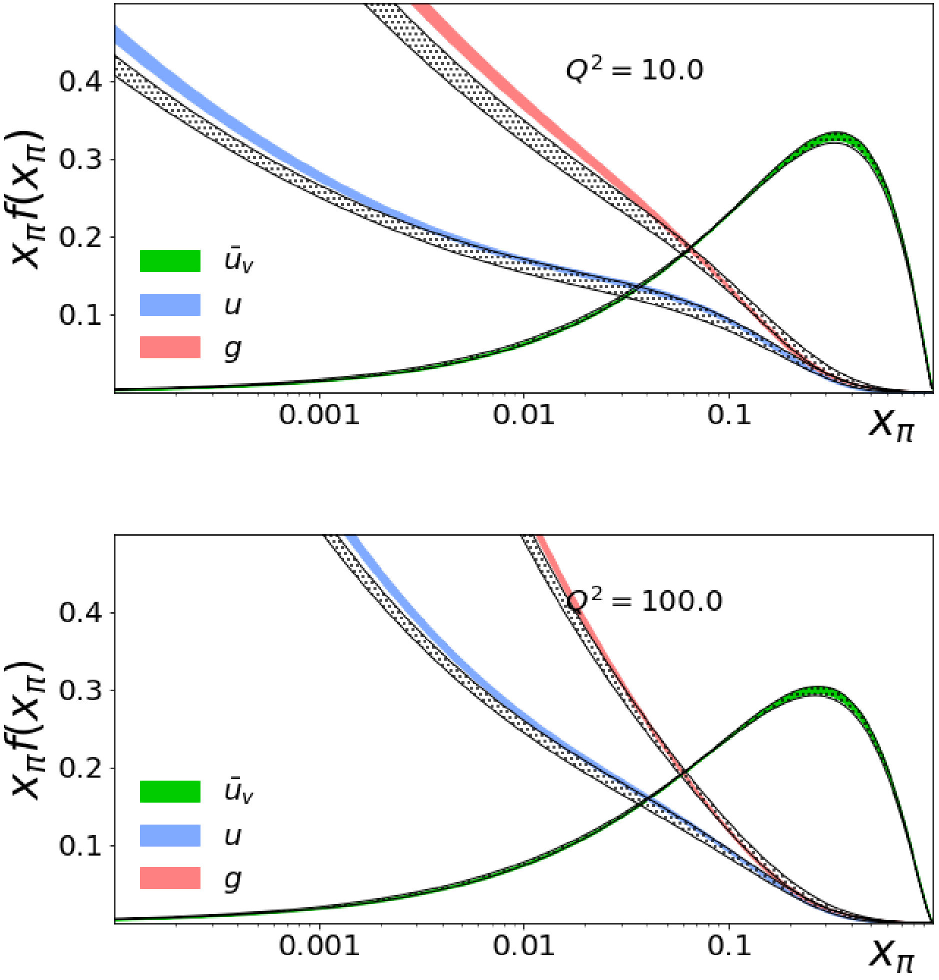
Github: https://github.com/JeffersonLab/jamfitter

Jupyter notebook: https://jupyter.jlab.org/

Global pion PDF fit with EIC pseudodata

- ☐ 5 GeV (e-) on 50 GeV (p)
- ☐ 0.1 < y < 0.8
- ☐ EIC pseudodata fitted existing data using self-serve pion PDF
- ☐ Work ongoing:
  - Why did the curves shift?
  - The pion D-Y data, even if not many, already do constrain the curves surprisingly well – due to symmetries and sum rules?
  - Curves to improve with the EIC projections, especially for kaon as will have similar-quality data.

Precision gluon constraints of pion and kaon pdfs <u>are</u> possible.



T. Horn, N. Sato, R. Trotta

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*

*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

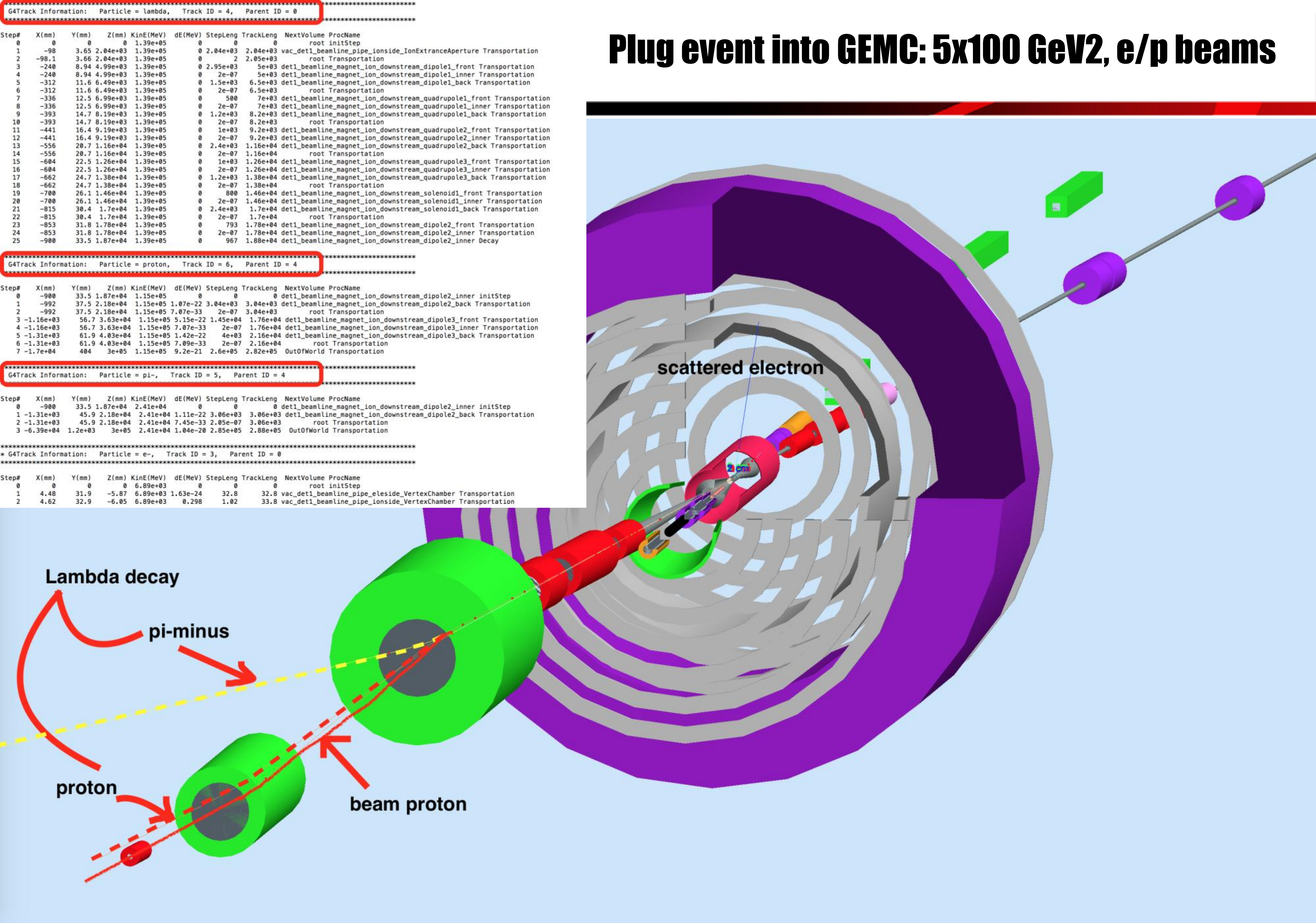
(these values can vary depending on what model one uses, so sometimes a range is used, *e.g.*, 13.1-13.5 for $g_{\pi NN}$)

- ☐ Good geometric detection efficiencies for n, Λ, Σ detection at low -t

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%

- ☐ 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.

Plug event into GEMC: 5x100 GeV2, e/p beams



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    3     -240     8.94 4.99e+03  1.39e+05        0 2.95e+03     5e+03 det1_beamline_magnet_ion_downstream_dipole1_front Transportation
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    5     -312     11.6 6.49e+03  1.39e+05        0  1.5e+03   6.5e+03 det1_beamline_magnet_ion_downstream_dipole1_back Transportation
    6     -312     11.6 6.49e+03  1.39e+05        0    2e-07   6.5e+03       root Transportation
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    3 -1.16e+03     56.7 3.63e+04  1.15e+05 5.15e-22 1.45e+04  1.76e+04 det1_beamline_magnet_ion_downstream_dipole3_front Transportation
    4 -1.16e+03     56.7 3.63e+04  1.15e+05 7.07e-33    2e-07  1.76e+04 det1_beamline_magnet_ion_downstream_dipole3_inner Transportation
    5 -1.31e+03     61.9 4.03e+04  1.15e+05 1.42e-22    4e+03  2.16e+04 det1_beamline_magnet_ion_downstream_dipole3_back Transportation
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    2 -1.31e+03     45.9 2.18e+04  2.41e+04 7.45e-33 2.05e-07  3.06e+03       root Transportation
    3 -6.39e+04  1.2e+03    3e+05  2.41e+04 1.04e-20 2.85e+05  2.88e+05  OutOfWorld Transportation

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    2     4.62     32.9    -6.05  6.89e+03    0.298     1.02      33.8 vac_det1_beamline_pipe_ionside_VertexChamber Transportation
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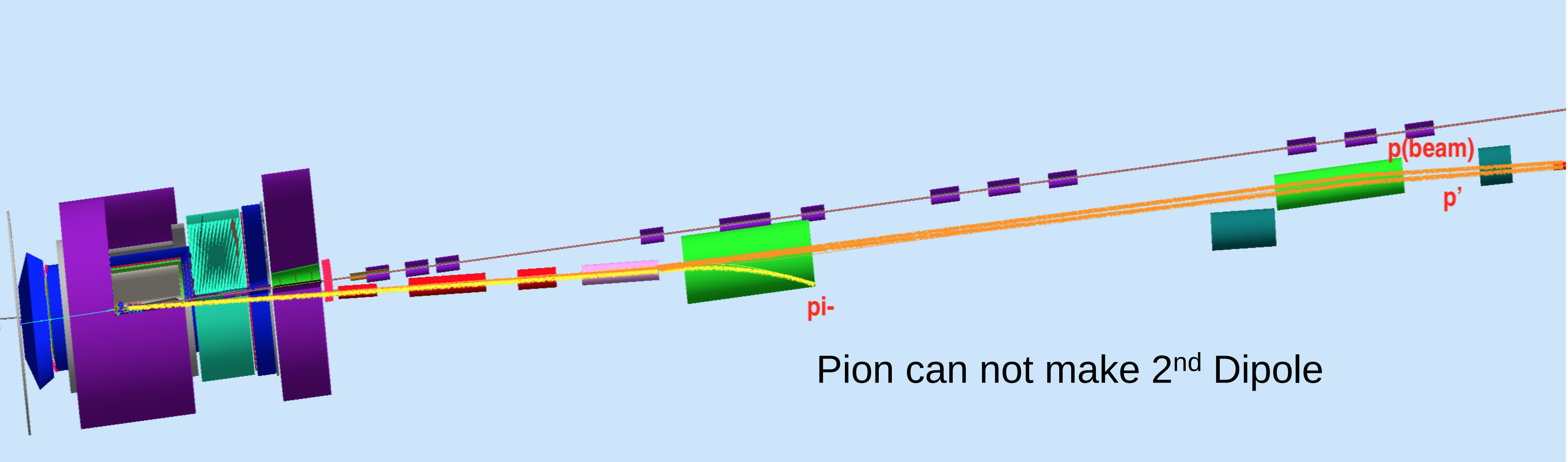
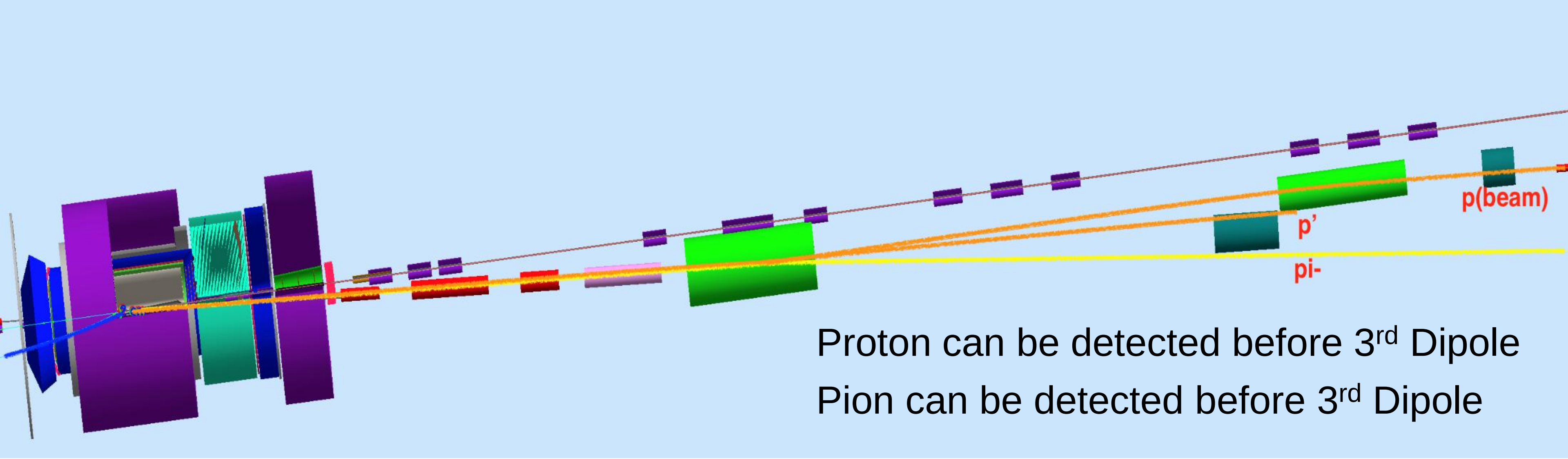
Detection of $^{1}H(e,e'K^{+})\Lambda$, Λ decay to $p + \pi^{-}$



Pion can not make 2nd Dipole



Proton can be detected before 3rd Dipole

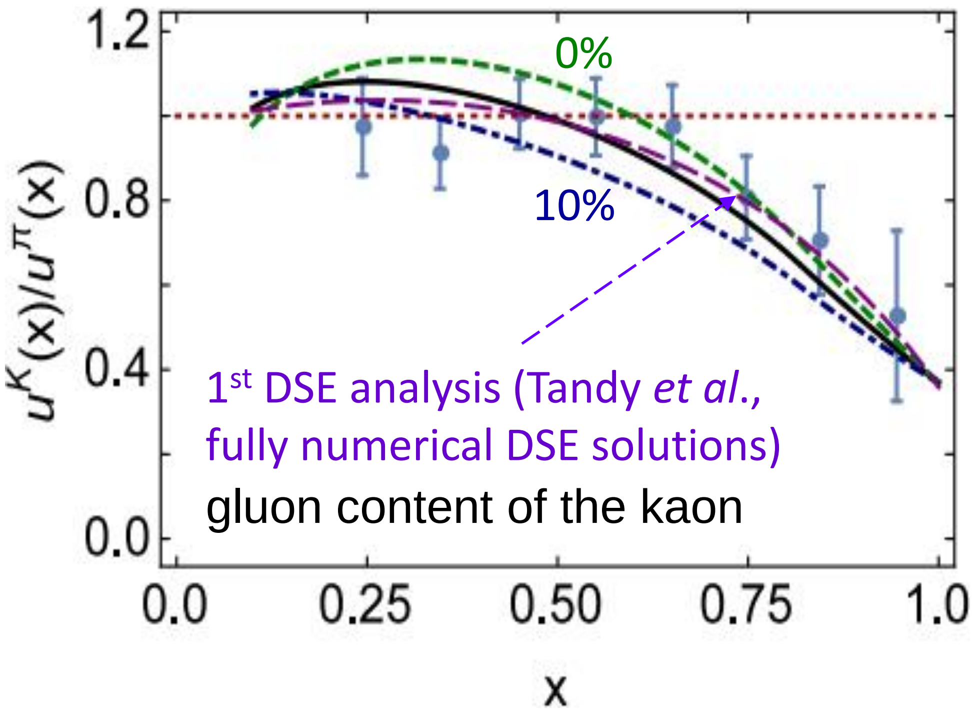
Pion can be detected before 3rd Dipole

Figure from K. Park

Kaon structure functions – gluon pdfs

Based on Lattice QCD calculations and DSE calculations:

- Valence quarks carry some 52% of the pion’s momentum at the light front, at the scale used for Lattice QCD calculations, or ~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



1^{st} DSE analysis (Tandy *et al.*, fully numerical DSE solutions)

gluon content of the kaon

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)

$$\left.\frac{u_V^K(x)}{u_V^\pi(x)}\right|_{x\to1} = 0.37\,, \qquad \left.\frac{u_V^\pi(x)}{\bar{s}_V^K(x)}\right|_{x\to1} = 0.29$$

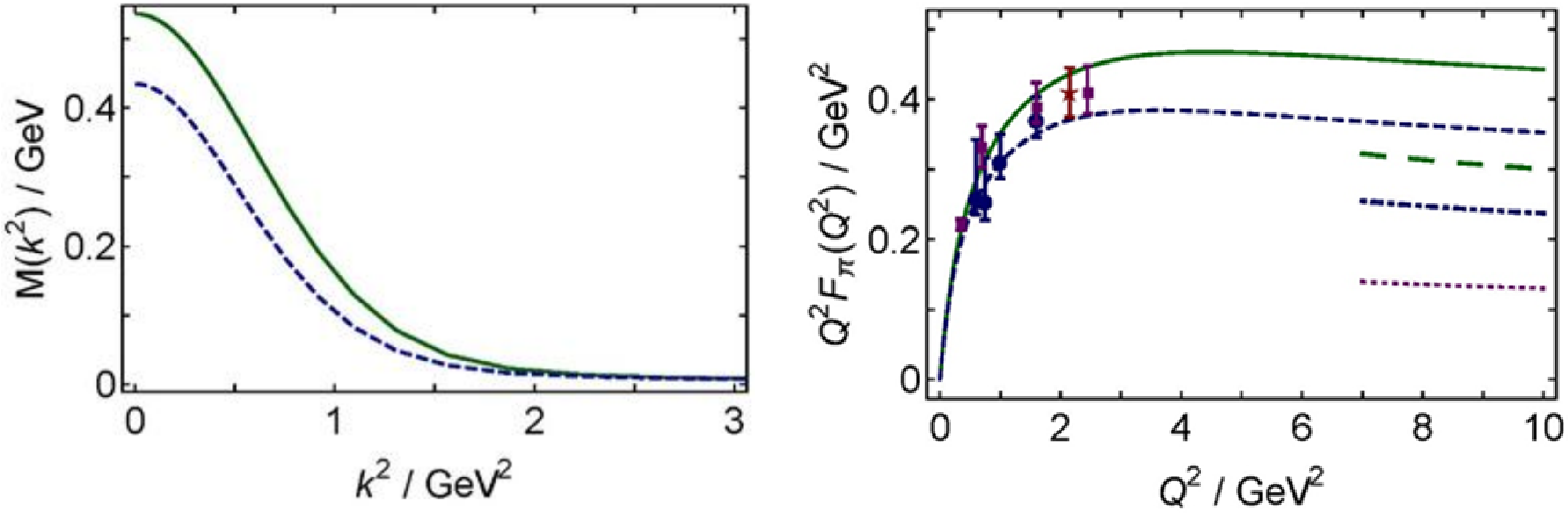
On the other hand, inexorable growth in both pions' and kaons' gluon and sea-quark content at asymptotic Q^2 should only be driven by pQCD splitting mechanisms. Hence, also calculable limits for ratios of PDFs at x = 0, *e.g.*,

$$\lim_{x\to0}\frac{u^K(x;\zeta)}{u^\pi(x;\zeta)} \overset{\Lambda_{\rm QCD}/\zeta\simeq0}{\to} 1$$

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

Pion Form Factor and Emergent Mass

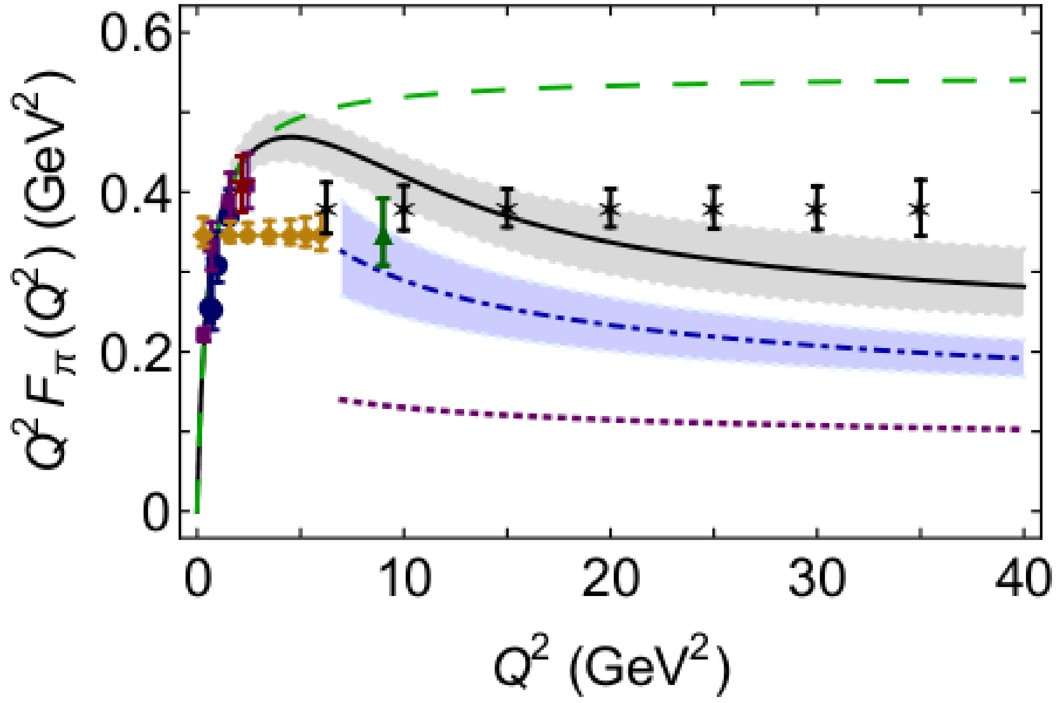
Muyang Chen, Craig Roberts



Left panel. Two dressed-quark mass functions distinguished by the amount of DCSB: emergent mass generation is 20% stronger in the system characterized by the solid green curve, which describes the more realistic case. Right panel. $F_\pi(Q^2)$ *obtained with the mass function in the left panel:* $r_\pi = 0.66$ *fm with the solid green curve and* $r_\pi = 0.73$ *fm with the dashed blue curve. The long-dashed green and dot-dashed blue curves are predictions from the QCD hard-scattering formula, obtained with the related, computed pion PDAs. The dotted purple curve is the result obtained from that formula if the conformal-limit PDA is used,* $\phi(x)=6x(1-x)$.

EIC: Pion Form Factor Prospects

1. Models show a strong dominance of σ_L at small –t at large Q^2.
2. Assume dominance of this longitudinal cross section
3. Measure the π^-/π^+ ratio to verify – it will be diluted (smaller than unity) if σ_T is not small, or if non-pole backgrounds are large



- ☐ Assumed 5 GeV(e^-) x 100 GeV(p) with an integrated luminosity of 20 fb^{-1}/year, and similar luminosities for d beam data
- ☐ $R=\sigma_L/\sigma_T$ assumed from VR model – and assume that π pole dominance at small t confirmed in ^{2}H π^-/π^+ ratios
- ☐ Assumed a 10% experimental systematic uncertainty, and a 100% systematic uncertainty in the model subtraction to isolate σ_L

Can we measure the kaon form factor at EIC?

Not clear – needs guidance from JLab 12- GeV

Garth Huber, Tanja Horn

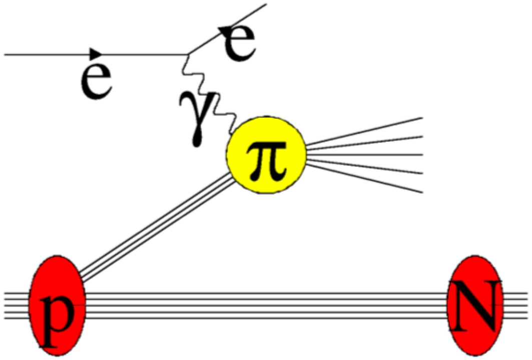
Conclusions – Pion and Kaon Structure

- 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, nucleons will differ.
  - Utilizing electroweak processes, be it through parity-violating processes or neutral vs charged-current interactions, some flavor dependence appears achievable.
  - If we can convince ourselves off-shellness considerations are under control, one could also access pion GPDs and TMDs.
- Is the origin of mass encoded in differences of gluons in pions, kaons and nucleons (at non-asymptotic Q^2)?
  - Gluons in pions and kaons can be constrained by structure function measurements or open charm measurements (in progress).
- The pion form factor may be measured at an EIC up to $Q^2 = 35\ \text{GeV}^2$, and could provide a direct connection to mass generation in the Standard Model.
- Some effects may appear 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 be **textbook material**.

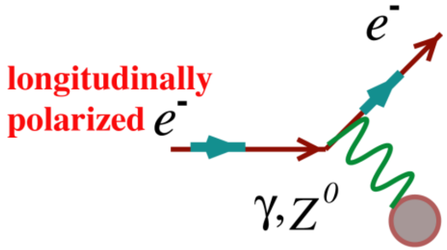
Active research ongoing - white paper under construction, draft near-final

BACKUP

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 flavor decomposition?



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

2) Determine xF_3 through neutral/charged-current interactions

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

In the parton model:

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

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

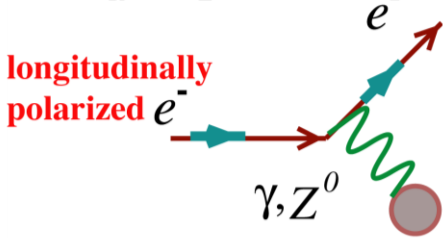
$$A = \frac{\sigma_R^{CC,e^+} \pm \sigma_L^{CC,e^-}}{\sigma_R^{NC} + \sigma_L^{NC}}$$

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

Disentangling the Flavor-Dependence

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

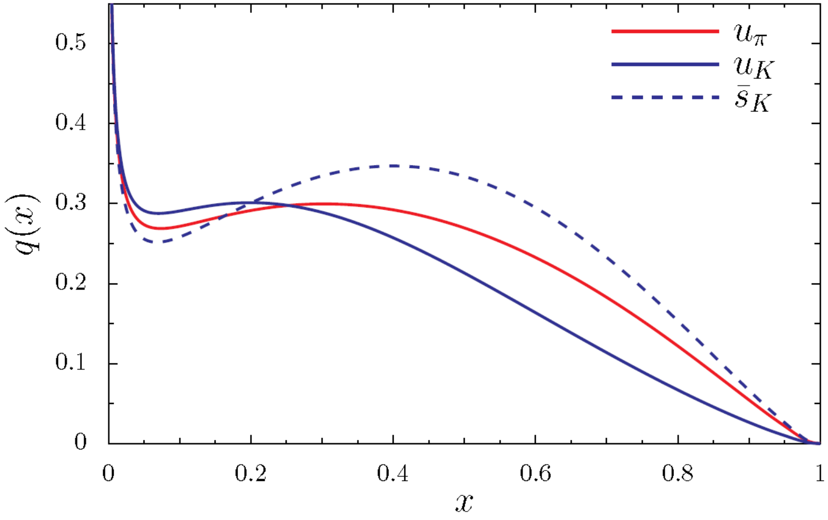
$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}$$



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

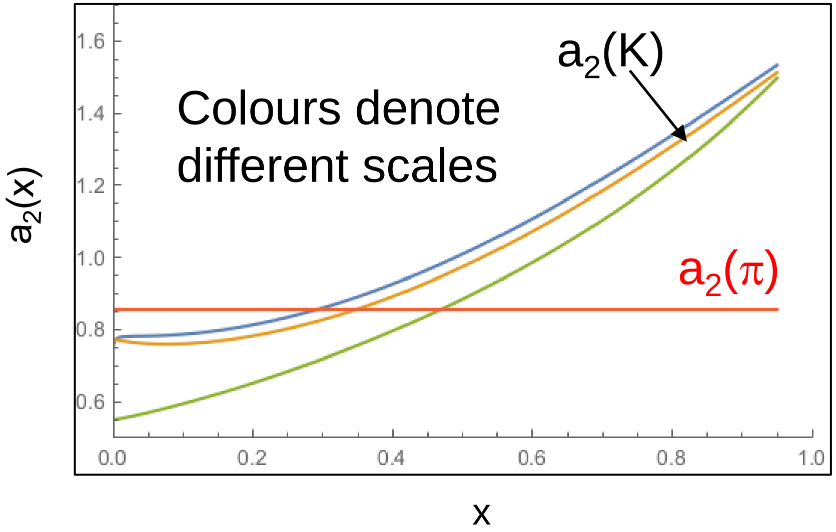
$$a_{2K}(x) = \frac{2\sum_q e_q\, g_V^q\,(q+\bar{q})}{\sum_q e_q^2\,(q+\bar{q})} \simeq \frac{6\,u_K^+ + 3\,s_K^+}{4\,u_K^+ + s_K^+} - 4\sin^2\theta_W$$

Figure from I. Cloet



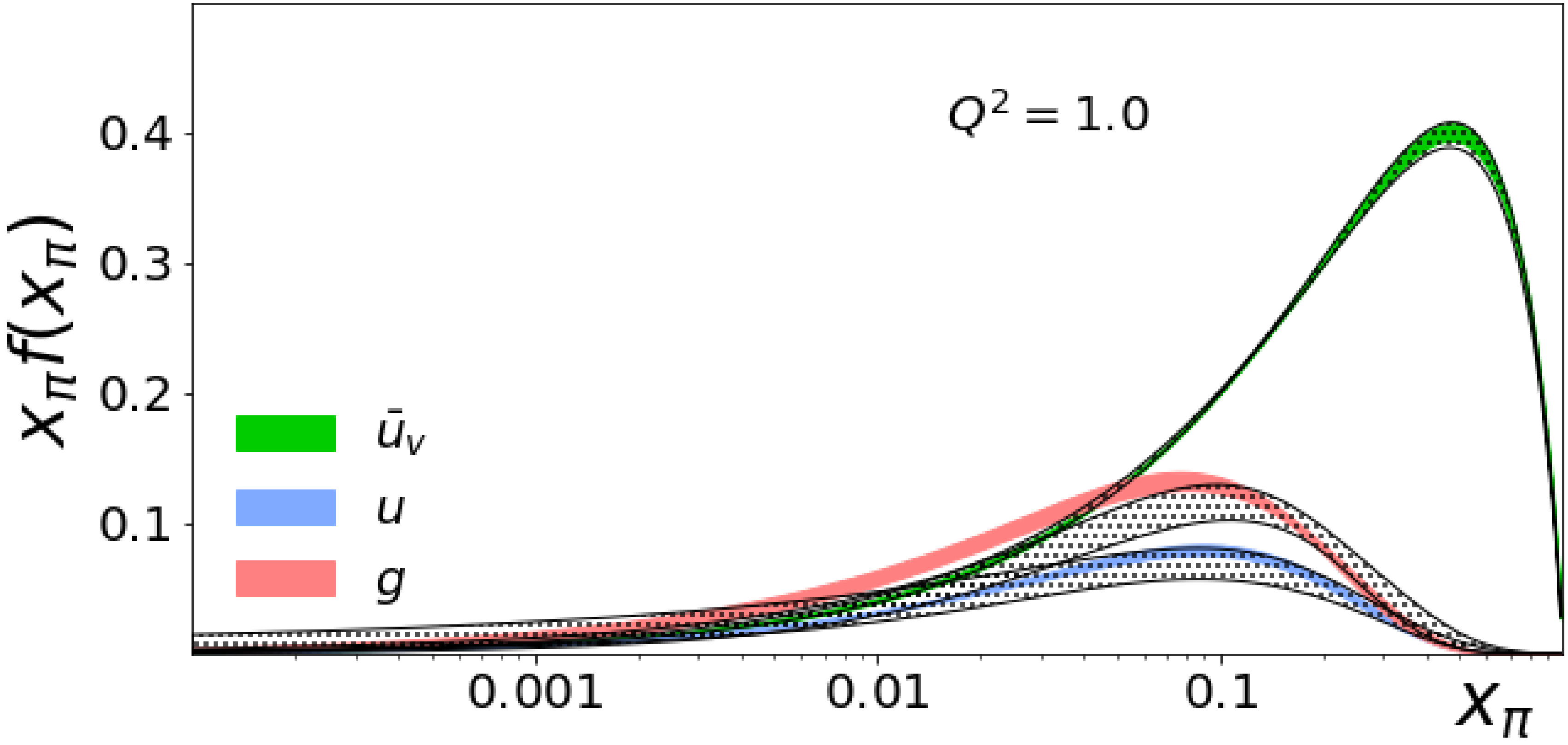
DSE-based parton distributions in pion and kaon

Calculation by C.D. Roberts et al.

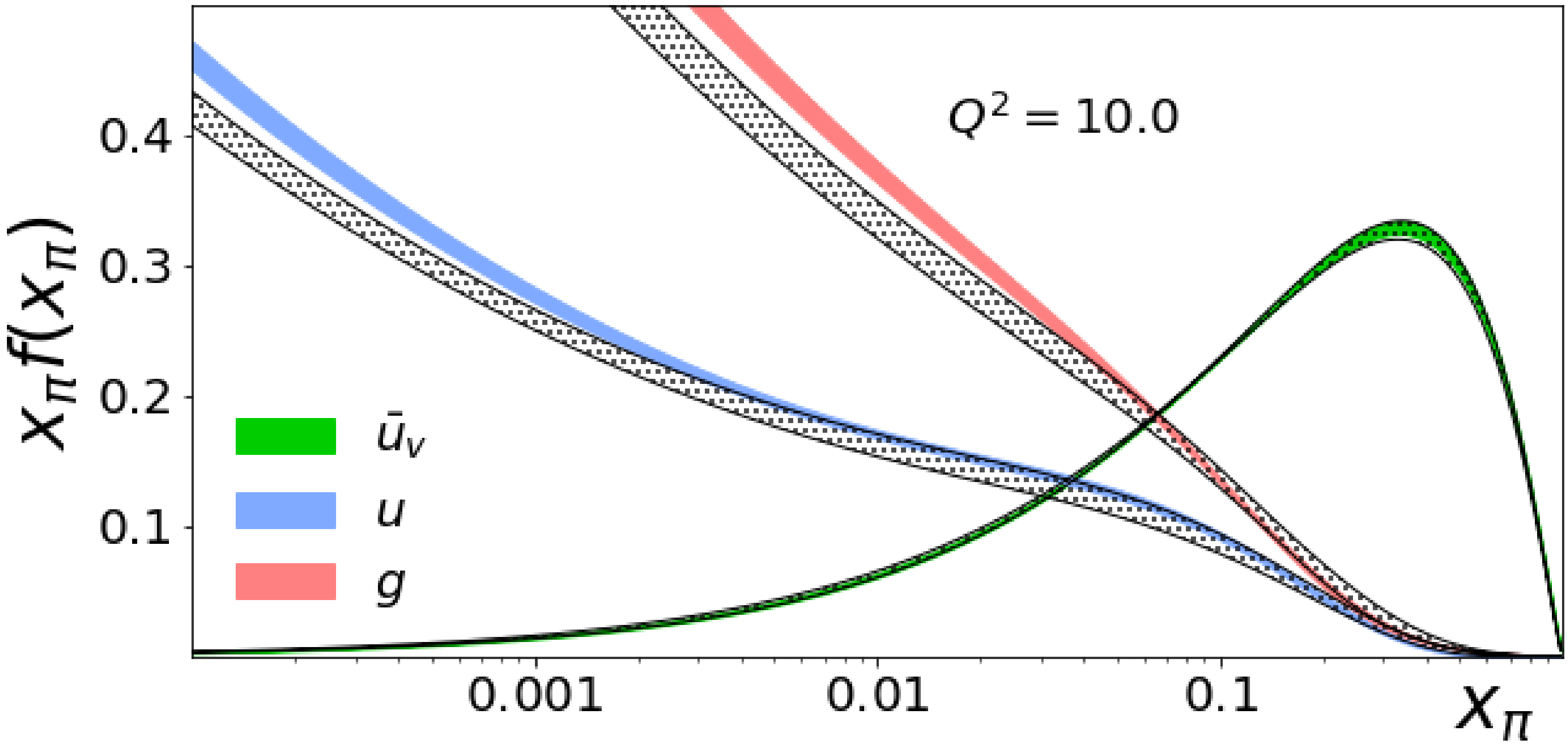


a_2 picks up different behavior of u and sbar. Flavor decomposition in kaon possible?

Present Projections



Present Projections



Present Projections