Further Studies of Pion and Kaon Structure at an EIC

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EIC Users Group Meeting 2019
(EICUGM2019)

Ecole Nationale Superieure de Chimie,
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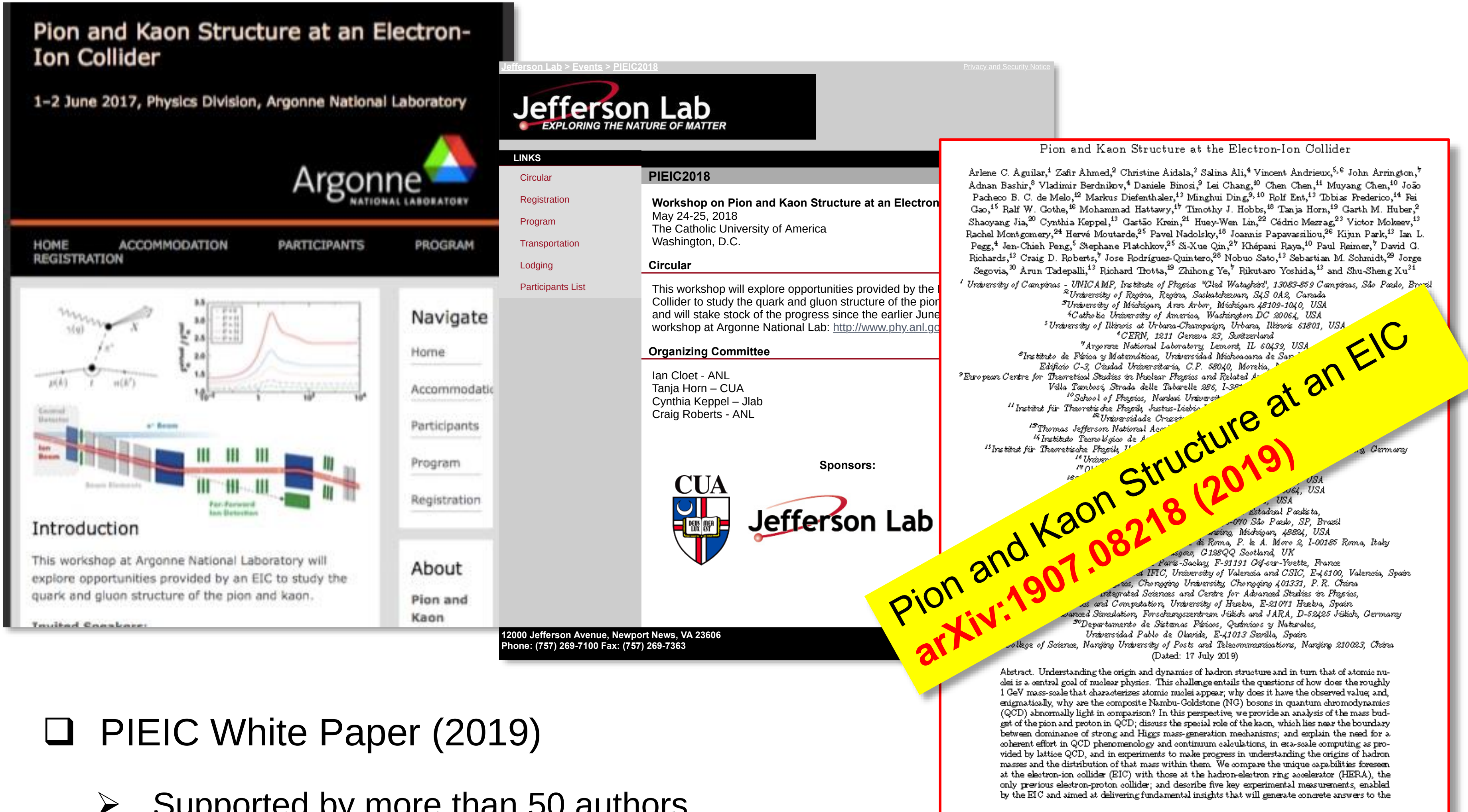
Based on…

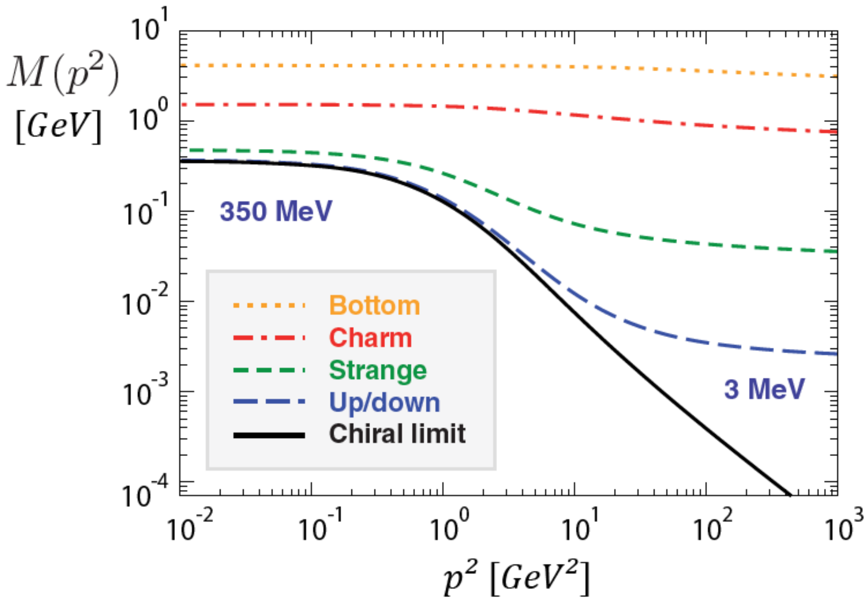
- ❑ PIEIC Workshops hosted at ANL (2017) and CUA (2018)

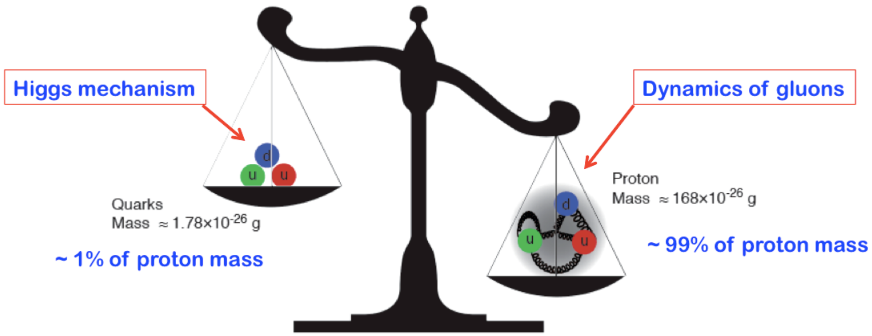


- ❑ PIEIC White Paper (2019)
  - ➢ Supported by more than 50 authors

The incomplete Hadron: Mass Puzzle

"Mass without mass!"





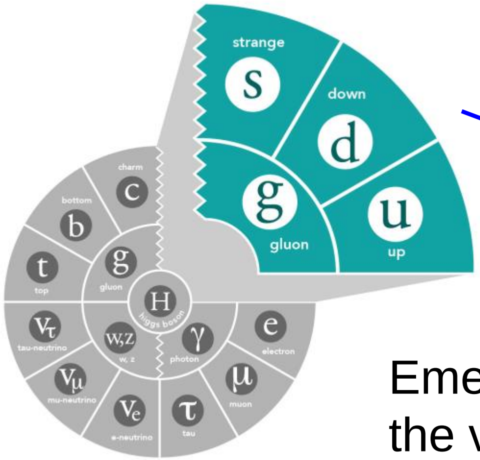
The light quarks acquire (most of) their masses as effect of the gluon cloud.

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

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)*

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

- Pseudoscalar masses are generated **dynamically**
  - 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 $m_Q \sim ⅓m_N \sim 310$ MeV, in the pion $m_Q \sim ½m_\pi \sim 70$ 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 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?

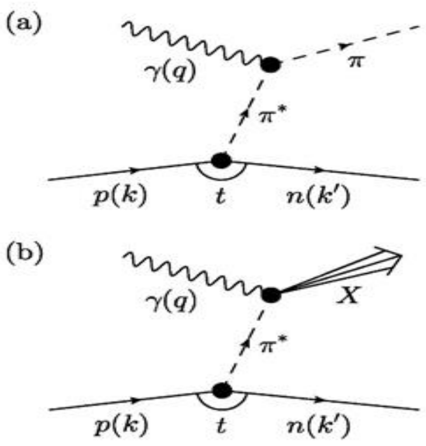
Requires coherent effort in QCD phenomenology and continuum calculations, exa-scale computing as provided by lattice QCD, and experiment

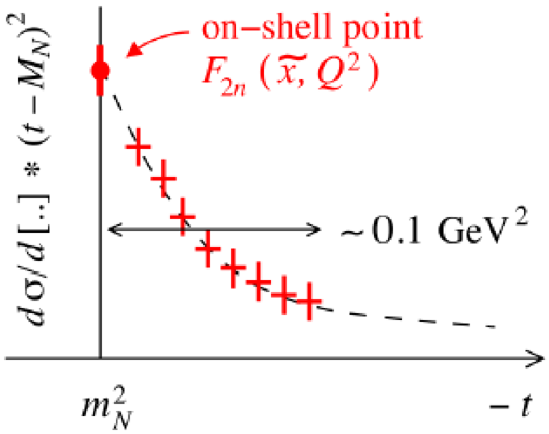
Key Experimental Efforts

- 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 $-t \leq 0.6$ 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 $-t \leq 0.9$ 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)

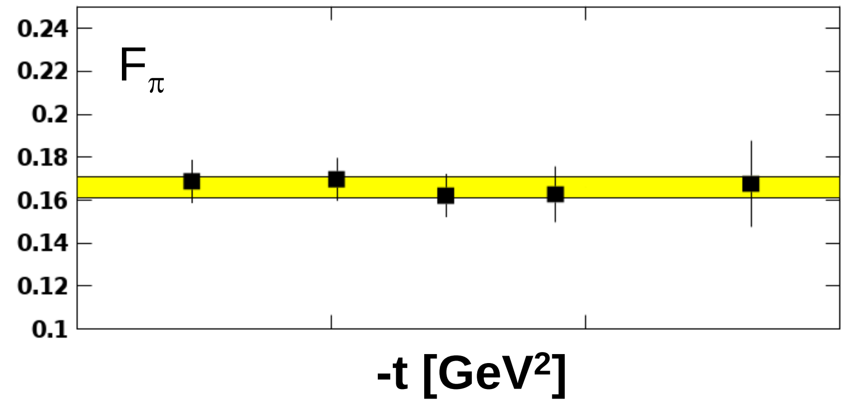
Experimental studies over the last decade have given ***confidence*** in the electroproduction method yielding the physical pion form factor

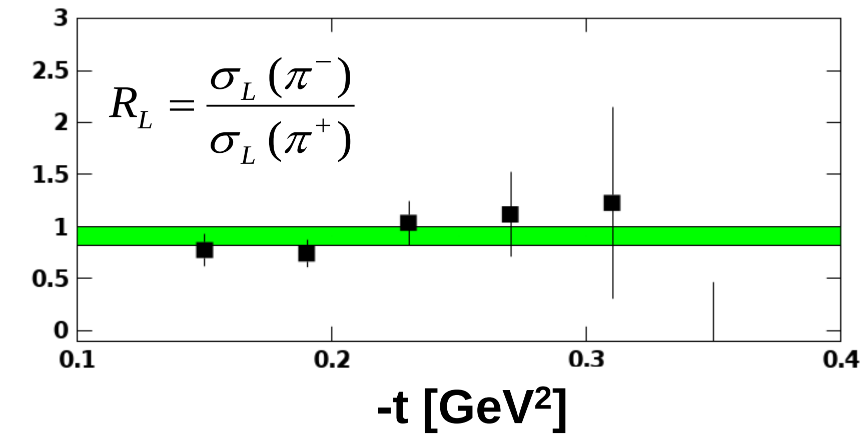
Experimental studies include:

- 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., arXiV:1811.09356 (2019).]



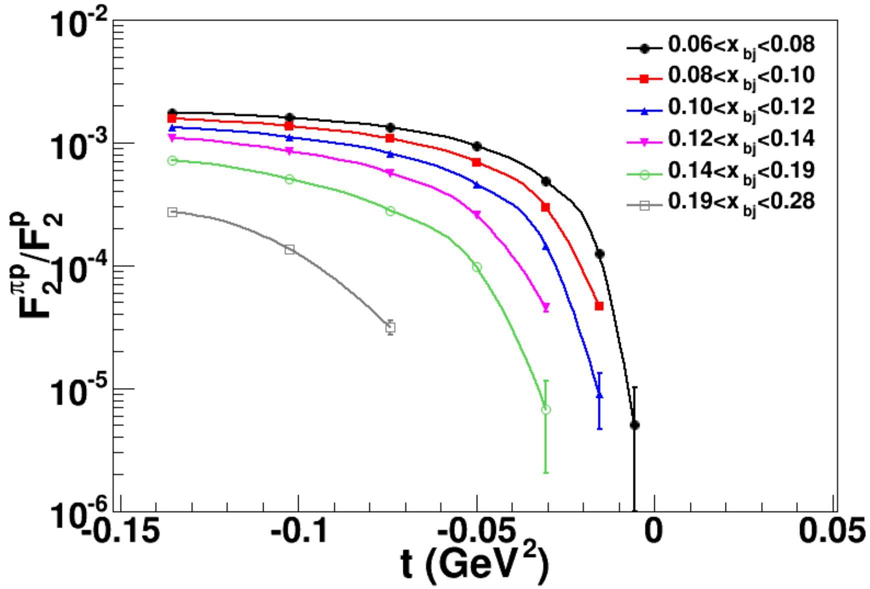


*[T. Horn, C.D. Roberts, J. Phys. G**43** (**2016**) no.7, 073001]*

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.



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)

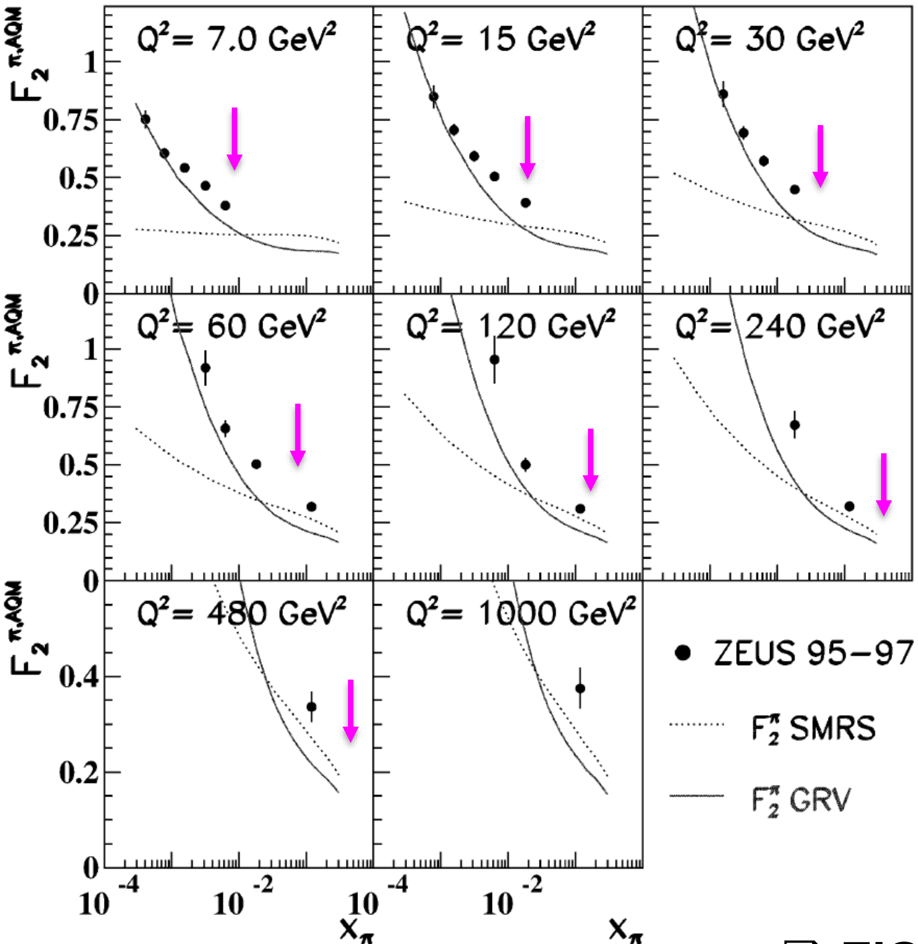
World Data on pion structure function F_2^{π}

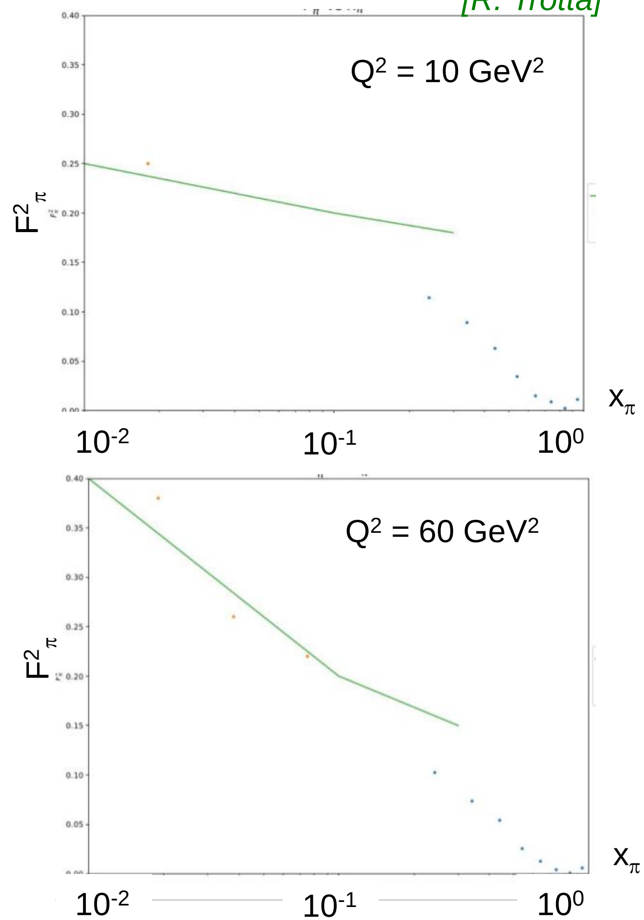
HERA

$\sim x_{min}$ for EIC

EIC

Here example for 5 GeV e- and 100 GeV p
[R. Trotta]



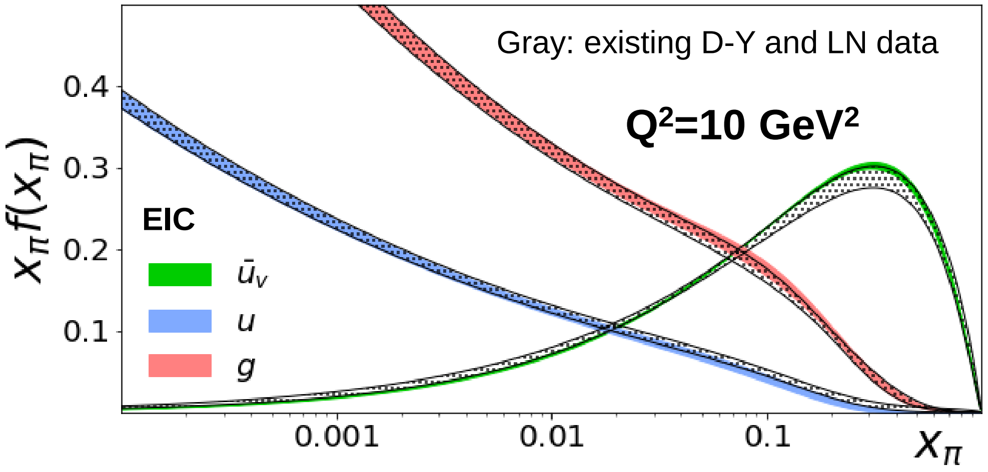


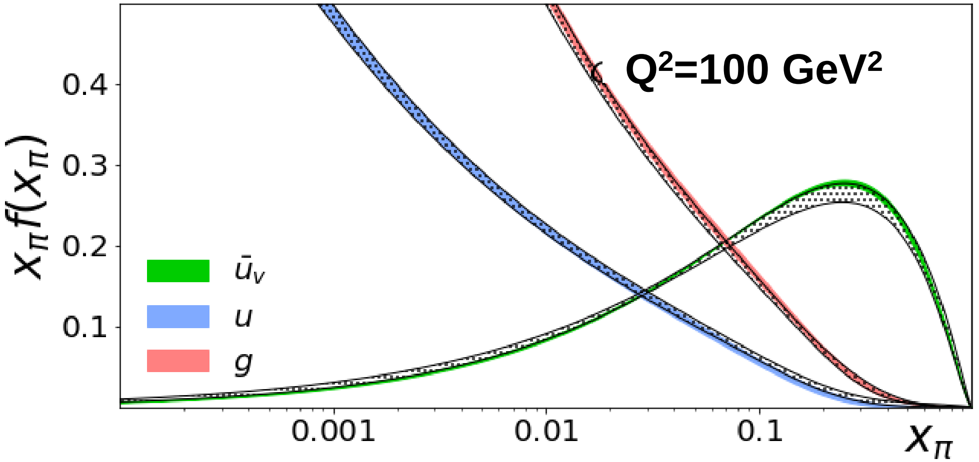
- ❑ **EIC kinematic reach down to a x = few 10^{-3}**
- ❑ **Lowest x constrained by HERA**

Global pion PDF fit with EIC pseudodata

[T. Horn, N. Sato, R. Trotta]

- ❑ 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>02





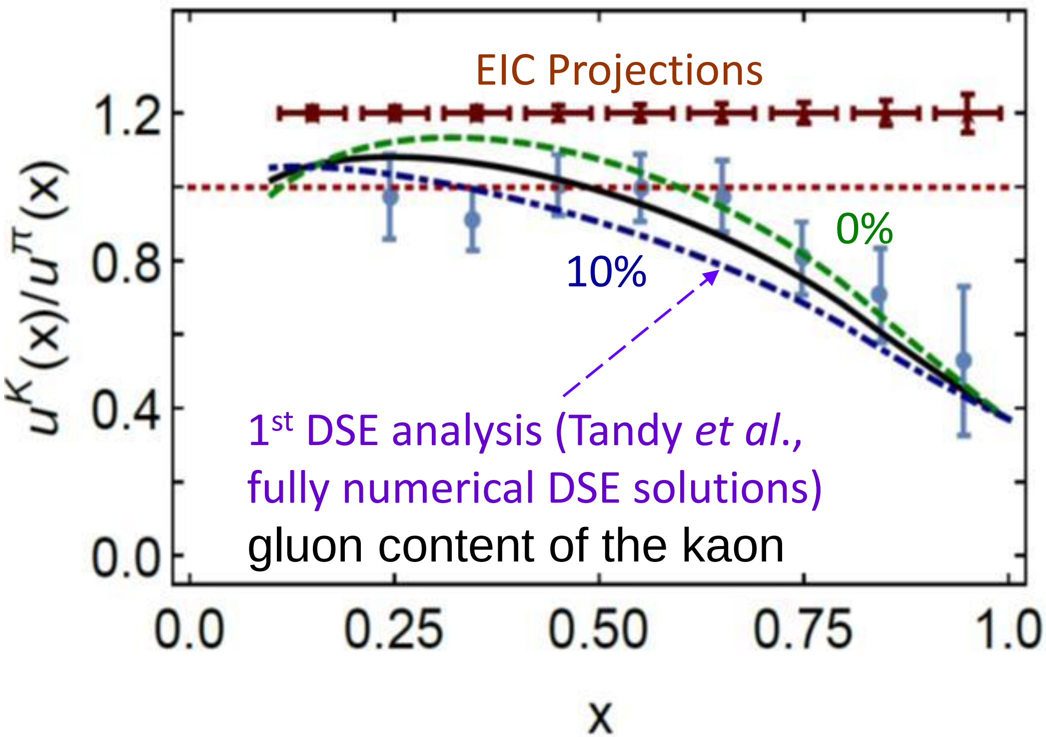
Precision gluon constraints of pion and kaon PDFs <u>are</u> possible.

Kaon structure functions – gluon pdfs

T. Horn, C. Roberts, R. Ent

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

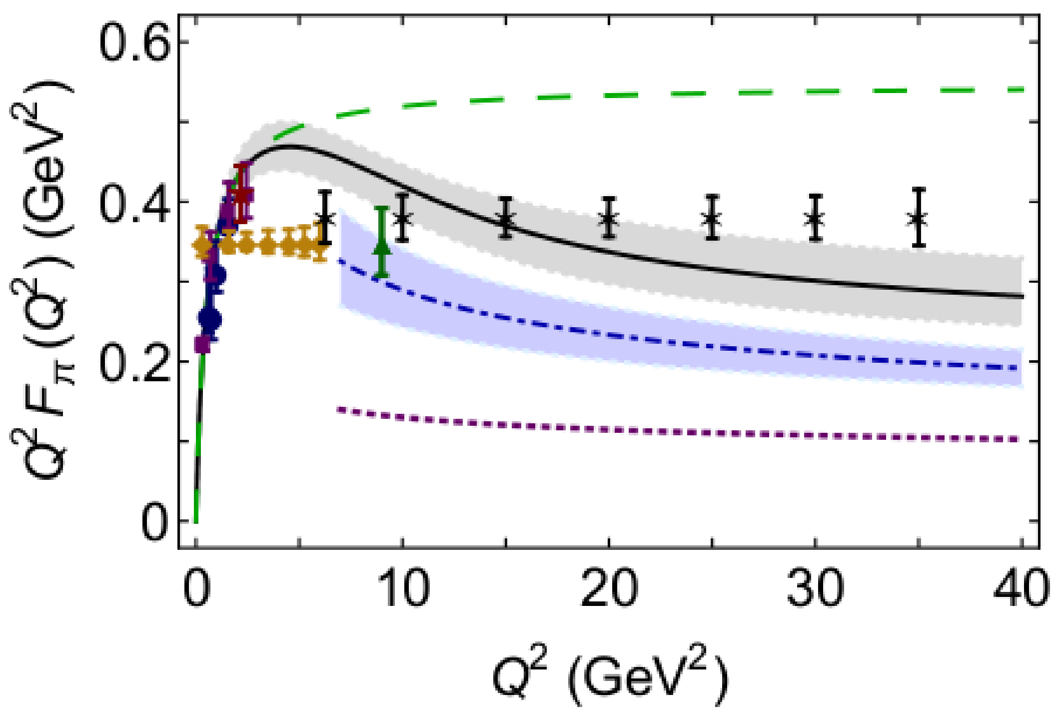


Thus, at a given scale, there is far **less glue in the kaon than in the pion**:

- 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.

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 ^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?

[Garth Huber, Tanja Horn]

Not clear – needs guidance from JLab 12- GeV

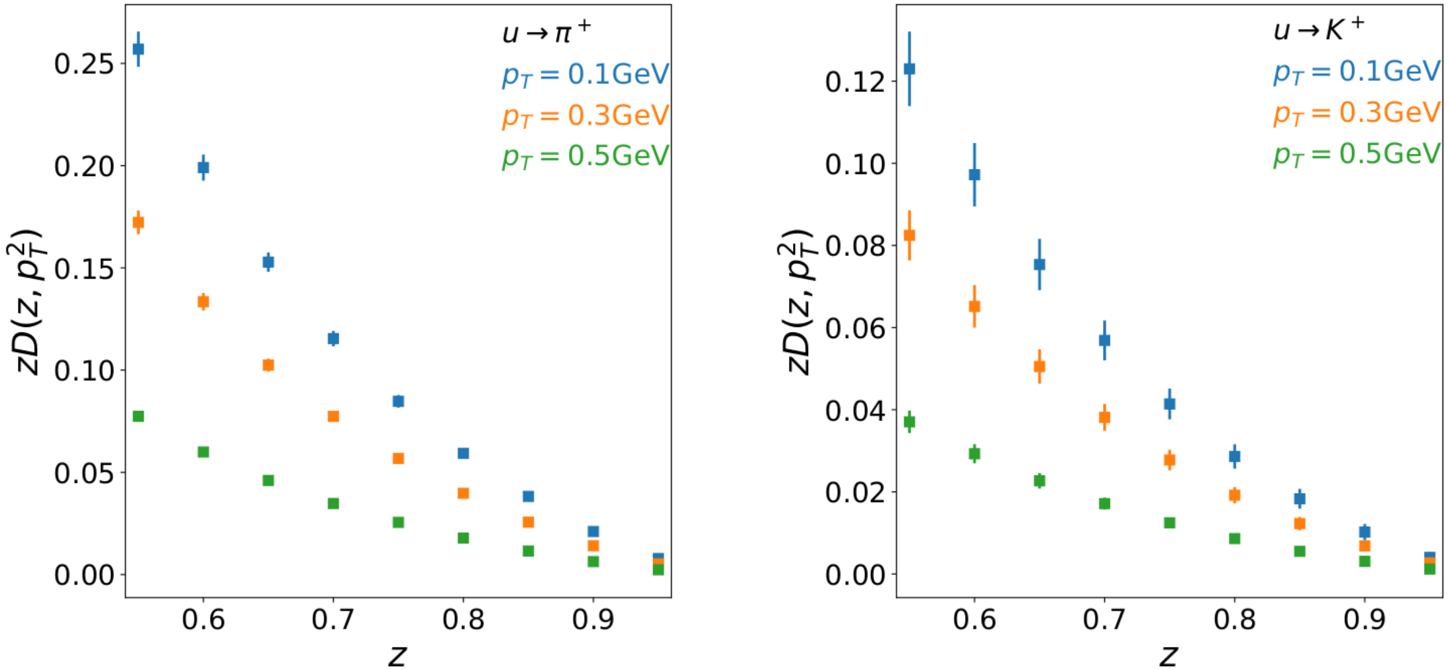
Conclusions – Pion and Kaon Structure

- 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**.

Quark Fragmentation into Pions and Kaons

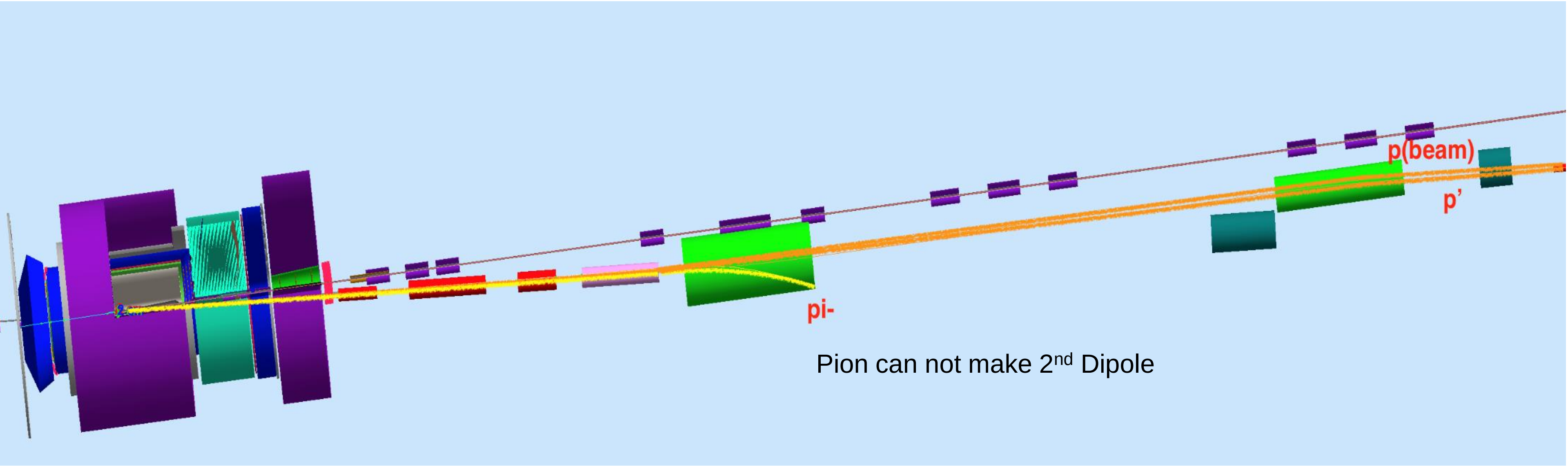
- ❑ Timelike analog of mass acquisition – measure fragmentation of quarks into pions and kaons

- ❑ Projections for integrated luminosity = 10 fb^{-1}



- ❑ EIC can provide precision data at large x (z>0.5) and transverse momentum (as picked up on the fragmentation process) of k_T=0.1, 0.3, 0.5

Detection of $^{1}H(e,e'K^{+})\Lambda$, Λ decay to $p + \pi^{-}$



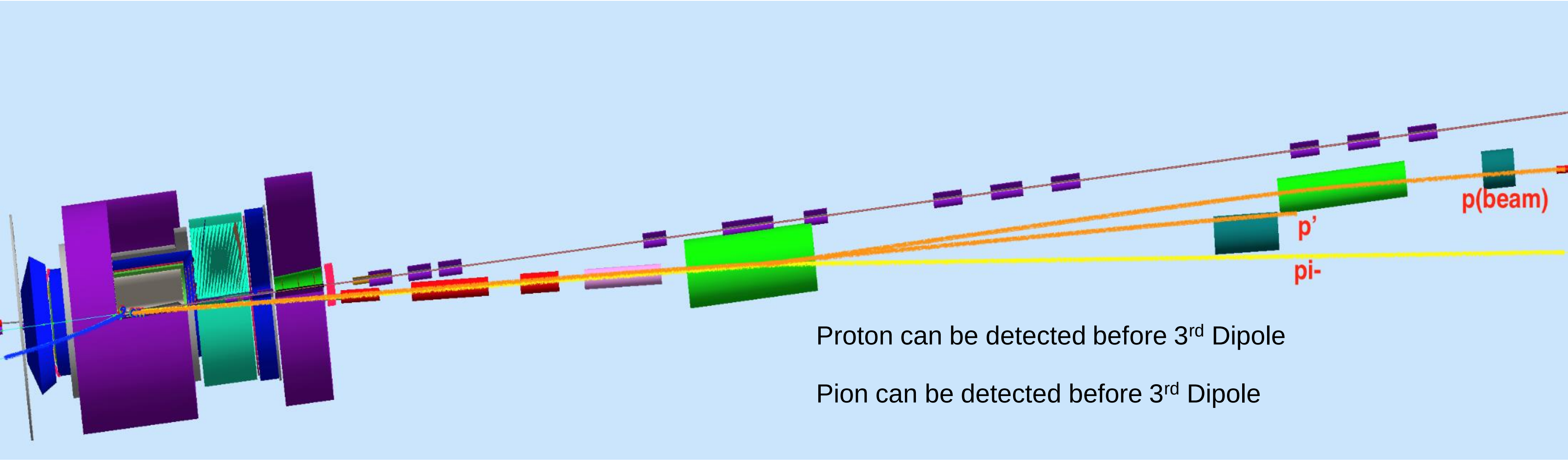
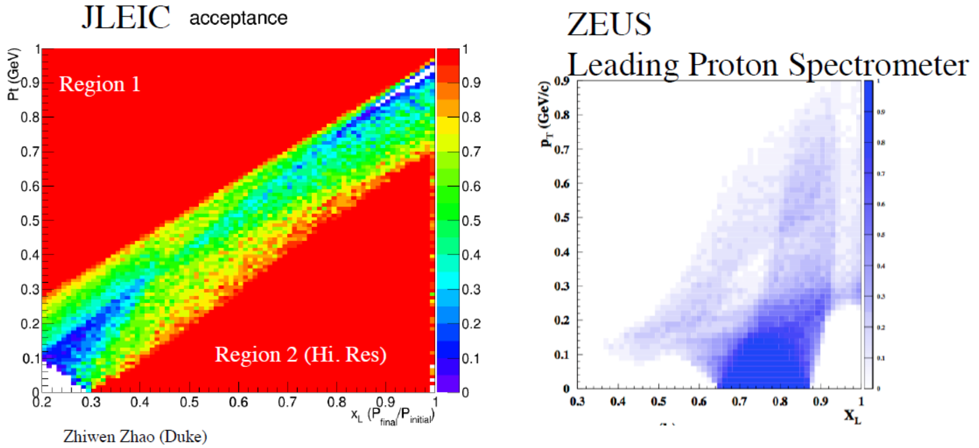


Figure from K.Park

Experimental Considerations

Need excellent detection capabilities, and good resolution in –t

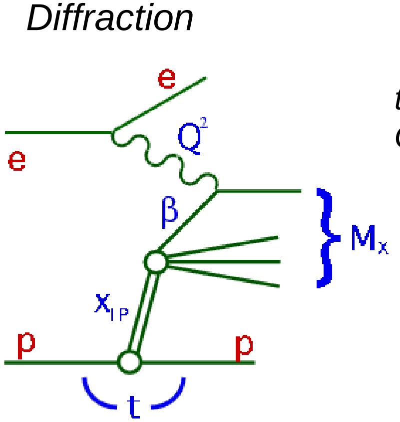


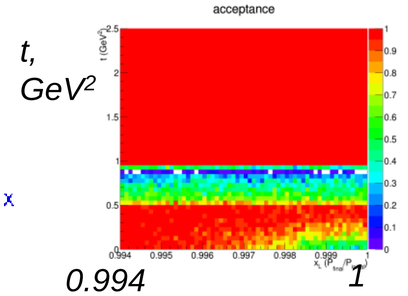
Acceptance in diffractive peak (X_L>~.98)

ZEUS: ~2%

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

EIC provides huge gain in acceptance for diffractive physics and forward tagging to measure F_2^n!!!





- ❑ Reconstruction of energy and position to sufficiently constrain the scattering kinematics and 4-momentum of the pion
- ❑ FFQ and ZDC: $\delta p_L/p_L$~10^{-4}, δp_T~20 MeV, complete coverage to p_T=0

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%

Geometric acceptance for decay products