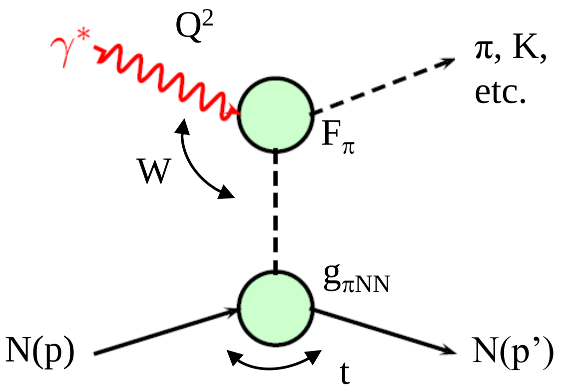
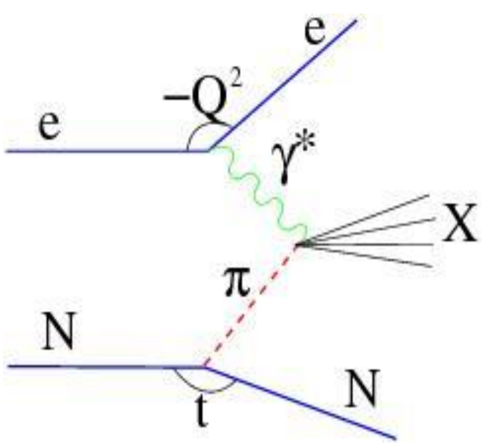
Pion and Kaon Structure at an EIC – White Paper





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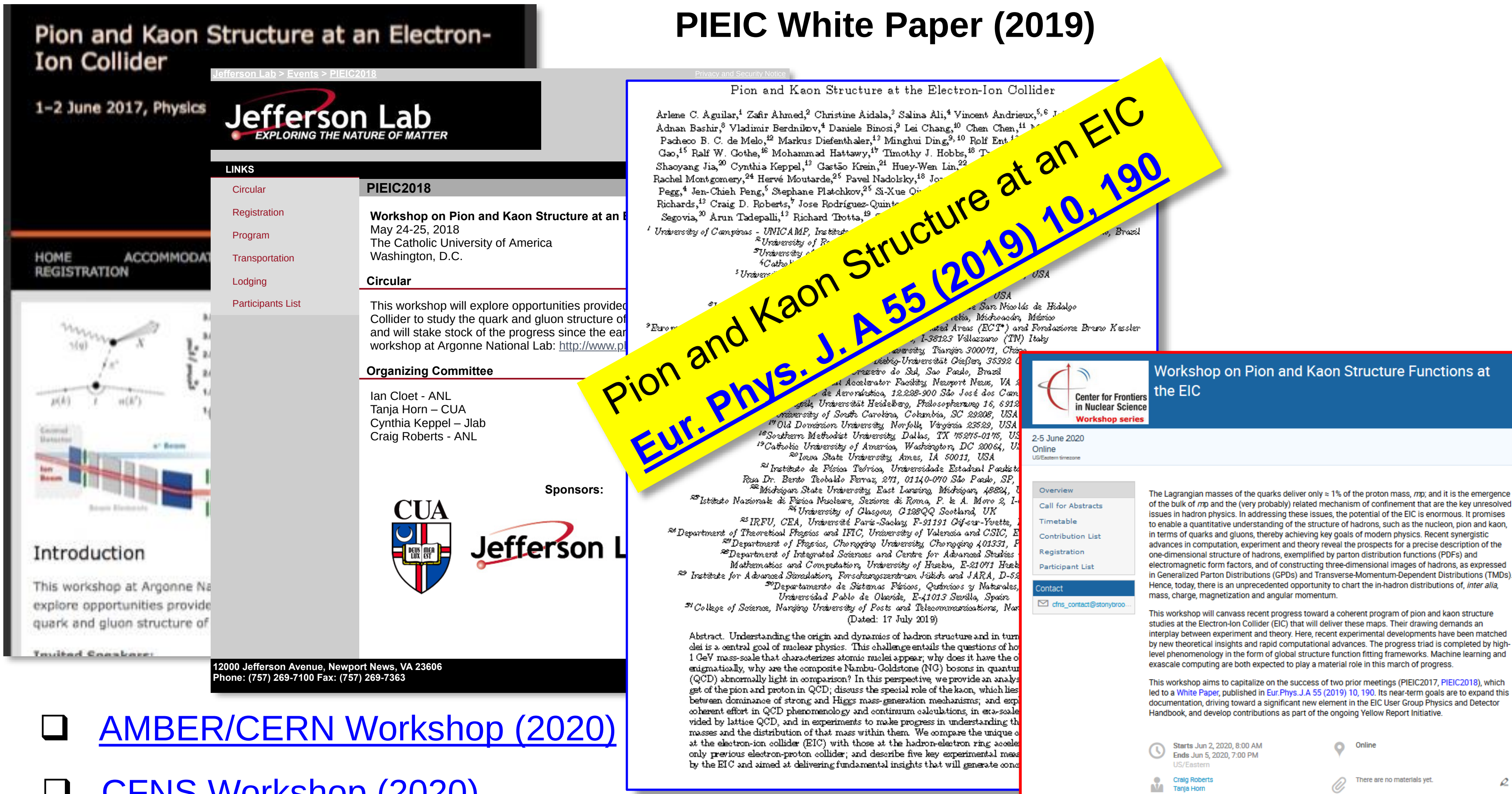
Pion and Kaon Structure at an EIC and Understanding Mass

- ❑ PIEIC Workshops hosted at [ANL (2017)]() and [CUA (2018)]()
- ❑ ECT* WS: [Emergent Mass and its Consequences (2018)]()

PIEIC White Paper (2019)



- ❑ [AMBER/CERN Workshop (2020)]()
- ❑ [CFNS Workshop (2020)]()
- ❑ ECT*: Workshop on Mass in the Standard Model and Consequences of its Emergence (2021)

Meson Structure Functions Yellow Report Working Group

Formed in 2019 in context of the EIC User Group Yellow Report Effort

- Meson SF WG: 22 members, 13 institutions, 7 countries
- BJ meetings every 2-3 weeks, 9 meetings since January 2020 (meeting archive: http://www.vsl.cua.edu/cua_phy/index.php/EIC_Meson_Structure_WG_Meetings)
- To join the Meson Structure Functions WG mailing list, contact T. Horn (hornt@cua.edu)
- Part of the EIC Diffractive Reactions & Tagging PWG

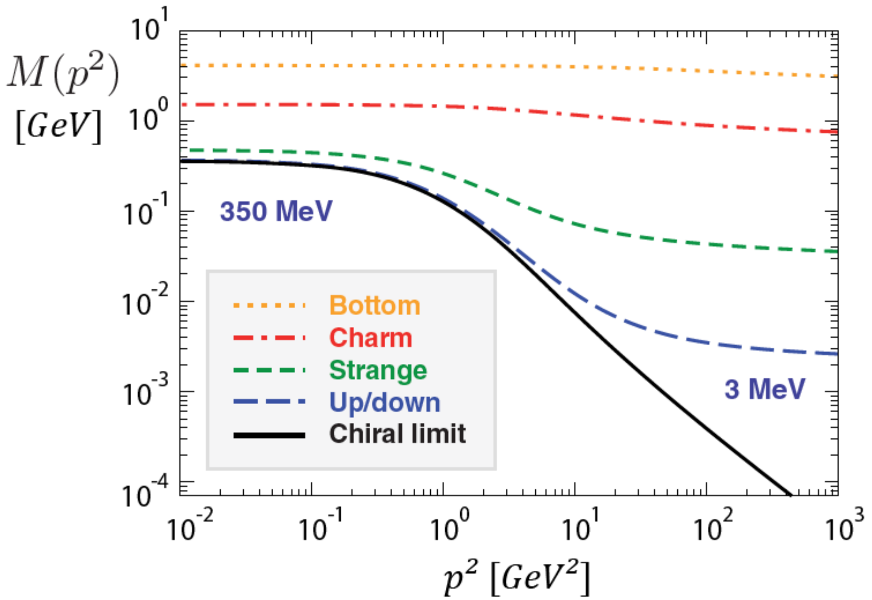
Meson SF Working group members:
John R. Arrington (ANL), Carlos Ayerbe, Daniele Binosi (ECT*), Lei Chang (Nankai U.), Rolf Ent (Jlab), Tobias Frederico (Instituto Tecnologico de Aeronautica), Timothy Hobbs (SMU), Tanja Horn (CUA), Garth Huber (U. Regina), Stephen Kay (U. Regina), Cynthia Keppel (Jlab), Bill Lee (W&M)), Huey-Wen Lin (MSU), Rachel Montgomery(U. Glasgow), Ian L. Pegg (CUA), Paul Reimer (ANL), David Richards (Jlab), Craig Roberts(Nanjng U.), Jorge Segovia (Universidad Pablo de Olavide), Arun Tadepalli (JLab), Richard Trotta (CUA), Rik Yoshida (ANL)

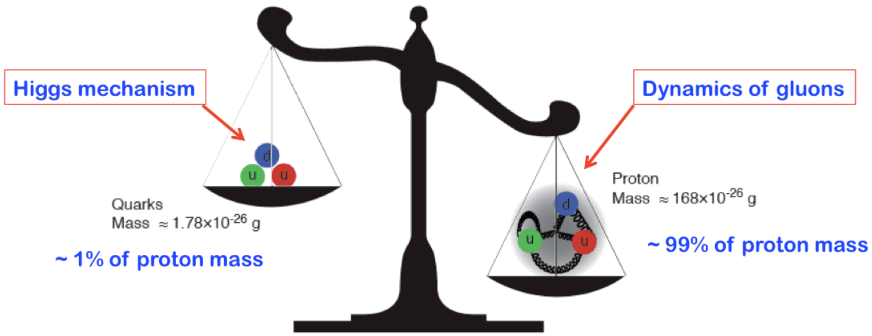
The Physics Working Group is divided in the following subgroups:

- **Inclusive Reactions:** to join this group and its mailing list, contact R. Fatemi
  - **Conveners:** Renee Fatemi (Kentucky), Nobuo Sato (JLab), Barak Schmookler (Stony Brook)
- **Semi-inclusive Reactions:** to join this group and its mailing list, contact R. Seidl
  - **Conveners:** Ralf Seidl (RIKEN), Justin Stevens (W&M), Alexey Vladimirov (Regensburg), Anselm Vossen (Duke), Bowen Xiao (CCNU, China)
- **Jets, Heavy Quarks:** to join this group and its mailing list, contact L. Mendez
  - **Conveners:** Leticia Mendez (ORNL), Brian Page (BNL), Frank Petriello (ANL & Northwestern U.), Ernst Sichtermann (LBL), Ivan Vitev (LANL)
- **Exclusive Reactions:** to join this group and its mailing list, contact S. Fazio
  - **Conveners:** Raphaël Dupré (Orsay), Salvatore Fazio (BNL), Tuomas Lappi (Jyvaskyla), Barbara Pasquini (Pavia), Daria Sokhan (Glasgow)
- **Diffractive Reactions & Tagging:** to join this group and its mailing list, contact W. Cosyn
  - **Conveners:** Wim Cosyn (Florida), Or Hen (MIT), Doug Higinbotham (JLab), Spencer Klein (LBNL), Anna Stasto (PSU)

The incomplete Hadron: Mass Puzzle

"Mass without mass!"





The light quarks acquire (most of) their masses as effect of the gluon cloud.

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

Proton: Mass ~ 940 MeV

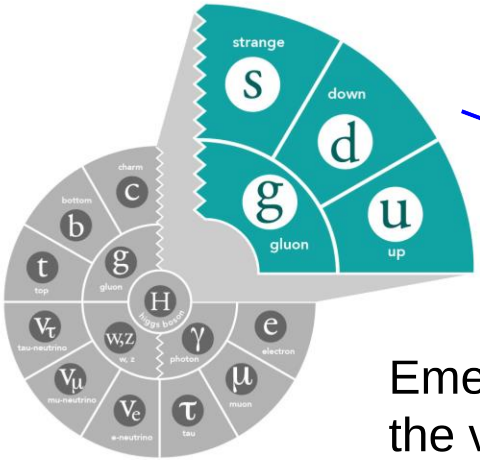
preliminary LQCD results on mass budget, or view as mass acquisition by DCSB

Kaon: Mass ~ 490 MeV

at a given scale, less gluons than in pion

Pion: Mass ~ 140 MeV

mass enigma – gluons vs Goldstone boson



Emergent mass of the visible universe

→ *also see talks by Craig Roberts, Jianwei Qiu, …*

Origin of Mass of QCD's Pseudoscalar Goldstone Modes

- The pion is both the lightest bound quark system with a valence $\bar{q}q$ 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)*

$$f_\pi m_\pi^2 = \left(m_u^\zeta + m_d^\zeta\right)\rho_\pi^\zeta$$
$$f_K m_K^2 = \left(m_u^\zeta + m_s^\zeta\right)\rho_K^\zeta$$

  - From these exact statements, it follows the mass of bound states increases as √m with the mass of the constituents.

  - In contrast, in, *e.g*. the CQM, bound state mass rises linearly with constituent mass, *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.

- Pseudoscalar masses are generated **dynamically**

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?

Fundamental Questions

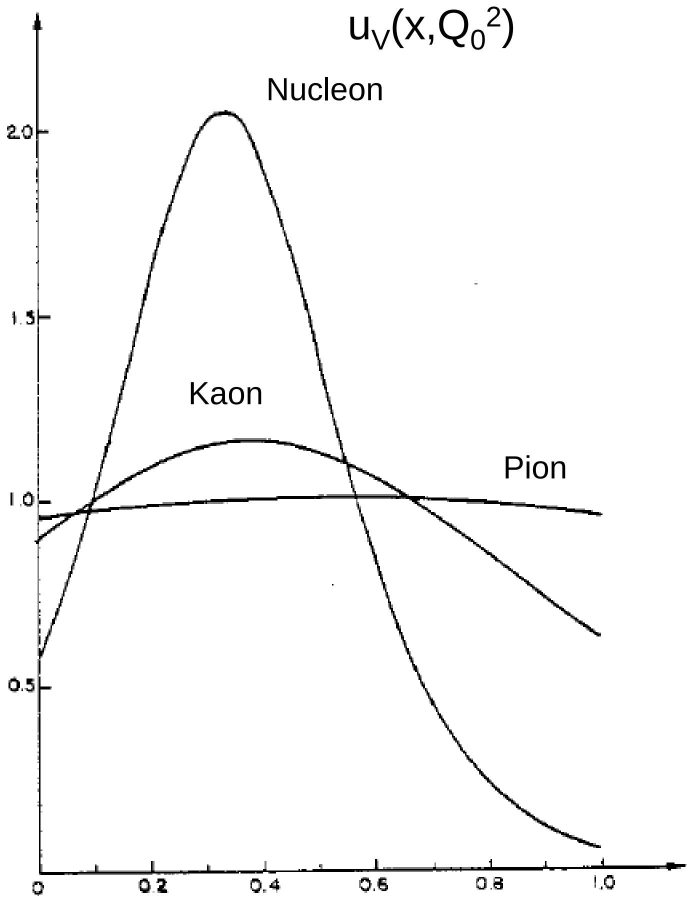
For understanding the origin of hadron masses and distribution of that mass within

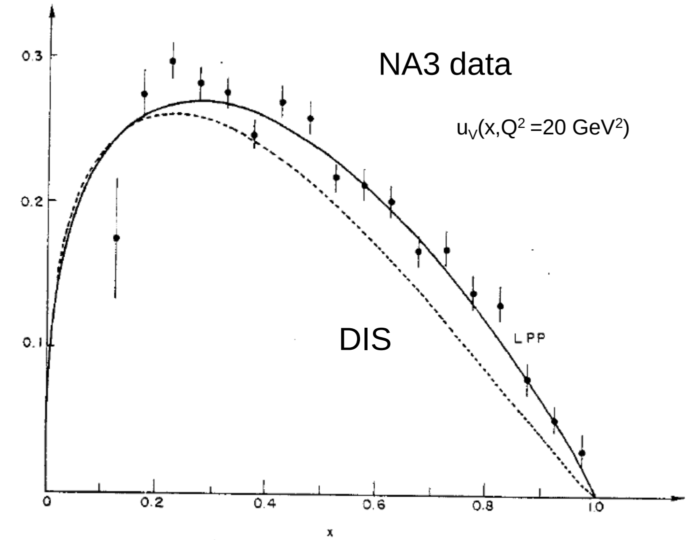
- How do hadron masses and radii emerge for light-quark systems from QCD?
- What is the origin and role of dynamical chiral symmetry breaking?
- What is the interplay of the strong-mass and Higgs generation mechanisms?
- What are the basic mechanisms that determine the distribution of mass, momentum, charge, spin, etc. within hadrons?

Requires coherent effort in QCD phenomenology and continuum calculations, exa-scale computing as provided by lattice QCD, and experiment

At some level an old story…

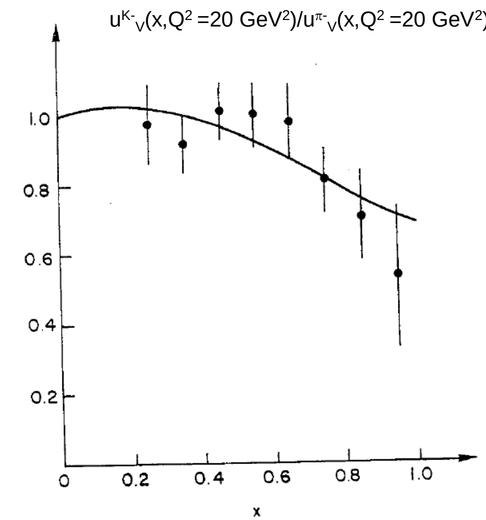
A model for nucleon, pion and kaon structure functions
F. Martin, CERN-TH 2845 (1980)





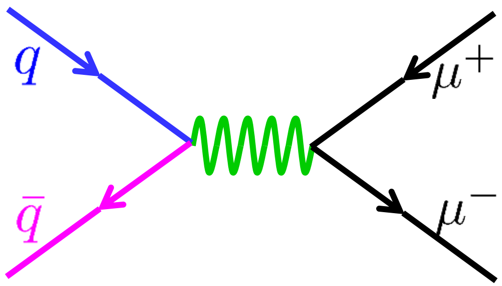
Predictions based on non-relativistic model with valence quarks only

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



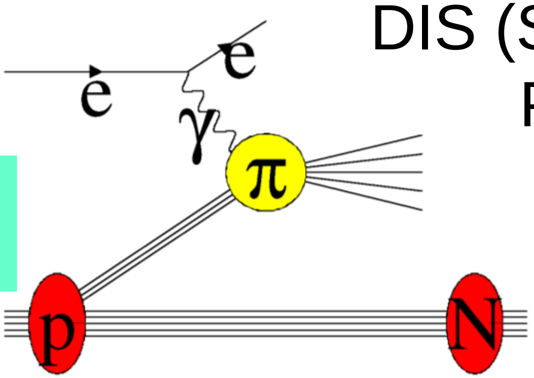
World Data on pion structure function F_2^{π}

Pion Drell-Yan

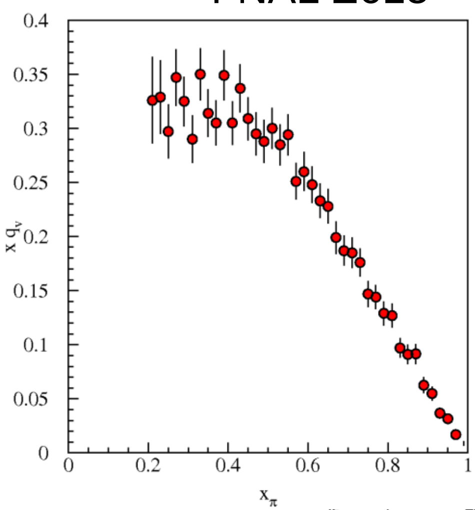


Amount of data is limited…

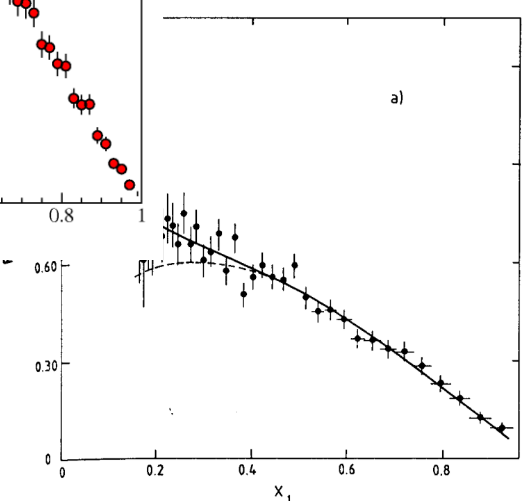
DIS (Sullivan Process)

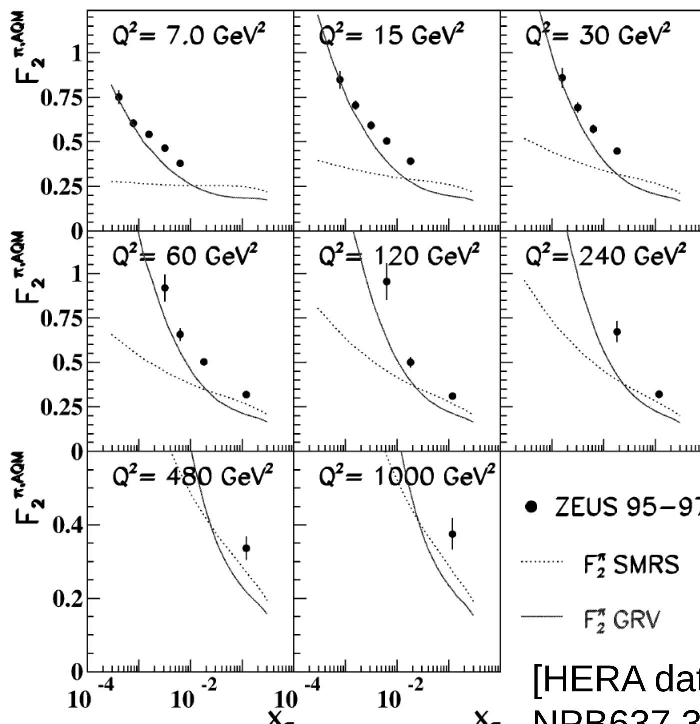


FNAL E615



CERN NA3

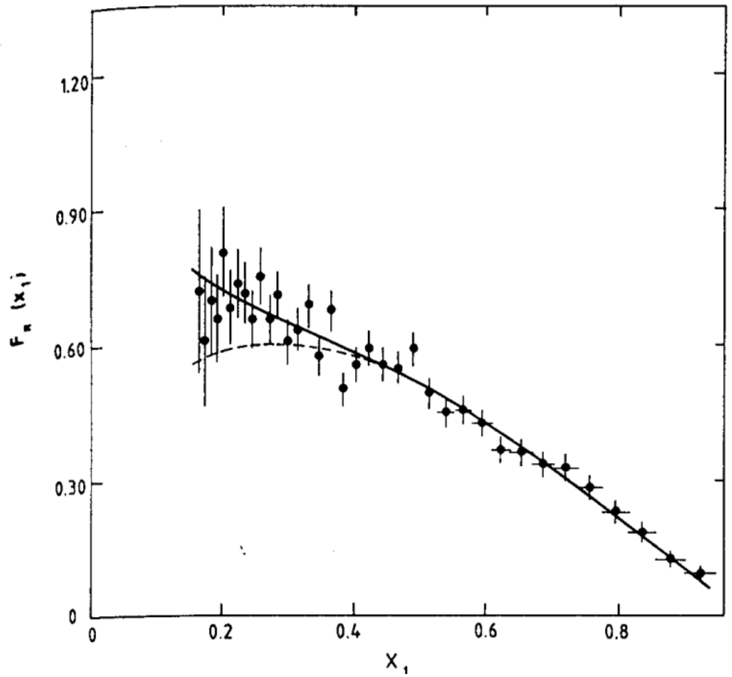




[HERA data [ZEUS, NPB637 3 (2002)]

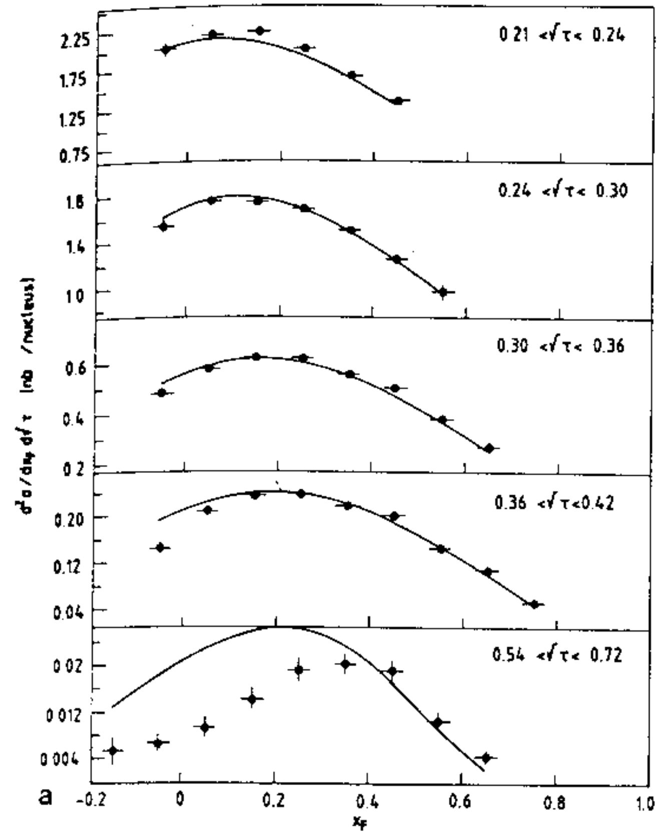
→ *also see talks by Oleg Denisov, Vincent Andrieux, Richard Trotta, Rachel Montgomery, …*

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*!

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



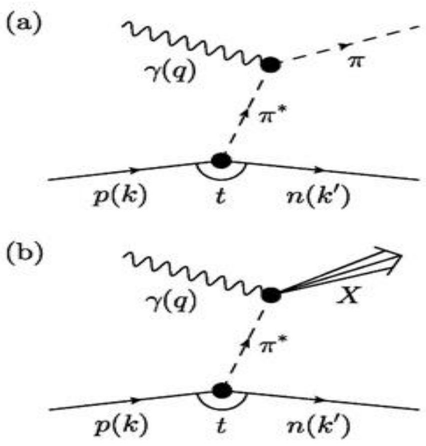
NA10 194 GeV π^- data

quark sea in pion is small – few %

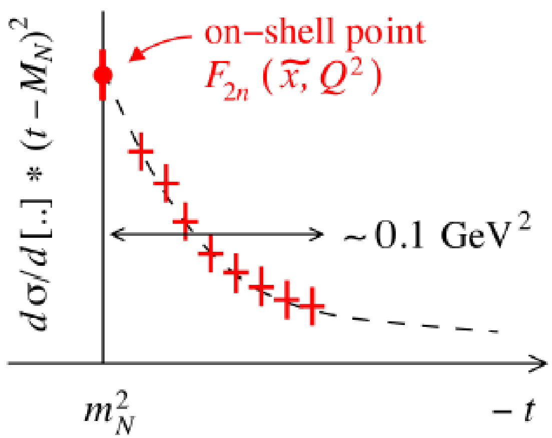
Key Experimental Efforts at an EIC

- Hadron masses in light quark systems
  - Pion and kaon parton distribution functions (PDFs) and generalized parton distributions (GPDs)
- Gluon (binding) energy in Nambu-Goldstone modes
  - Open charm production from pion and kaon
- Mass acquisition from Dynamical Chiral Symmetry Breaking (DCSB)
  - Pion and kaon form factors
- Strong vs. Higgs mass generating mechanisms
  - Valence quark distributions in pion and kaon at large momentum fraction x
- Timelike analog of mass acquisition
  - Fragmentation of a quark into pions or kaons

Pion and Kaon Sullivan Process



- The **Sullivan process can provide reliable access to a meson target** as t becomes space-like if the pole associated with the ground-state meson remains the dominant feature of the process and the structure of the related correlation evolves slowly and smoothly with virtuality.



- To **check these conditions** are satisfied empirically, one can **take data covering a range in *t*** and compare with phenomenological and theoretical expectations.

- Recent **theoretical calculations found that for $-t \leq 0.6\ \mathrm{GeV}^2$, all changes in pion structure are modest** so that a well-constrained experimental analysis should be reliable Similar analysis for the kaon indicates that Sullivan processes can provide a valid kaon target for $-t \leq 0.9\ \mathrm{GeV}^2$

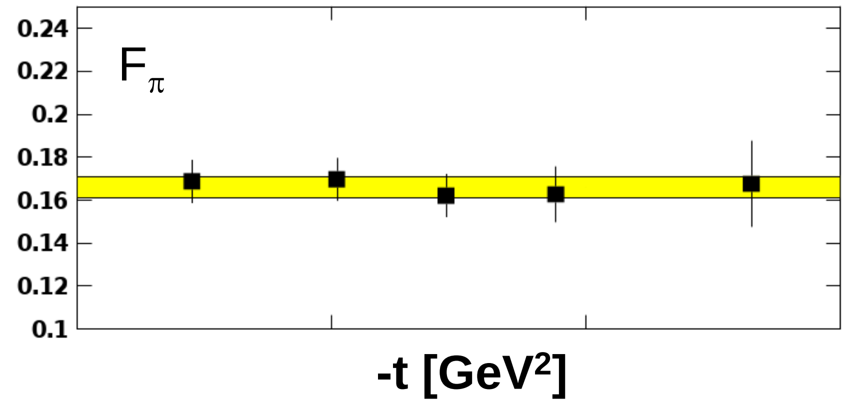
*[S.-X. Qin, C. Chen, C. Mezrag and C. D. Roberts, Phys. Rev. C **97** (**2018**) 015203.]*

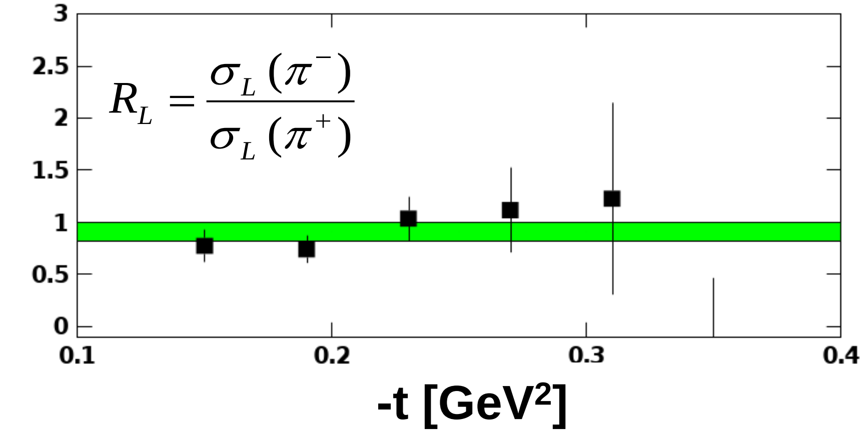
Experimental Validation (Pion Form Factor example)

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]*

*[R. J. Perry et al., PRC**100** (**2019**) 2, 025206.]*

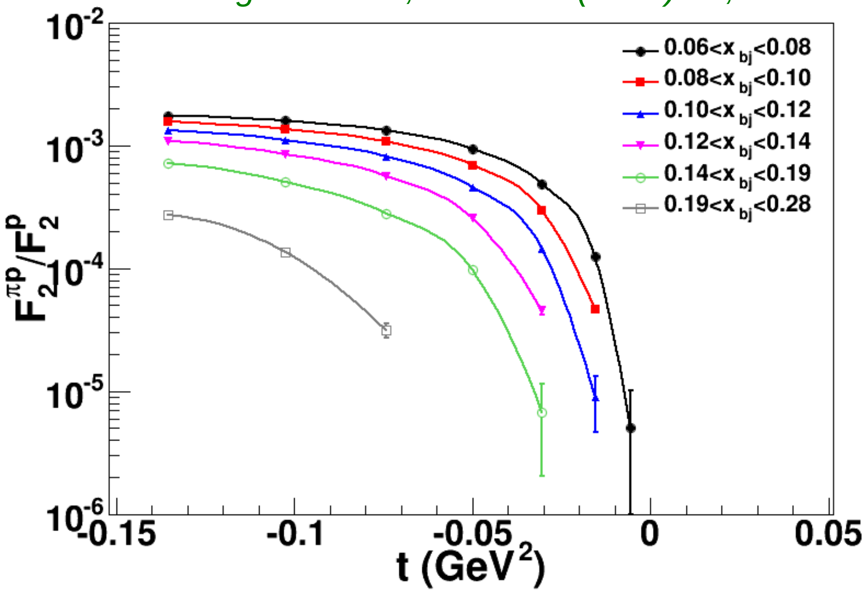
*[T. Horn, C.D. Roberts, J. Phys. G**43** (**2016**) no.7, 073001]*

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.

*A.C. Aguilar et al., EPJ A **55** (**2019**) 10, 190*

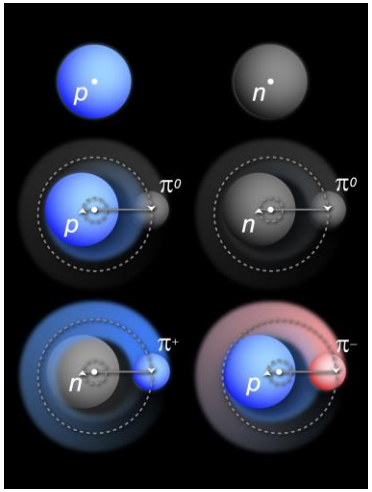


*Ratio of the F_2 structure function related to the pion Sullivan process as compared to the proton F_2 structure function in the low-t vicinity of the pion pole, as a function of Bjorken-x (Jefferson Lab TDIS Collaboration, JLab Exp. **C12-15-005**)*

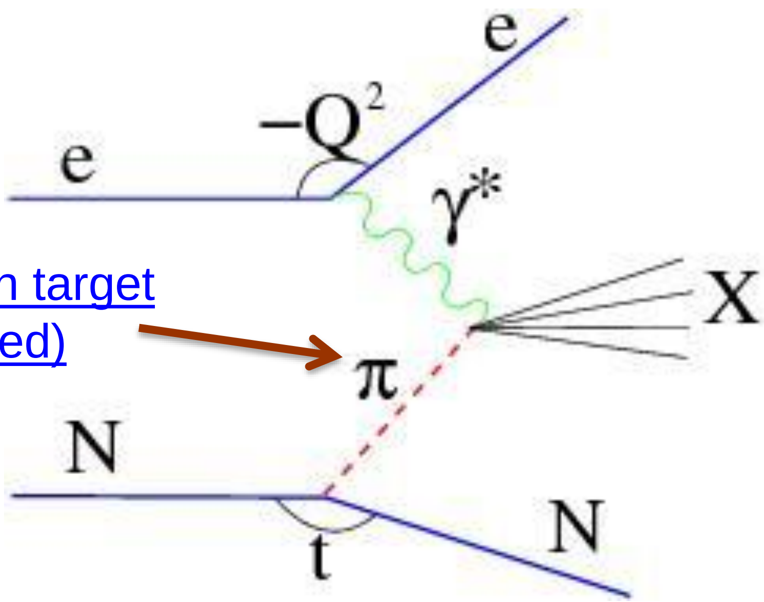
→ see talk by Thia Keppel

Physics Objects for Pion/Kaon Structure Studies

- Sullivan process – scattering from nucleon-meson fluctuations



Detect scattered electron



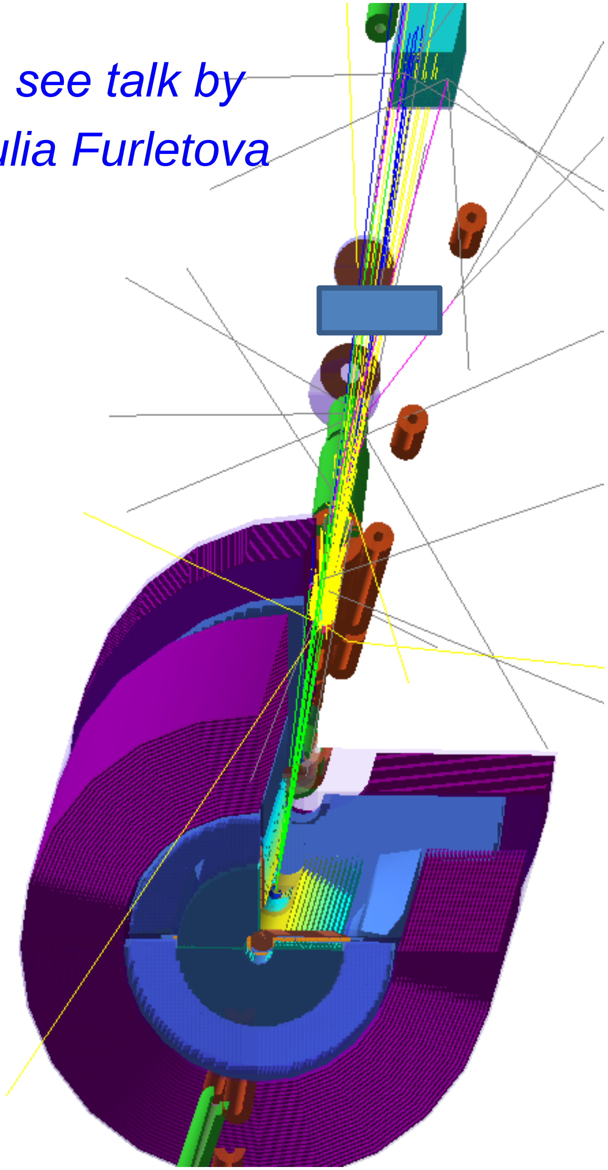
DIS event – reconstruct x, Q^2, W^2, also M_X (W_π) of undetected recoiling hadronic system

Pion/Kaon target (undetected)

Detect “tagged” neutron/lambda

Summary of Detector Requirements

→ see talk by Yulia Furletova

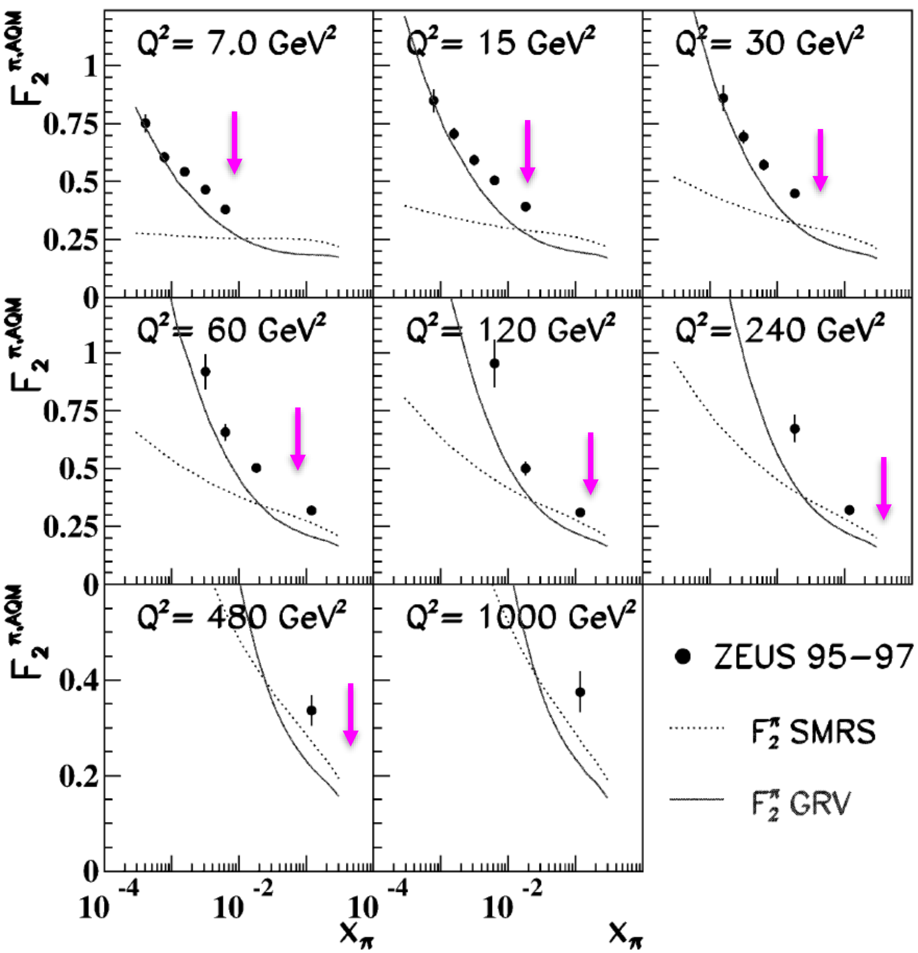


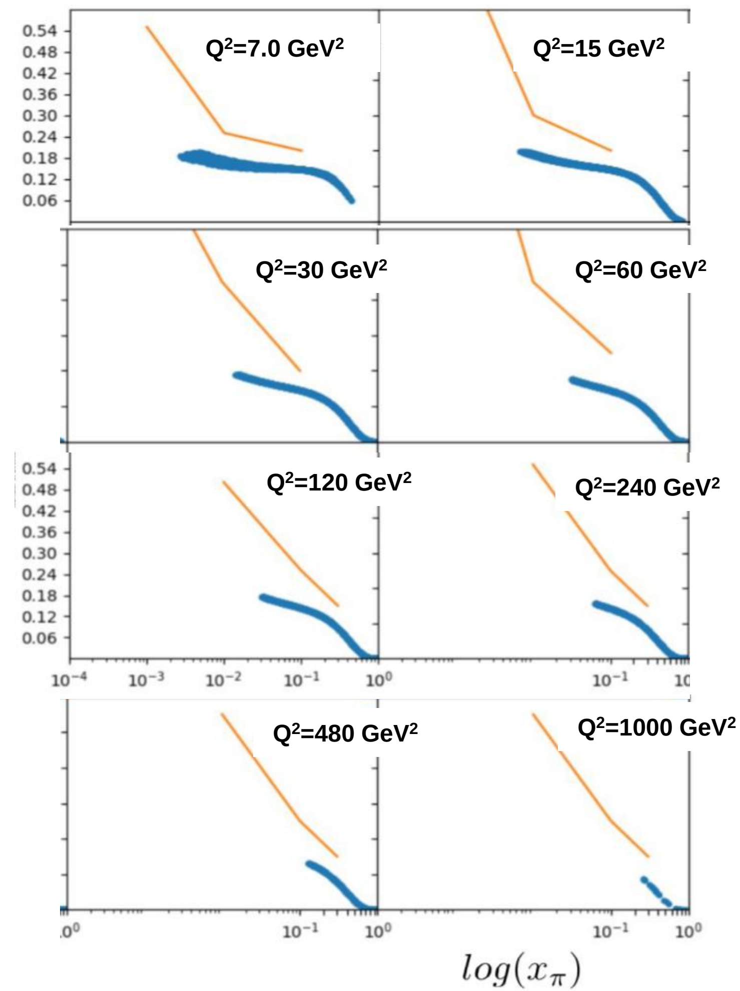
- **For π-n:**
  - For all energies, the neutron detection efficiency is 100% with the planned ZDC
  - Lower energies (5 on 41, 5 on 100) require at least 60cm x 60cm to access wider range of energies
- **For π-n and K^+/Λ:**
  - All energies need good ZDC angular resolution for the required -t resolution
  - High energies (10 on 100, 10 on 135, 18 on 275) require resolution of 1cm or better
- **K^+/Λ benefits from low energies (5 on 41, 5 on 100) and also need:**
  - $\Lambda \rightarrow n + \pi^0$: additional high-res/granularity EMCal+tracking before ZDC – seems doable
  - $\Lambda \rightarrow p + \pi^-$: additional trackers in opposite direction on path to ZDC – more challenging
- Standard electron detection requirements
- Good hadron calorimetry for good x resolution at large x

World Data on pion structure function F_2^{π}

HERA ↓ $\sim x_{min}$ for EIC

EIC *Example for 5 GeV e^- and 100 GeV p*





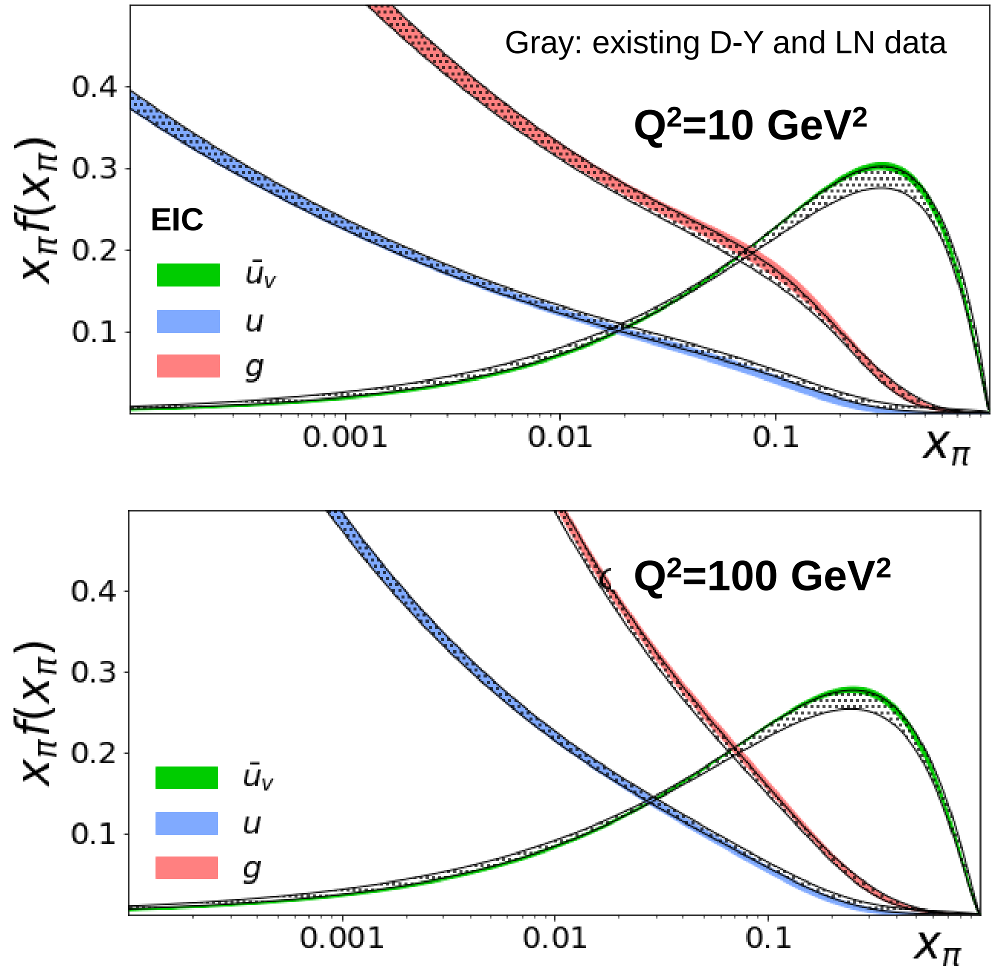
- ❑ **EIC kinematic reach down to a x = few 10^{-3}**
- ❑ **Lowest x constrained by HERA**

→ see talk by Richard Trotta

Global pion PDF fit with EIC pseudodata

- 5 GeV (e-) on 50 GeV (p)
- 0.1 < y < 0.8
- EIC pseudodata fitted using self-serve pion PDF framework
- EIC will improve the PDFs, especially for kaons as will have similar-quality data.
- DY measurements by COMPASS++/AMBER could constrain x>0.02

*A.C. Aguilar et al., EPJ A **55 (2019**) 10, 190*



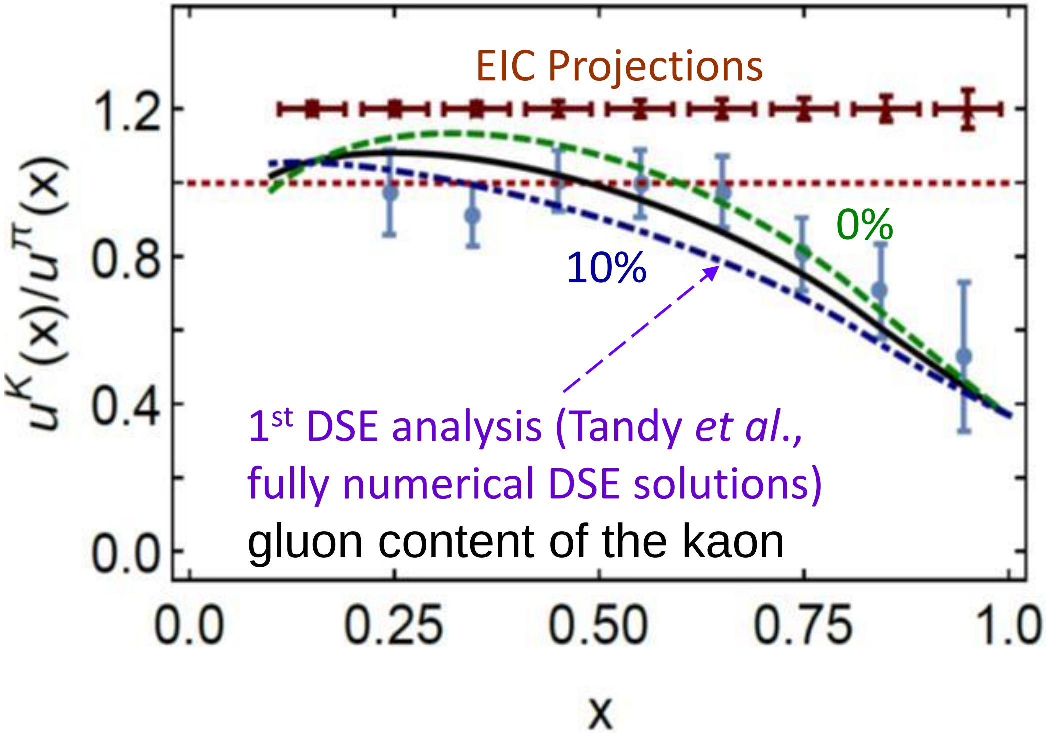
Precision gluon constraints of pion and kaon PDFs <u>are</u> possible.

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 ~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

A.C. Aguilar et al., EPJ A ***55*** *(****2019****) 10, 190*



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

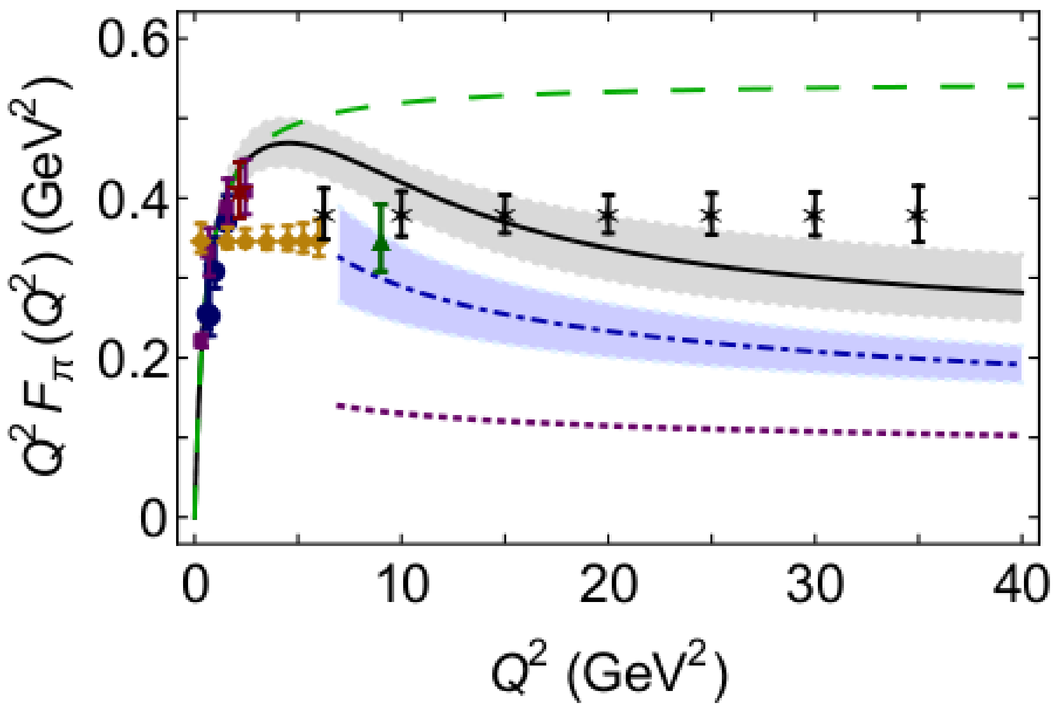
- heavier quarks radiate less readily than lighter quarks
- heavier quarks radiate softer gluons than do lighter quarks
- Landau-Pomeranchuk effect: softer gluons have longer wavelength and multiple scatterings are suppressed by interference.
- Momentum conservation communicates these effects to the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

→ also see talks by Huey-Wen Lin, David Richards, …

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

A.C. Aguilar et al., EPJ A ***55*** *(**2019**) 10, 190*



- ❑ 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 ^2H 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

→ *see talk by Stephen Kay*

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)?
  - How much glue is in the pion?
- The pion form factor may be measured at an EIC up to $Q^2 = 35$ 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**.