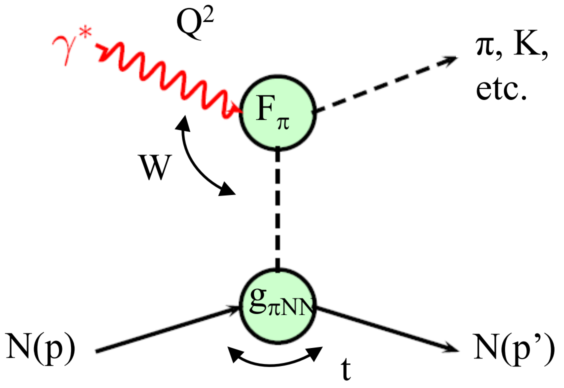
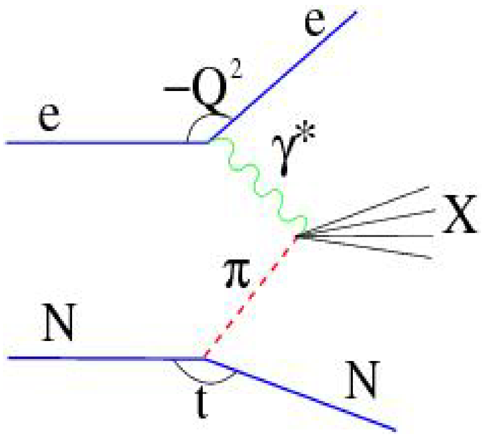
Pion and Kaon Structure





Tanja Horn

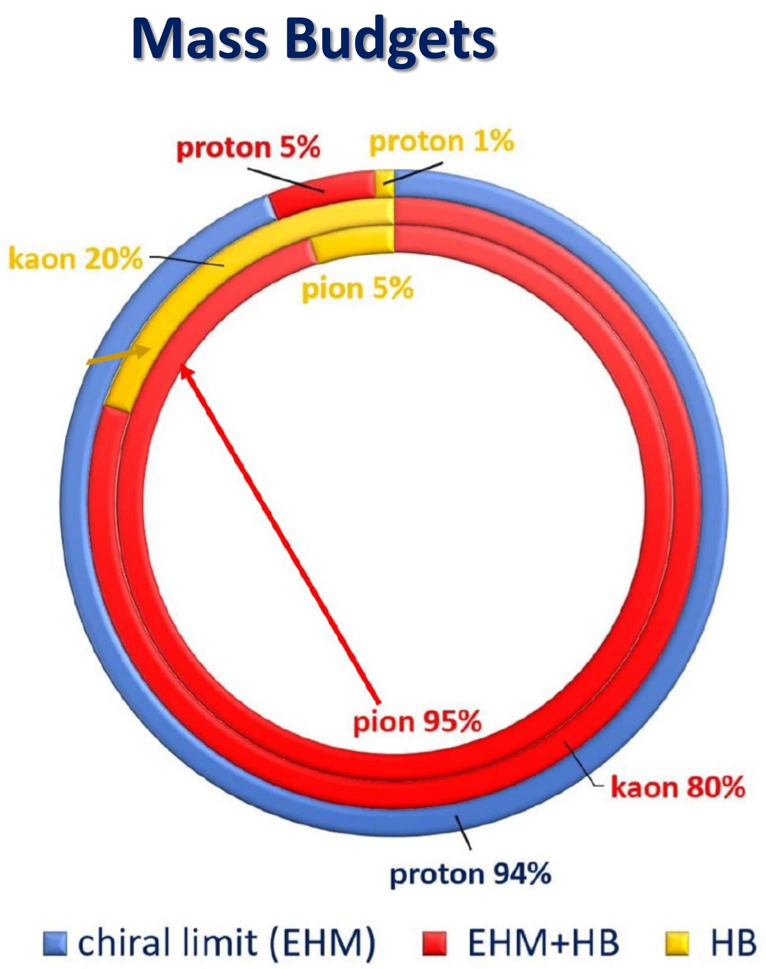
THE CATHOLIC UNIVERSITY OF AMERICA

Jefferson Lab
Thomas Jefferson National Accelerator Facility

Seville, Spain
7-11 November 2022

BARYONS2022 – International Conference on the Structure of Baryons

Insights into hadron structure and mass through pions/kaons

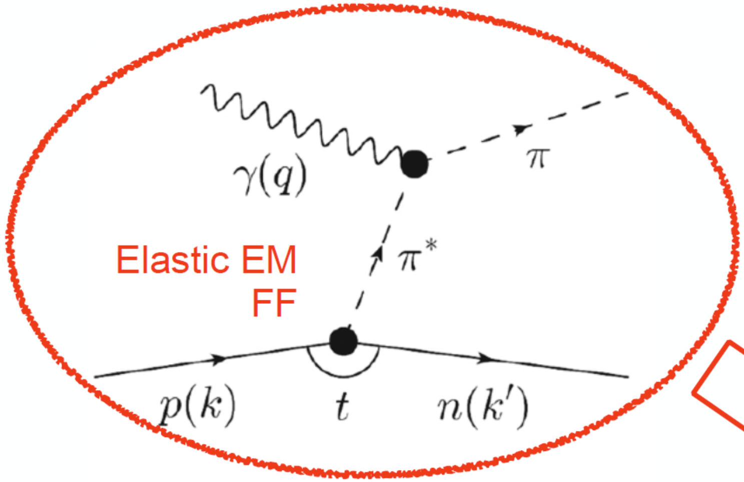


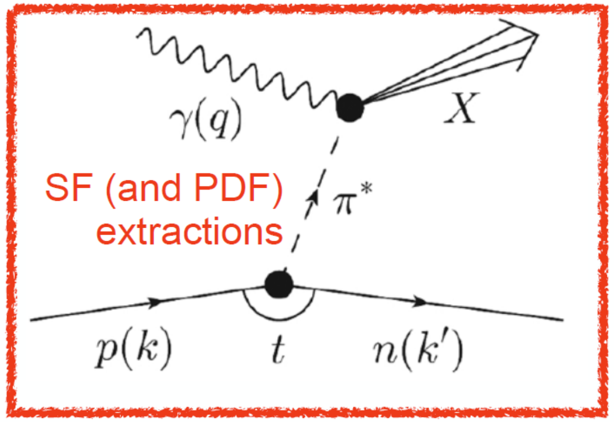
- Properties of hadrons are emergent phenomena
- Experimental insight is crucial to complete the understanding of how hadrons and nuclei emerge from quarks and gluons
- Studies of π/K structure can validate and shed light on the interplay between Emergent Hadronic Mass (EHM) and the Higgs mechanism

Accessing Pion/Kaon Structure Information

Sullivan

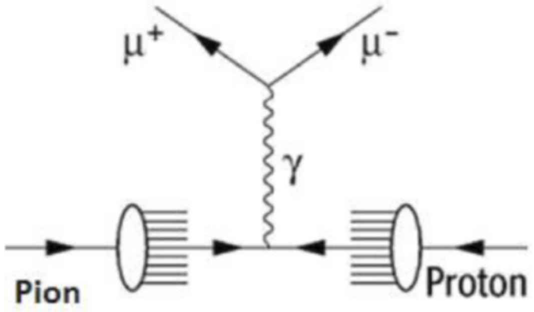
Hard scattering from virtual meson cloud of nucleon





Drell-Yan

Quark of pion (e.g.) annihilates with anti-quark of proton (e.g.), virtual photon decays into lepton pair



- ❑ **Pion/Kaon elastic EM Form Factor**
  - Informs how emergent mass manifests in the wave function
- ❑ **Pion/Kaon Structure Functions**
  - Informs about the quark-gluon momentum fractions

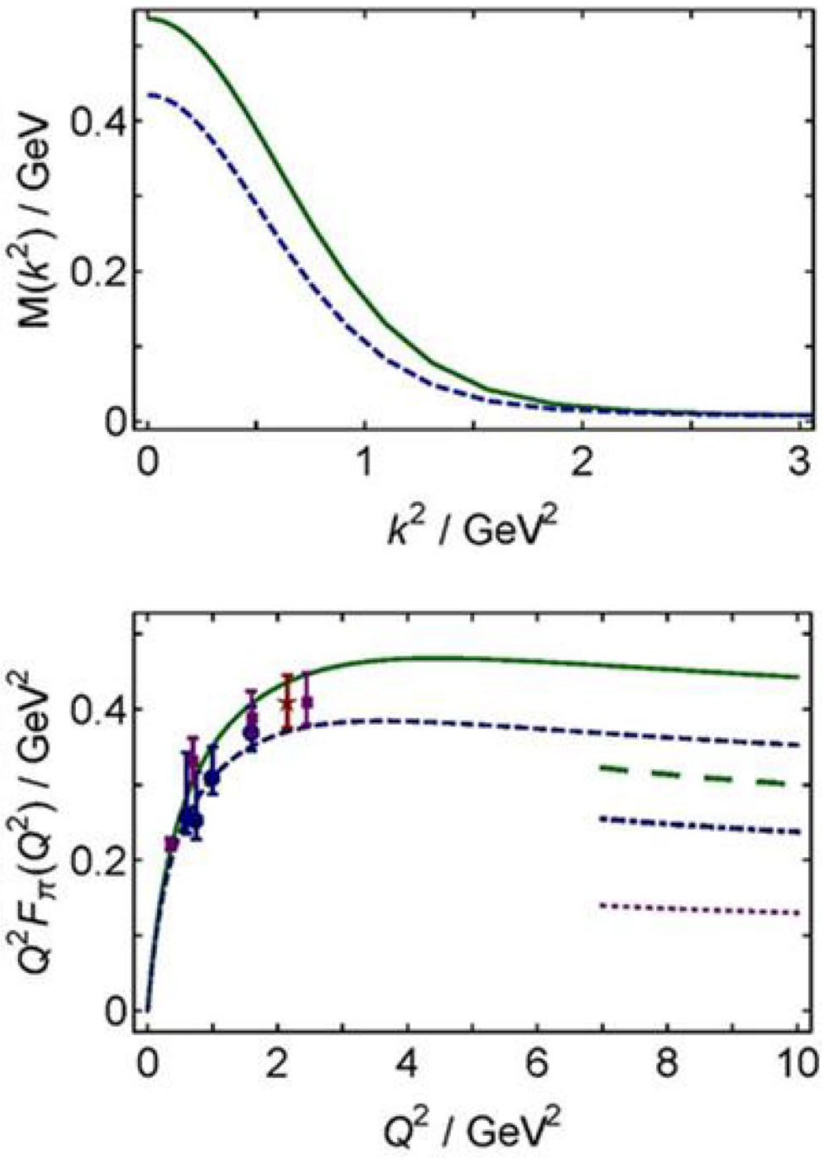
Meson Form Factors

A.C. Aguilar et al., Eur. Phys. J. A **55** (**2019**) 10, 190

J. Arrington et al., Phys. G **48** (**2021**) 7, 075106

C.D. Roberts et al., Prog.Part.Nucl.Phys. **120** (**2021**) 103883

T. Horn, C.D. Roberts, J.Phys.G **43** (**2016**) 7, 073001

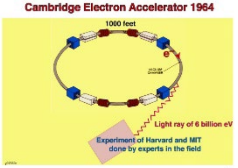


- ***Pion and kaon form factors*** are key observables. They describe the spatial distribution of partons within a hadron
- Pion and kaon form factors are of special interest in hadron structure studies
  - ***Pion***: lightest QCD quarks system, vital in understanding dynamic mass generation
  - ***Kaon***: next simplest system, containing strangeness
- Clearest case for studying the transition from non-perturbative to perturbative regime
- Much progress over the last decade, but need to further push the frontier to higher Q^2

Meson Production Data Evolution

Experiment

Capability to reliably access large Q^2 regime



DESY

Jefferson Lab

JLab 6 GeV

JLab 12 GeV

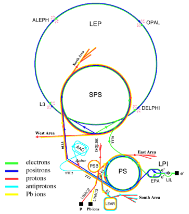
EIC

1959 1971 1976 1979 1981 1984 1986 1997 2003 2004 2017+ 2030+

JLab 20+ GeV?

Cornell University

Fermilab



Theory

- Accessing the form factor through electroproduction
- Extraction of meson form factor from data
- Electroproduction formalism

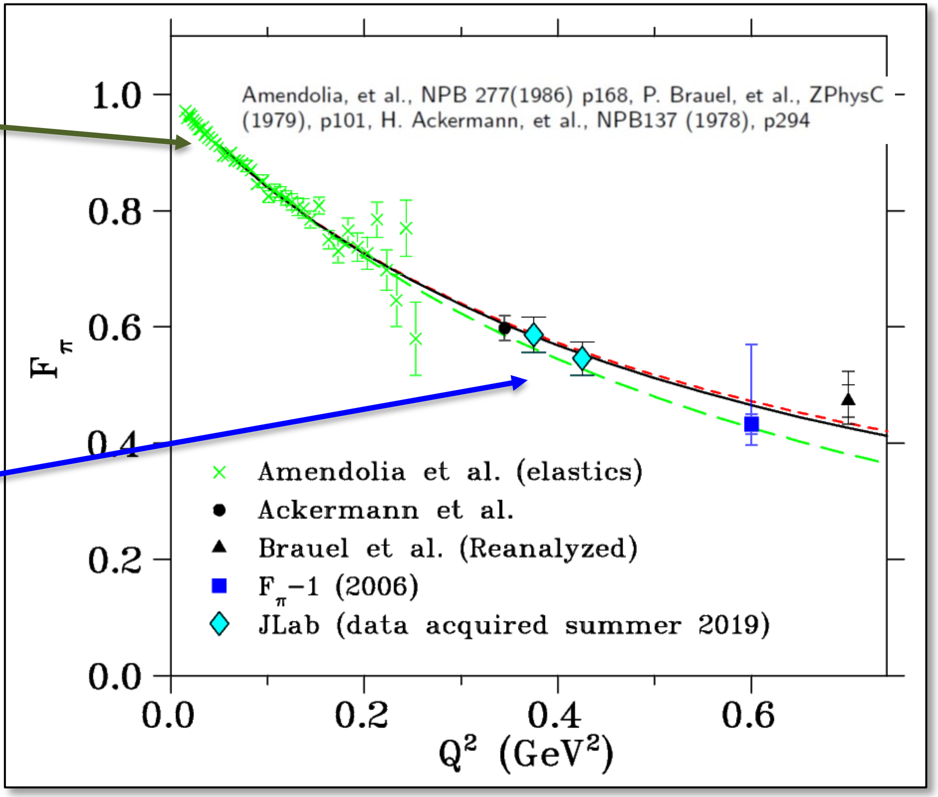
Theory/Lattice/Global Fitting

Major progress on hadron structure calculations (also lattice and global fitting), e.g. large Q^2 behavior of meson form factor

Experimental Determination of the π^+ Form Factor

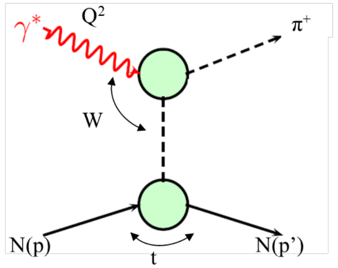
Through π-e elastic scattering

- At low Q^2, $F_{\pi+}$ can be measured directly via high energy elastic π^+ scattering from atomic electrons
  - CERN SPS used 300 GeV pions to measure form factor up to $Q^2 = 0.25$ GeV^2 *Amendolia et al, NPB277,168 (1986)*
  - These data used to constrain the pion charge radius: $r_\pi = 0.657 \pm 0.012$ fm



Through pion electroproduction

- At larger Q^2, $F_{\pi+}$ must be measured indirectly using the "pion cloud" of the proton via the *p(e,e'π^+)n process*
  - At small $-t$, the pion pole process dominates the longitudinal cross section, σ_L
  - In the Born term model, F_π^2 appears as



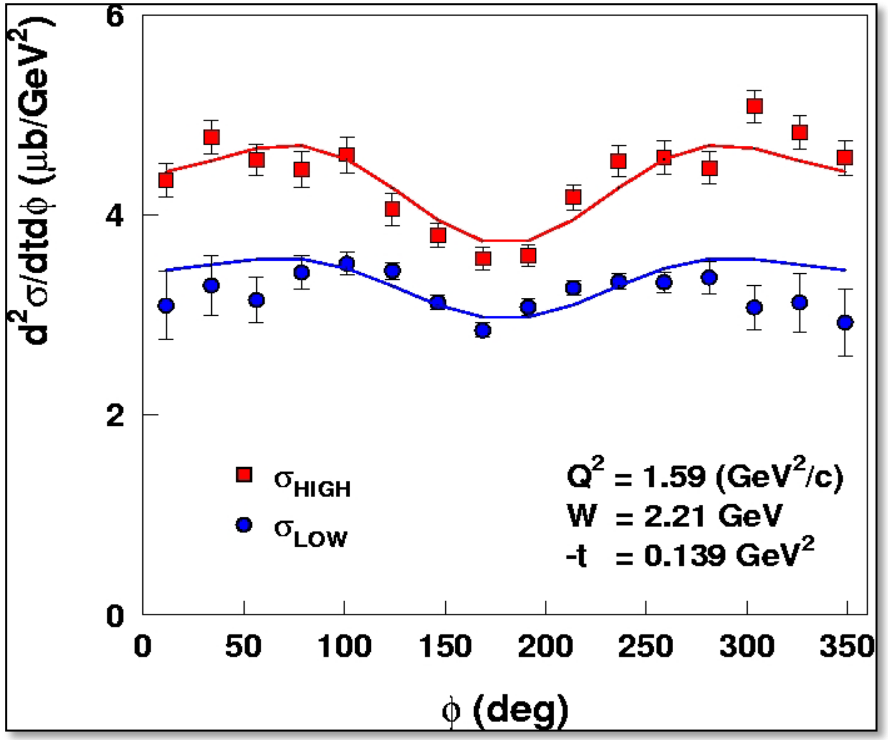
$$\frac{d\sigma_L}{dt} \propto \frac{-t}{(t-m_\pi^2)} g_{\pi NN}^2(t) Q^2 F_\pi^2(Q^2,t)$$

[In practice one uses a more sophisticated model]

Requirements:
- Full L/T separation of the cross section – isolation of σ_L
- Selection of the pion pole process
- Extraction of the form factor using a model
- Validation of the technique - model dependent checks

L/T Separation Example

*T. Horn et al., PRL **97**, (2006) 192001*



- σ_L is isolated using the Rosenbluth separation technique
  - Measure the cross section at two beam energies and fixed W, Q^2, -t
  - Simultaneous fit using the measured azimuthal angle (ϕ_π) allows for extracting L, T, LT, and TT
- Careful evaluation of the systematic uncertainties is important due to the $1/\varepsilon$ amplification in the σ_L extraction
  - Spectrometer acceptance, kinematics, and efficiencies

$$2\pi \frac{d^2\sigma}{dt\,d\phi} = \varepsilon \frac{d\sigma_L}{dt} + \frac{d\sigma_T}{dt} + \sqrt{2\varepsilon(\varepsilon+1)}\,\frac{d\sigma_{LT}}{dt}\cos\phi + \varepsilon \frac{d\sigma_{TT}}{dt}\cos 2\phi$$

σ_L will give us F_π

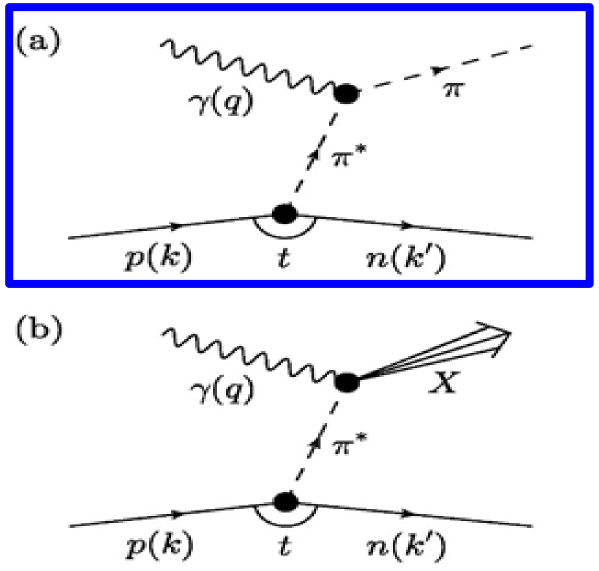
Magnetic spectrometers a must for such precision cross section measurements

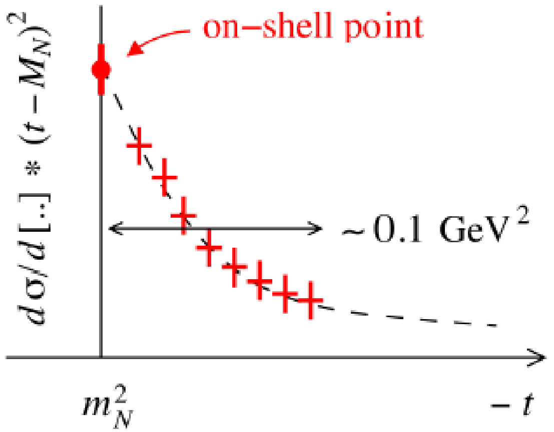
- This is only possible in Hall C at JLab

Accessing meson structure through the 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 is the dominant feature of the process and the structure of the (off-shell) meson evolves slowly and smoothly with virtuality.

*S-X Qin, C. Chen, C. Mezrag, C.D. Roberts, Phys.Rev. C **97** (**2018**) 7, 015203*





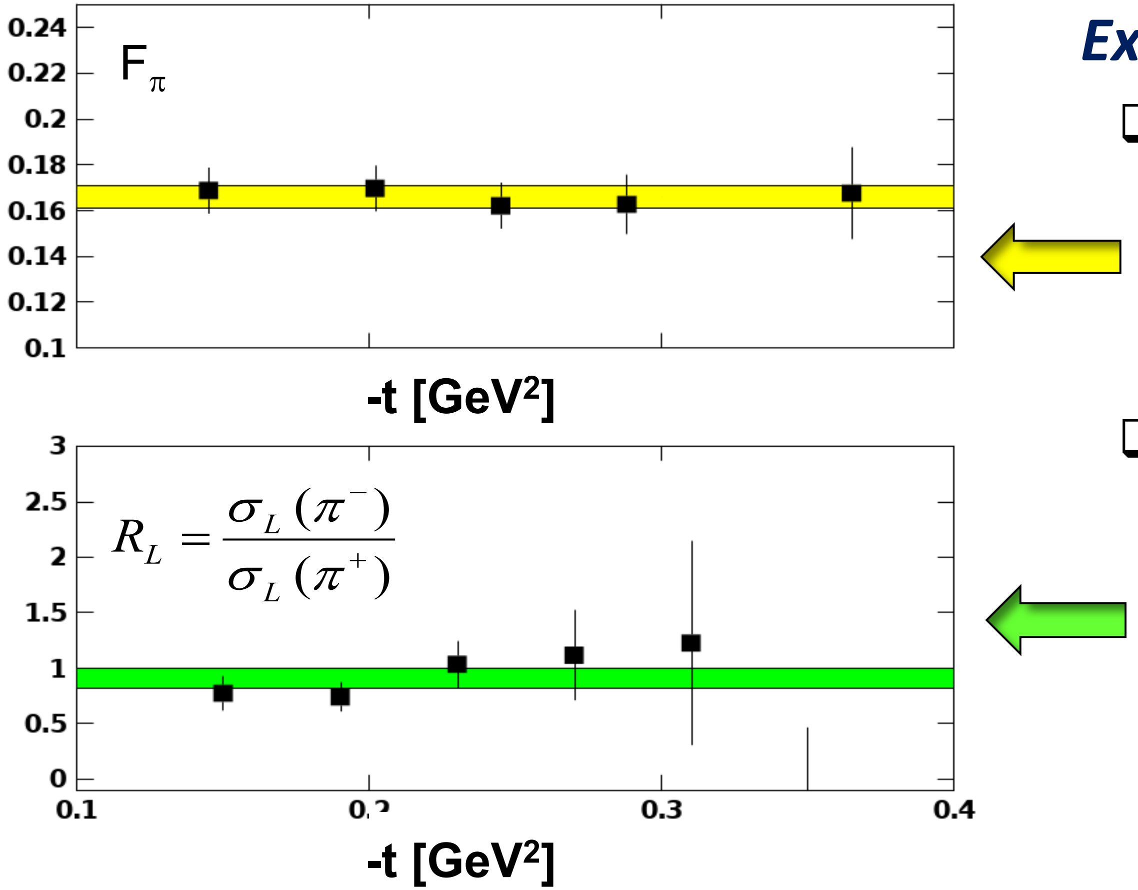
- To **check these conditions** are satisfied empirically, one can **take data covering a range in t** and compare with phenomenological and theoretical expectations.

- **Theoretical calculations found that for $-t \leq 0.6$ (0.9) GeV^2, changes in pion (kaon) structure do evolve slowly** so that a well-constrained experimental analysis should be reliable, and the Sullivan processes can provide a valid pion target.

- Also **progress with elastic form factors – experimental validation**

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

*T. Horn, C.D. Roberts, J.Phys.G **43** (**2016**) 7, 073001*

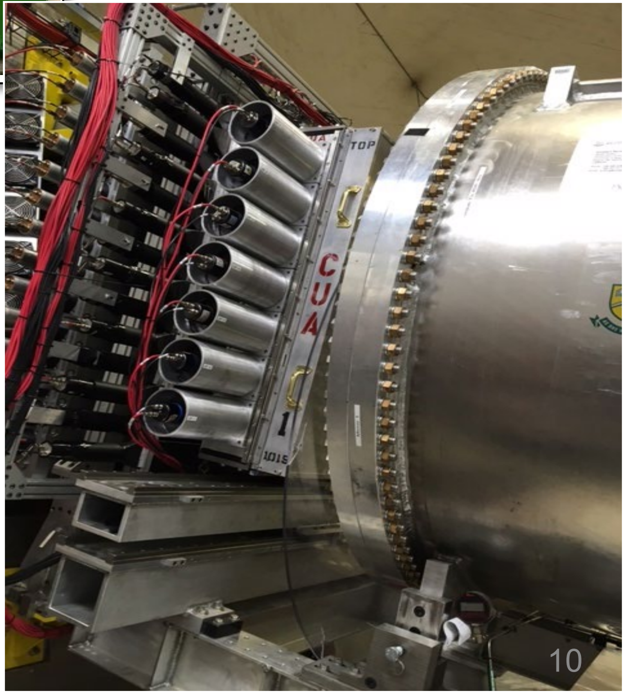
*G. Huber et al, PRL**112** (**2014**)182501*

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

Exclusive Meson Experiments in Hall C @ 12 GeV

Two experiments
- **PionLT** (E12-19-006)
- **KaonLT** (E12-09-011)

- CEBAF 10.9 GeV electron beam and SHMS small angle capability and controlled systematics are essential for precision measurements to higher Q^2
- New SHMS fulfills the meson experiments L/T separation requirements
- Dedicated key SHMS Particle Identification detectors for the experiments
  - Aerogel Cherenkov – funded by NSF MRI (CUA)
  - Heavy gas Cherenkov – partially funded by NSERC (U Regina)



T. Horn, H. Mkrtchyan, et al., Nucl.Instrum.Meth.A **842** (**2017**) 28-47

PionLT (E12-19-006) Program at 12 GeV Overview

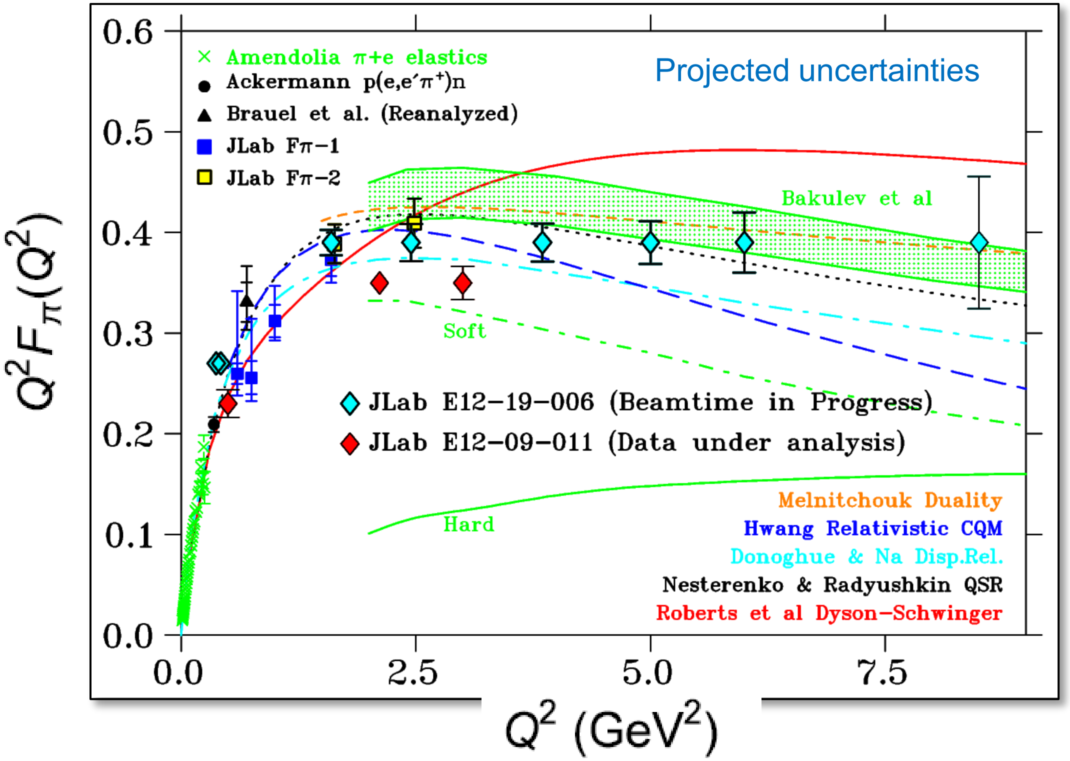
Spokespersons: Dave Gaskell (JLab), Tanja Horn (CUA), Garth Huber (URegina)

Grad. Students: J. Muhammed (URegina), J. Murphy (OU), A. Usman (URegina), R. Trotta (CUA)

Setting	Low ε data	High ε data
Q^2=0.375	✔	✔
Q^2=0.425	✔	✔
Q^2=1.45 W=2.02	✔	✔
Q^2=1.6 W=3.0	✔	✔
Q^2=2.12 W=2.05	✔	✔
Q^2=2.45 W=3.2	✔	✔
Q^2=2.73 W=2.63	✔	✔
Q^2=3.85 W=3.07	✔	✔
Q^2=5.0 W=2.95	✔	✔
Q^2=6.0 W=3.19	✔	✔
Q^2=8.5 W=2.79	✔	✔

PionLT experiment (completed 9 Sept 2022!) features:

- L/T separated cross sections at fixed x=0.3, 0.4, 0.55 up to Q^2=8.5 GeV^2
- Pion form factor at Q^2 values up to 8.5 GeV^2



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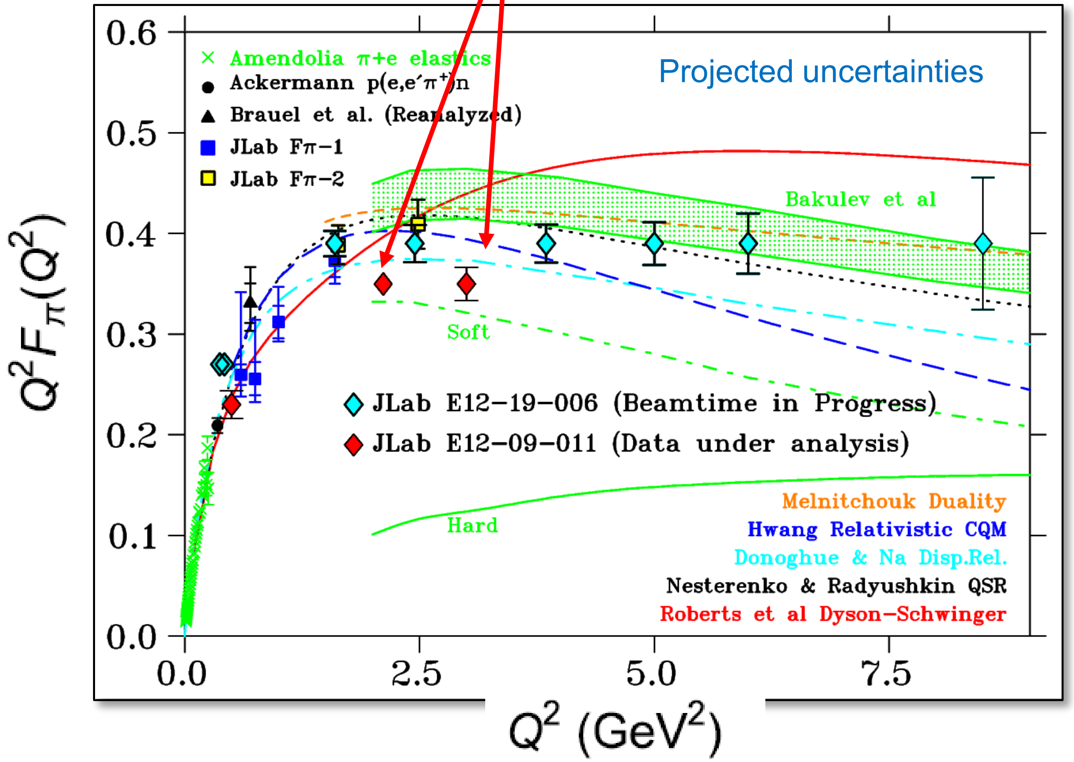
Q^2=0.425	✓	✓
Q^2=1.45 W=2.02	✓	✓
Q^2=1.6 W=3.0	✓	✓
Q^2=2.12 W=2.05	✓	✓
Q^2=2.45 W=3.2	✓	✓
Q^2=2.73 W=2.63	✓	✓
Q^2=3.85 W=3.07	✓	✓
Q^2=5.0 W=2.95	✓	✓
Q^2=6.0 W=3.19	✓	✓
Q^2=8.5 W=2.79	✓	✓

PionLT experiment (completed 9 Sept 2022!) features:

- L/T separated cross sections at fixed x=0.3, 0.4, 0.55 up to Q^2=8.5 GeV^2
- Pion form factor at Q^2 values up to 8.5 GeV^2
- Additional data from *KaonLT* experiment (E12-09-011, completed in 2018/19)



KaonLT (E12-09-011) Program at 12 GeV Overview

Spokespersons: Tanja Horn (CUA), Garth Huber (URegina), Pete Markowitz

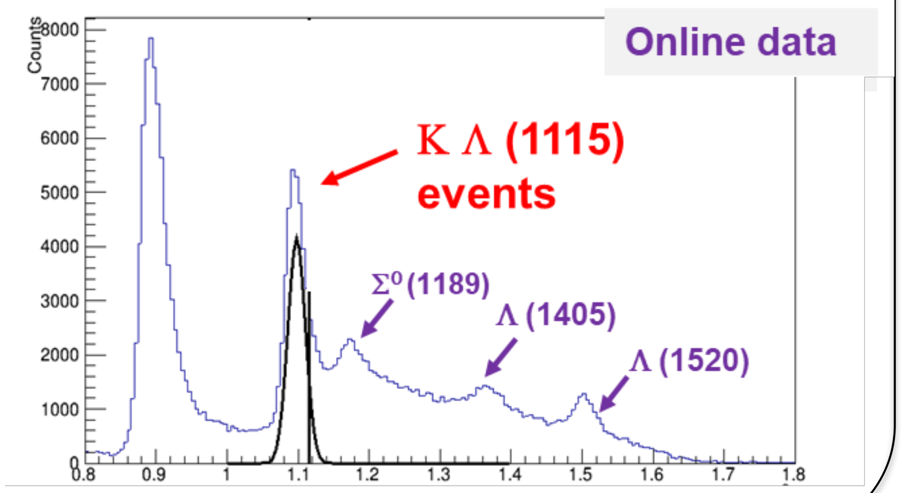
Grad. Students: Vijay Kumar (URegina), Richard Trotta (CUA), Ali Usman (URegina)

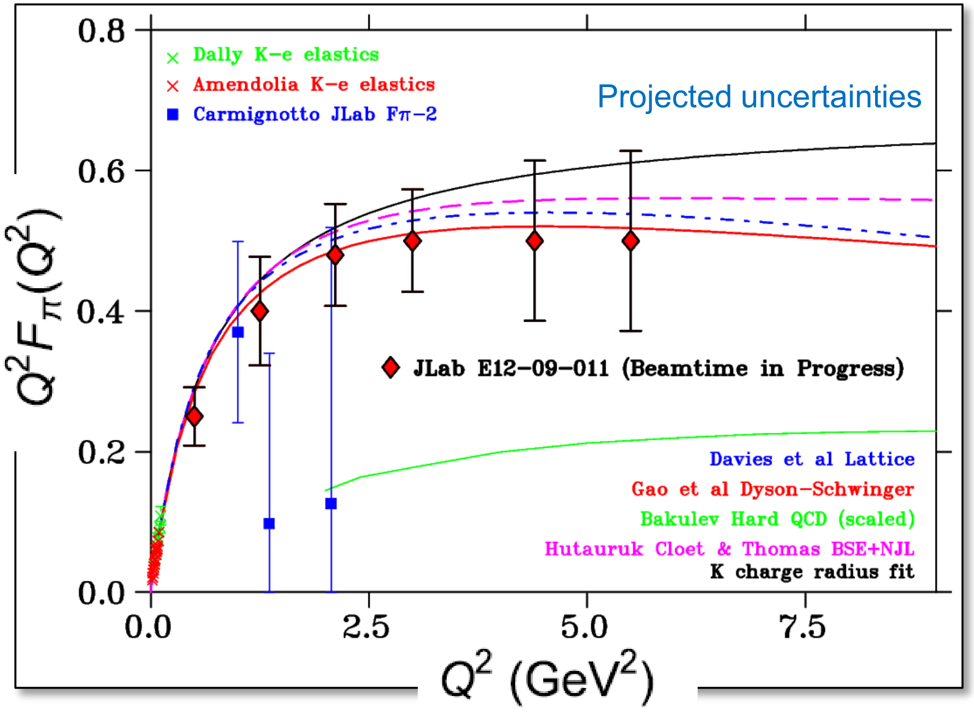
Separated cross sections: L, T, LT, TT over a wide range of Q^2,and t

KaonLT experiment (completed in 2018/19):

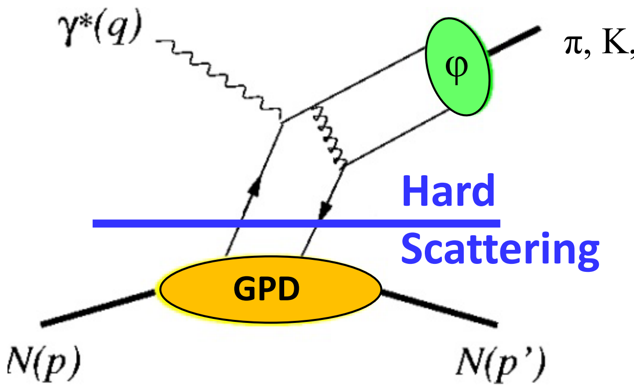
- First cross section data for Q^2 scaling tests with kaons
- Highest Q^2 for L/T separated kaon electroproduction cross section
- First separated kaon cross section measurement above W=2.2 GeV

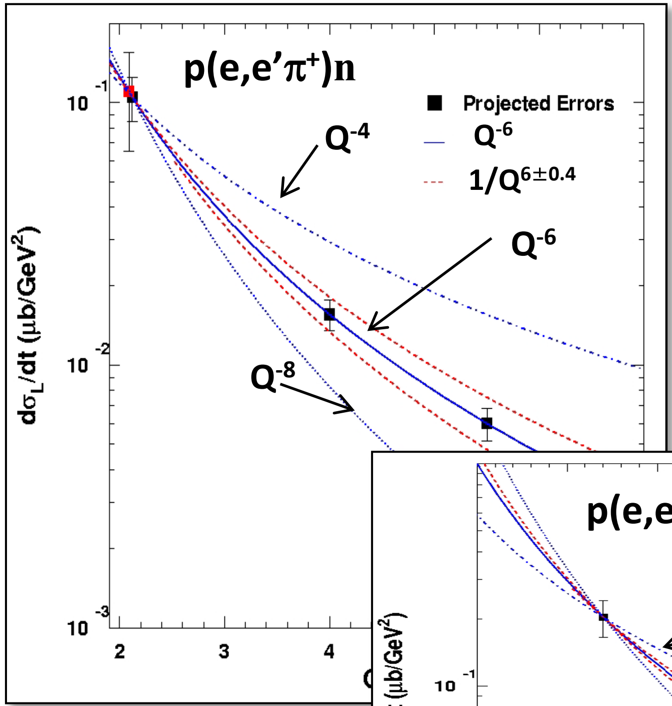
Additional Physics Channels/Topics





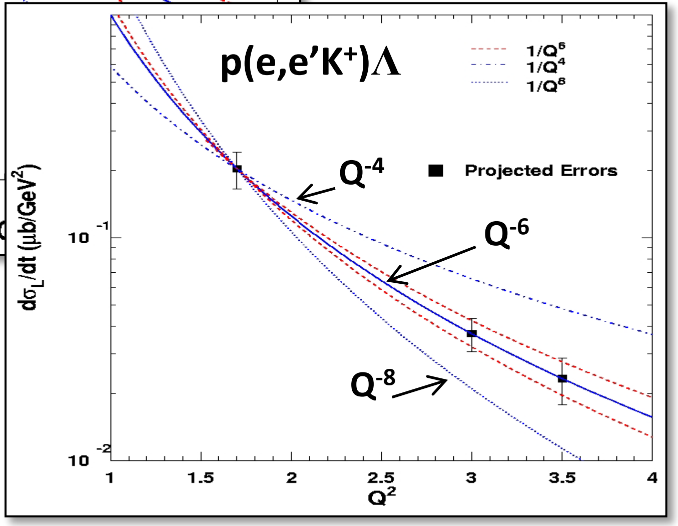
L/T Separated π^+/K^+ Cross Sections with 12 GeV JLab





π^+: to Q^2~9 GeV^2
K^+: to Q^2~6 GeV^2

Fit: $1/Q^n$



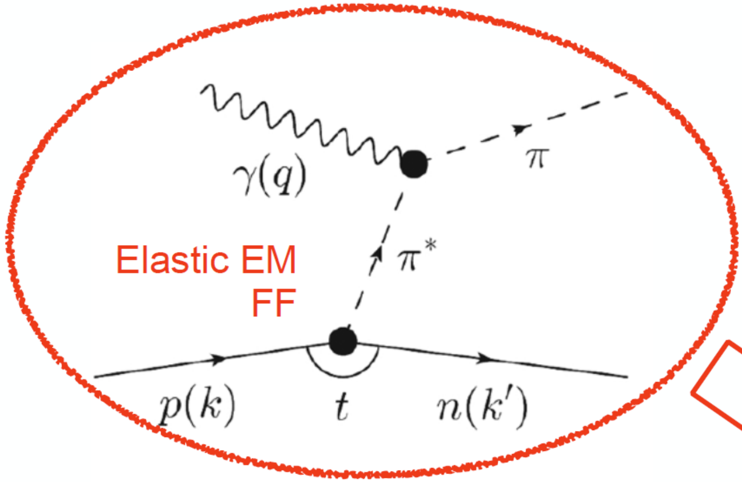
- One of the most stringent tests of the reaction mechanism is the Q^2 dependence of cross section
  - σ_L scales to leading order as Q^{-6}
  - σ_T does not
- Need to validate the reaction mechanism for reliable interpretation of the GPD program – key are precision longitudinal-transverse (L/T) separated data over a range of Q^2 at fixed x/t
  - **If σ_T is confirmed to be large, it could allow for detailed investigations of transversity GPDs. If, on the other hand, σ_L is measured to be large, this would allow for probing the usual GPDs**

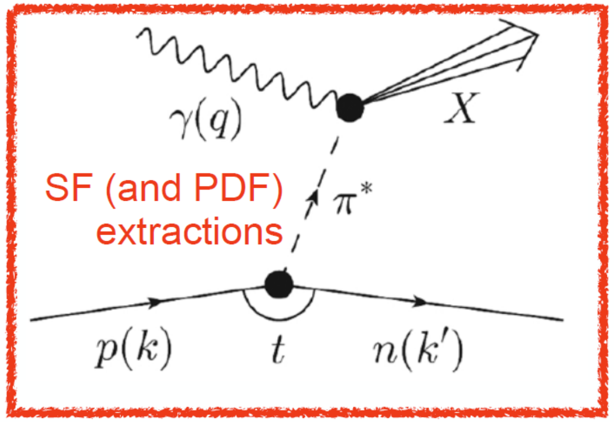
Q^{-n} scaling test range doubles with 18 GeV beam and HMS+SHMS

Accessing Pion/Kaon Structure Information

Sullivan

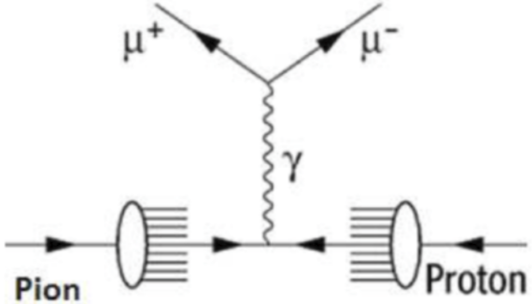
Hard scattering from virtual meson cloud of nucleon





Drell-Yan

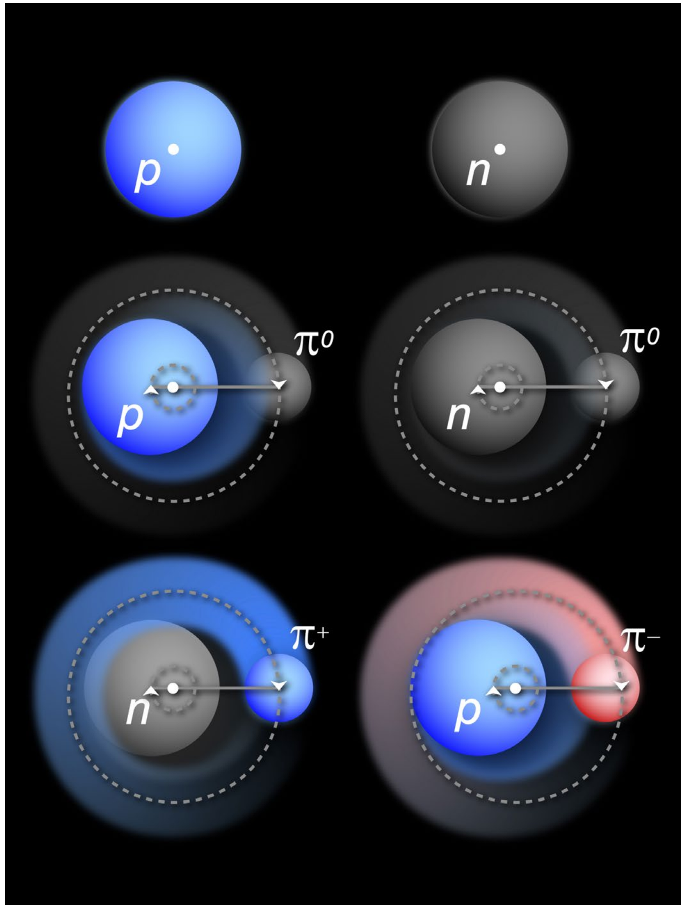
Quark of pion (e.g.) annihilates with anti-quark of proton (e.g.), virtual photon decays into lepton pair



- **Pion/Kaon elastic EM Form Factor**
  - Informs how emergent mass manifests in the wave function
- **Pion/Kaon Structure Functions**
  - Informs about the quark-gluon momentum fractions

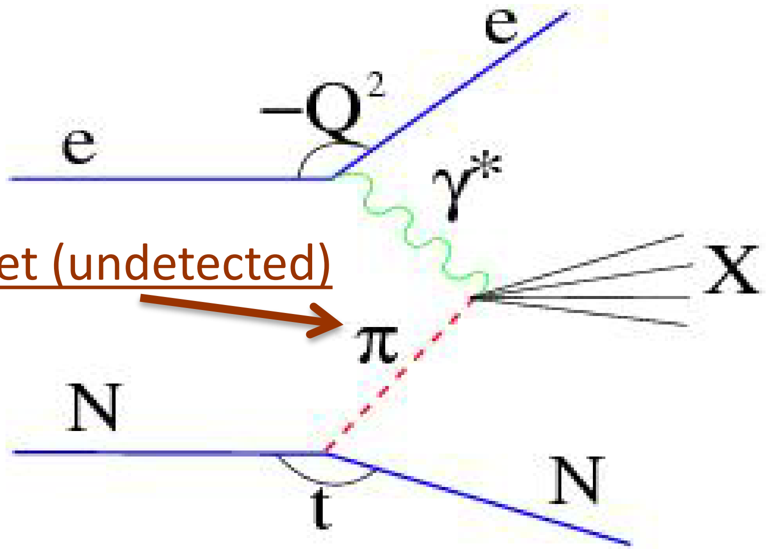
Tagged Deep Inelastic Scattering (TDIS)

Use Sullivan process – scattering from nucleon-meson fluctuations



Detect scattered electron

pion target (undetected)



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

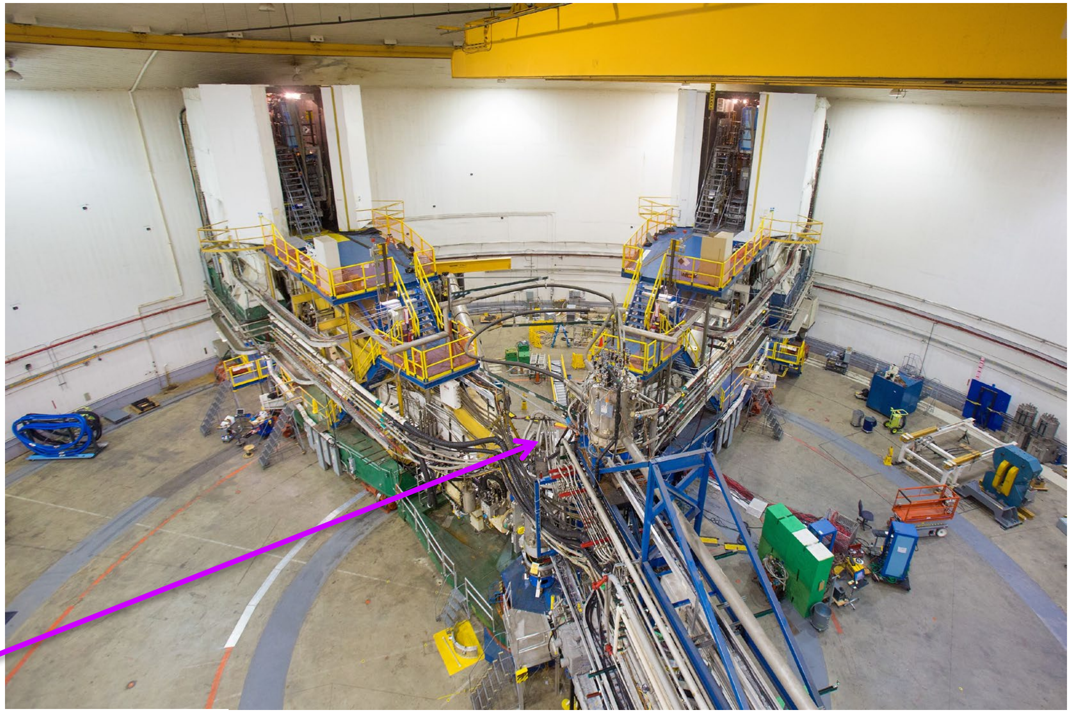
Detect "tagged" neutron/lambda

$$F_2^{LP(3)} = \sum_i \left[\int_{t_0}^{t_{min}} f_i(z,t)dt \right] F_2^i(x_i, Q^2)$$

"Flux factor"

i = π, ρ, …

JLab Hall A TDIS Experiment



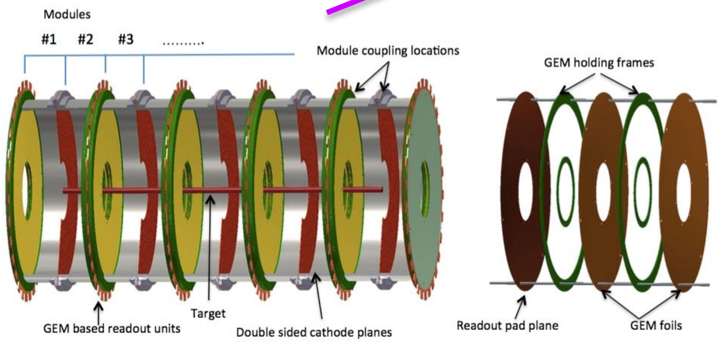
proton tag detection in GEM-based mTPC at pivot

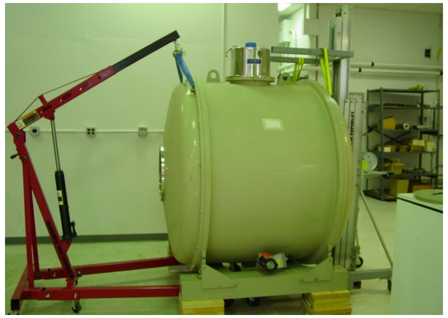
e- beam

Hall A with SBS:

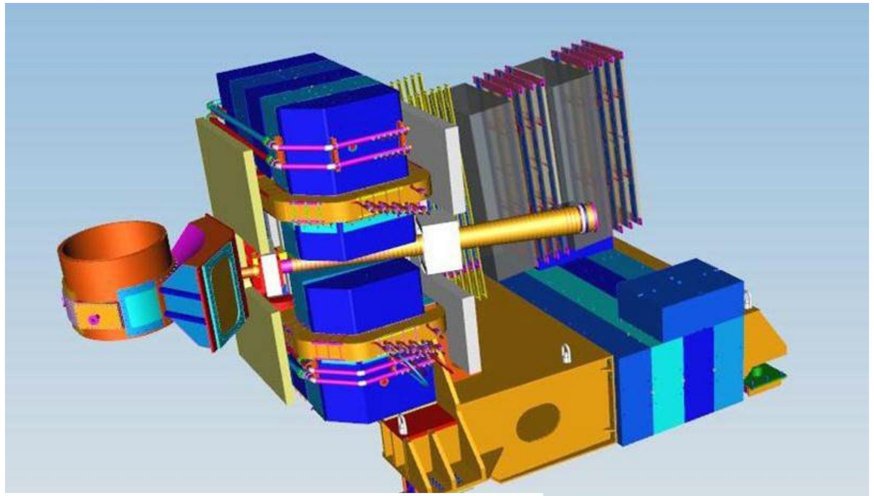
- ✓High luminosity,
  - 50 μAmp,
  - $\mathcal{L} = 3\text{x}10^{36}/\text{cm}^2\ \text{s}$
- ✓Large acceptance
  - ~70 msr

Important for small cross sections



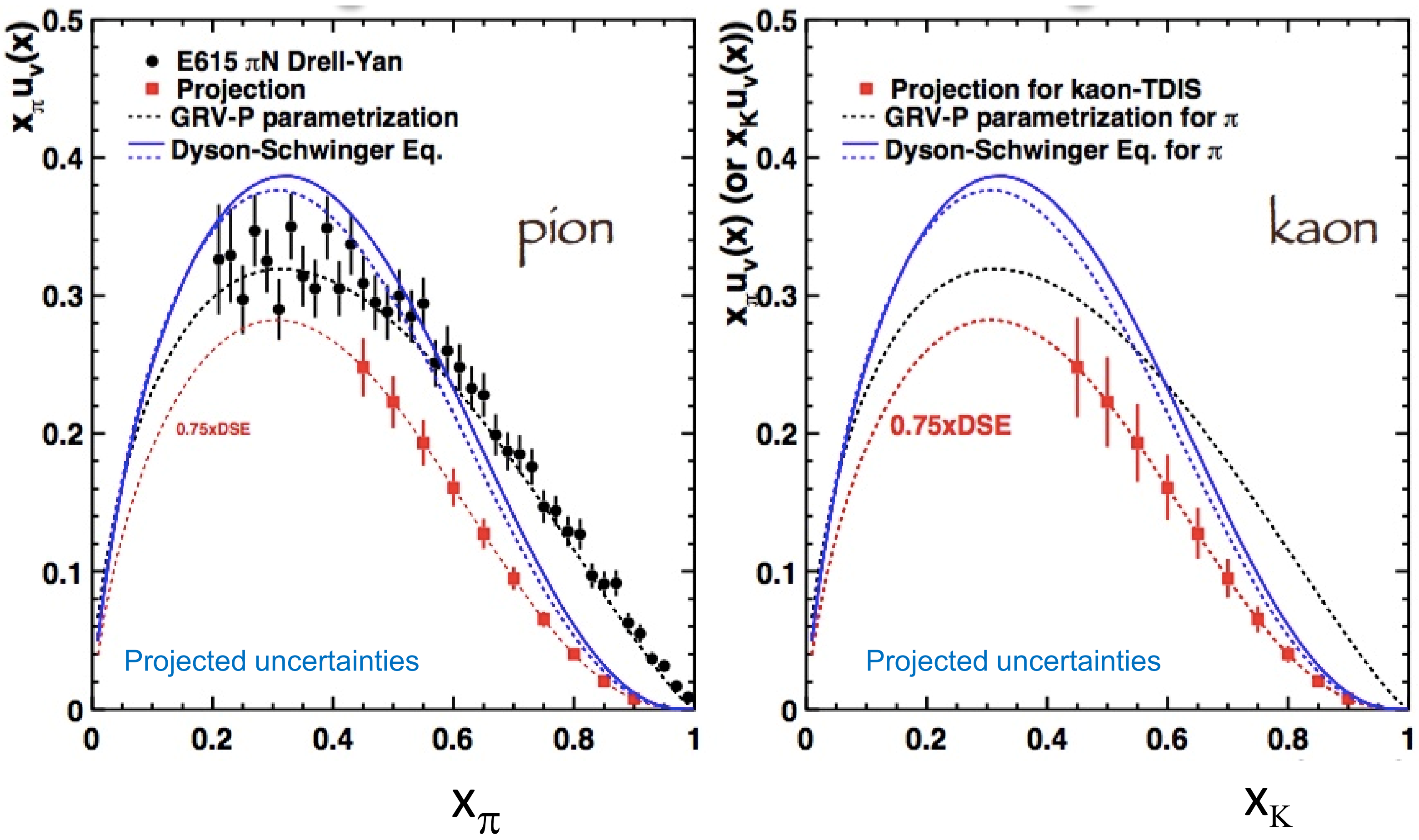


mTPC inside superconducting solenoid



Scattered electron detection in new Super Bigbite Spectrometer (SBS)

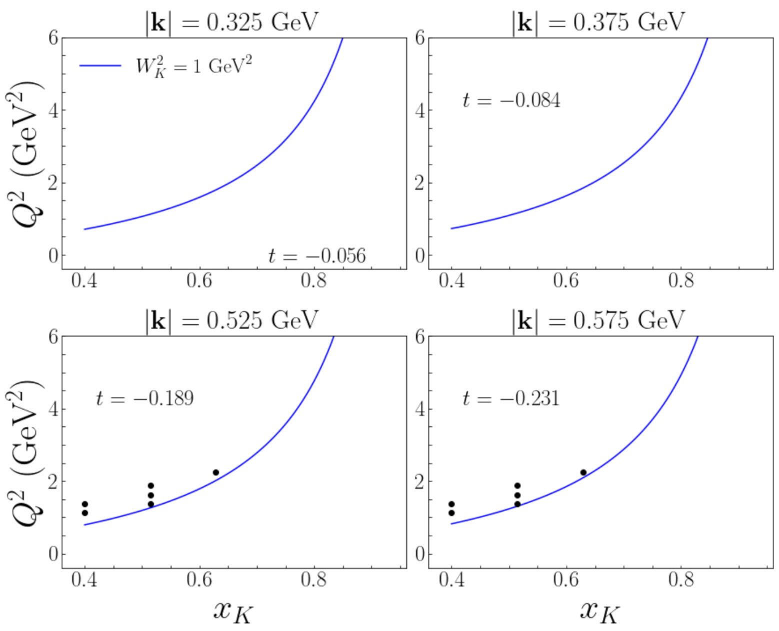
Projected JLab TDIS Results for π, K Structure Functions



- Projected valence quark distributions
- Projections based on phenomenological pion cloud model
  T.J. Hobbs, Few Body Syst. 56 (2015) no. 6-9;
  J.R. McKenney et al., Phys. Rev. D93 (2016), 05011

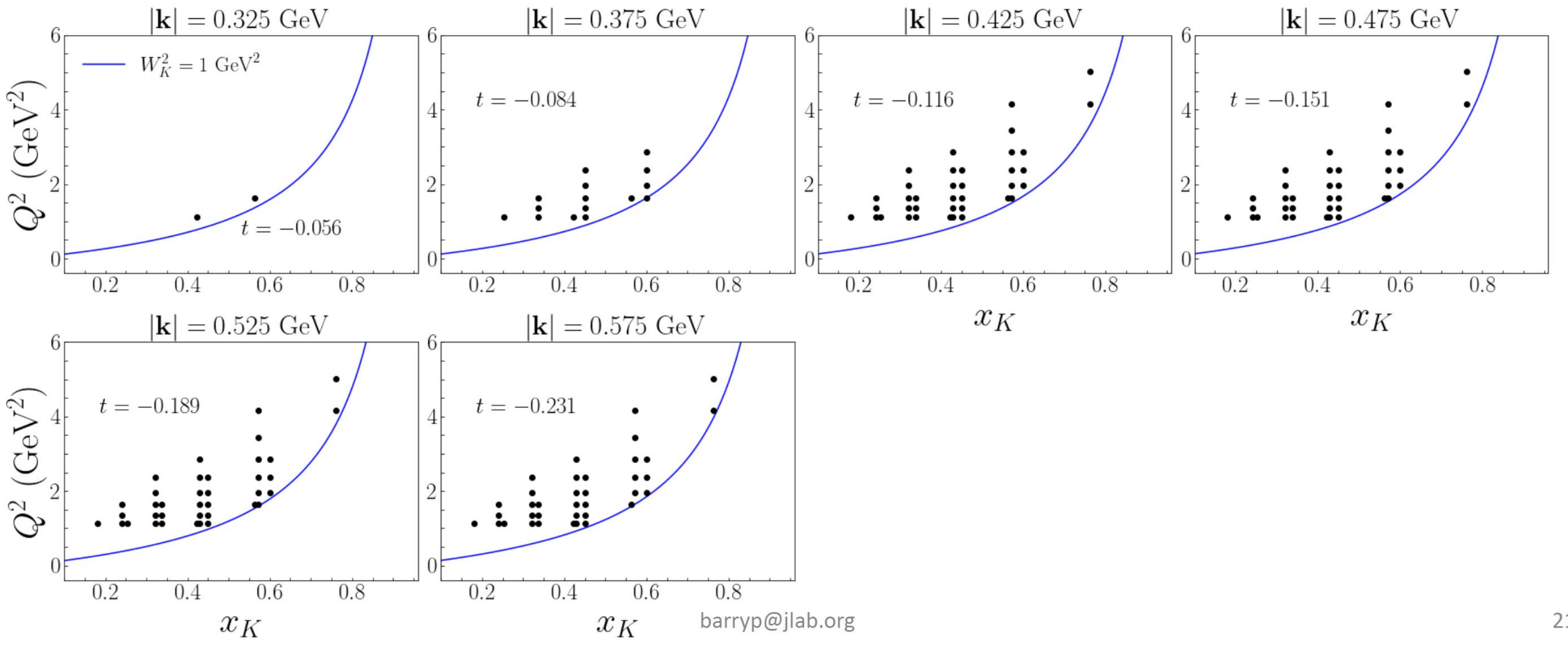
Essentially no data currently

Kinematics for 11 GeV Kaon TDIS



Kaon Structure Functions at JLab 12 GeV and higher energy

Kinematics for 22 GeV Kaon TDIS



Plots from P. Barry presentation at the Jefferson Lab High Energy Workshop Series (2022)

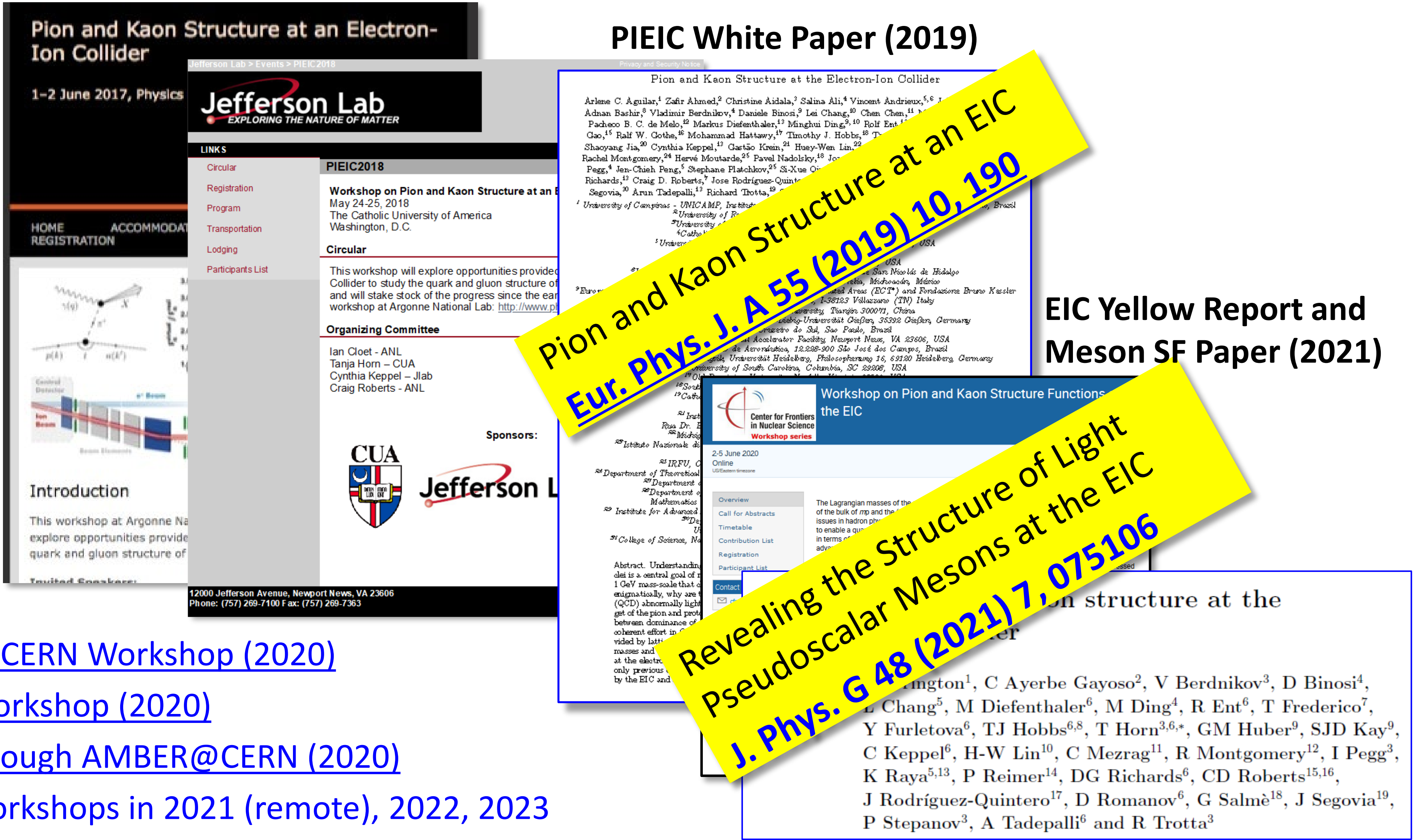
barryp@jlab.org

Pion and Kaon Structure at the EIC

- JLab 12 GeV measurements push the Q^2 reach of data considerably
- Still can't answer some of the key questions regarding the emergence of hadronic mass however
- Can we get quantitative guidance on the emergent pion mass mechanism?
  - Need F_{π} data for Q^2=10-40 GeV^2
- What is the size and range of interference between emergent mass and the Higgs-mass mechanism?
  - Need F_K data for Q^2=10-20 GeV^2
- Beyond what is possible at JLab in the 12 GeV era
  - Different machine → **The Electron-Ion Collider (EIC)**

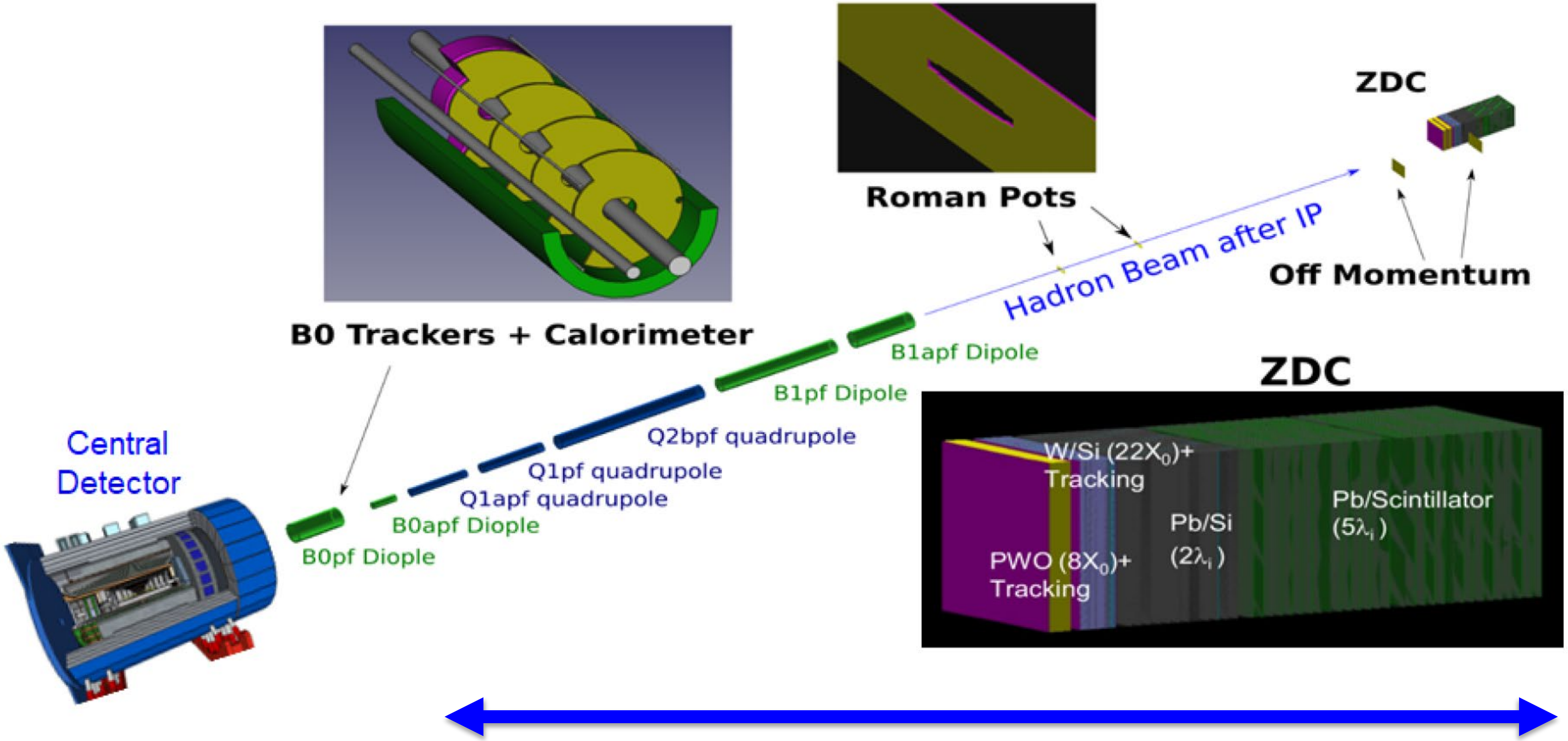
Pion and Kaon Structure at the EIC – History

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



- [AMBER/CERN Workshop (2020)]
- [CFNS Workshop (2020)]
- [EHM through AMBER@CERN (2020)]
- ECT* Workshops in 2021 (remote), 2022, 2023

EIC Detector Overview

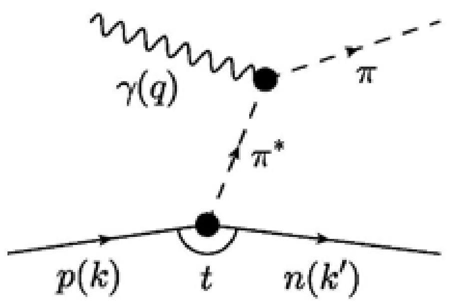


Far forward detectors critical for pion and kaon structure function studies at the EIC

Pion Form Factor Prospects @ EIC

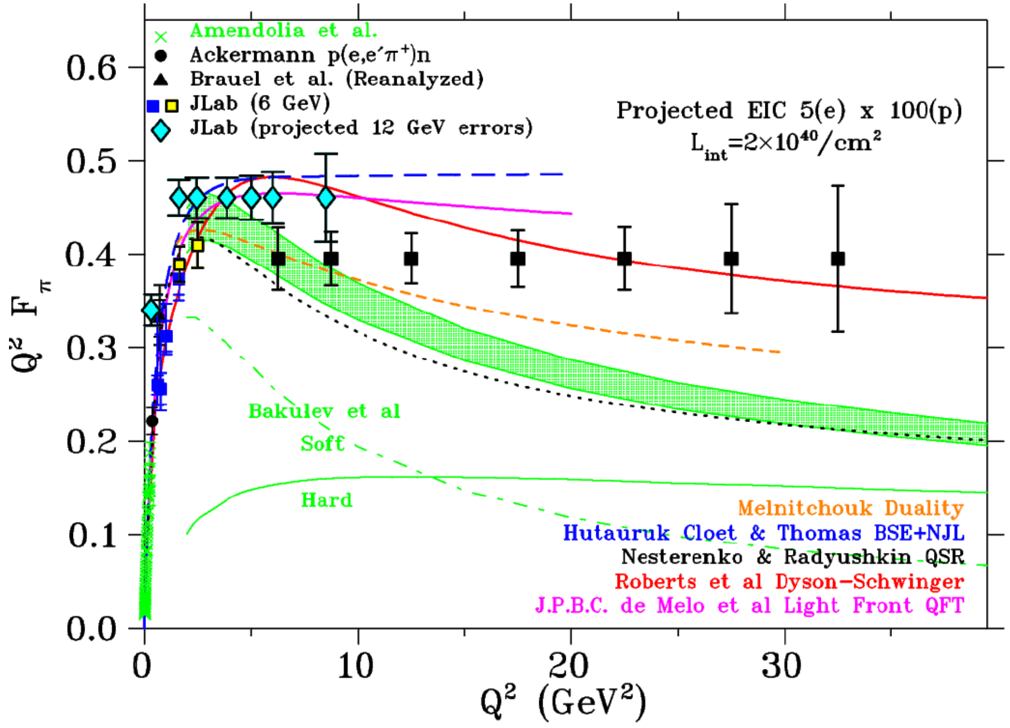
*J. Arrington et al., J.Phys.G **48** (**2021**) 7, 075106*

*A. Bylinkin et al., arXiv:2208.14575 (**2022**); submitted to NIMA*



σ_L isolation with a model at the EIC

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 2.5% pt-pt and 12% scale systematic uncertainty, and a 100% systematic uncertainty in the model subtraction to isolate σ_L

Results look promising – reach of pion form factor measurements into the Q^2~30 GeV^2 range. Need to test π^- too.

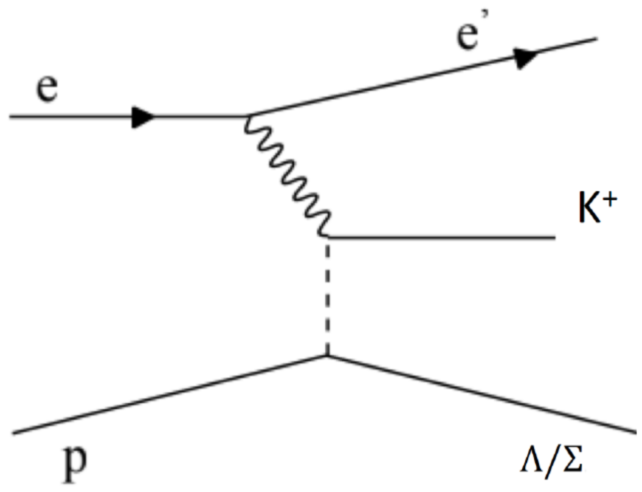
Kaon Form Factor Prospects @ EIC

- Kaon Form Factor Measurements via Deep Exclusive Meson Production is extremely challenging
- One would need to measure two reactions

$$p(e, e' K^+ \Lambda)$$
$$p(e, e' K^+ \Sigma)$$

  - need both for pole dominance tests

$$R = \frac{\sigma_L \left[p(e, e' K^+ \Sigma^0)\right]}{\sigma_L \left[p(e, e' K^+ \Lambda^0)\right]} \rightarrow R \approx \frac{g^2_{pK\Sigma}}{g^2_{pK\Lambda}}$$



- Considering the Lambda channel
  - Lambda plays a similar role to the neutron in p studies
  - Very forward focused, but the Lambda will decay
    - $\Lambda \rightarrow n\pi^0$ - ~ 36 %
    - $\Lambda \rightarrow p\pi^-$ - ~ 64 %

  Neutral channel potentially best option
    - **Very challenging 3 particle final state**

Ongoing work on development of a kaon reaction module and event generator in the EPIC simulation framework

Reduction of Pion 1-D Structure Information by EIC

J. Arrington et al., J.Phys.G ***48*** *(**2021**) 7, 075106*

R. Abdul Khalek et al., Nucl. Phys. A ***1026****, 122447 (**2022**)*

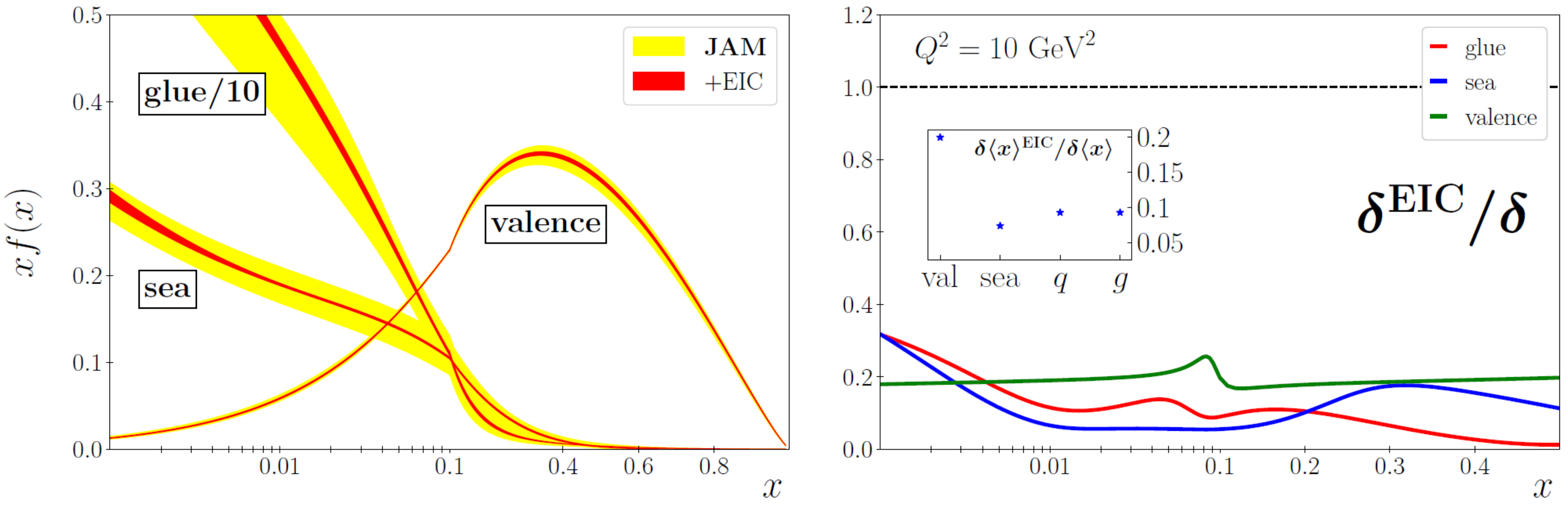


Figure 7: *Left panel.* Comparison of uncertainties on the pion's valence, sea quark and gluon PDFs before (yellow bands) and after (red bands) inclusion of EIC data. *Right panel.* Ratio of uncertainties with EIC data to without, $\delta^{\text{EIC}}/\delta$, for the valence (green line), sea quark (blue) and gluon (red) PDFs, assuming 1.2% experimental systematic uncertainty but no model systematic uncertainty, and (inset) the corresponding ratios of the momentum fraction uncertainties, $\delta\langle x\rangle^{\text{EIC}}/\delta\langle x\rangle$, for valence, sea, total quark and gluon PDFs [70], at a scale $Q^2 = 10$ GeV^2.

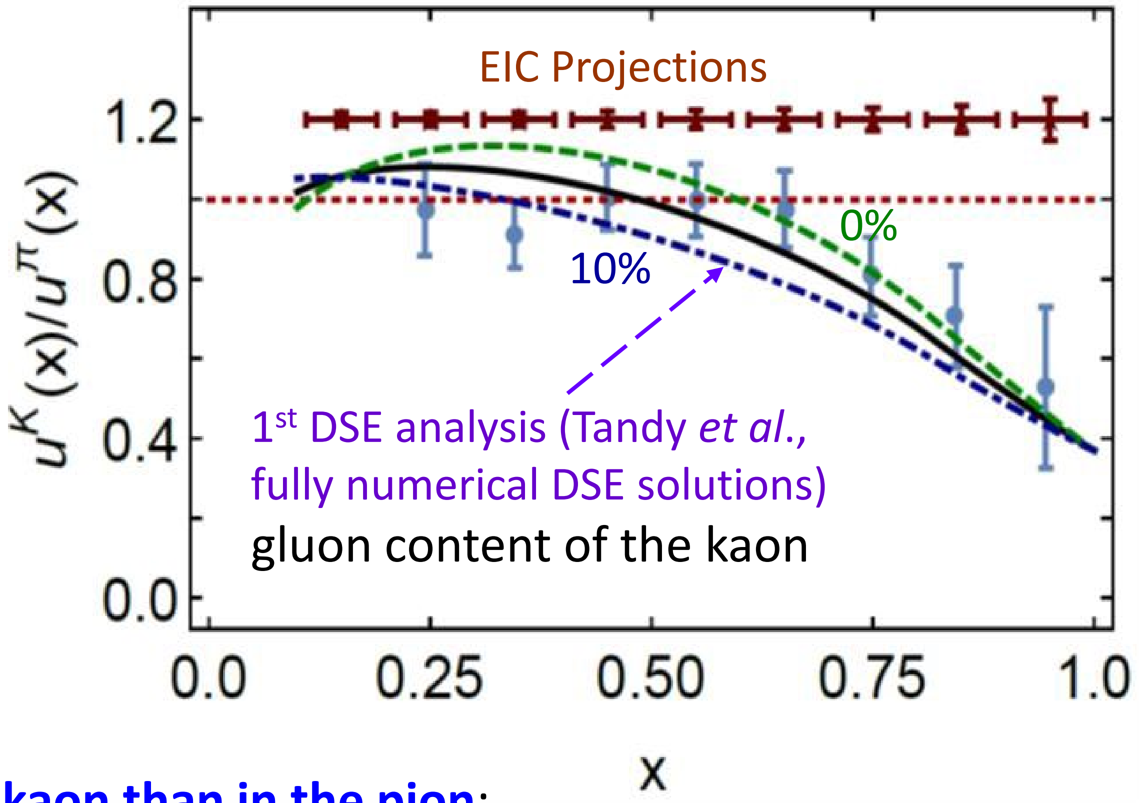
Error reduction factor of 5-10 in x-range >0.001

Kaon structure functions – gluon pdfs

*A.C. Aguilar et al., Eur.Phys.J.A **55** (**2019**) 10, 190*

Based on Lattice QCD calculations and DSE calculations:

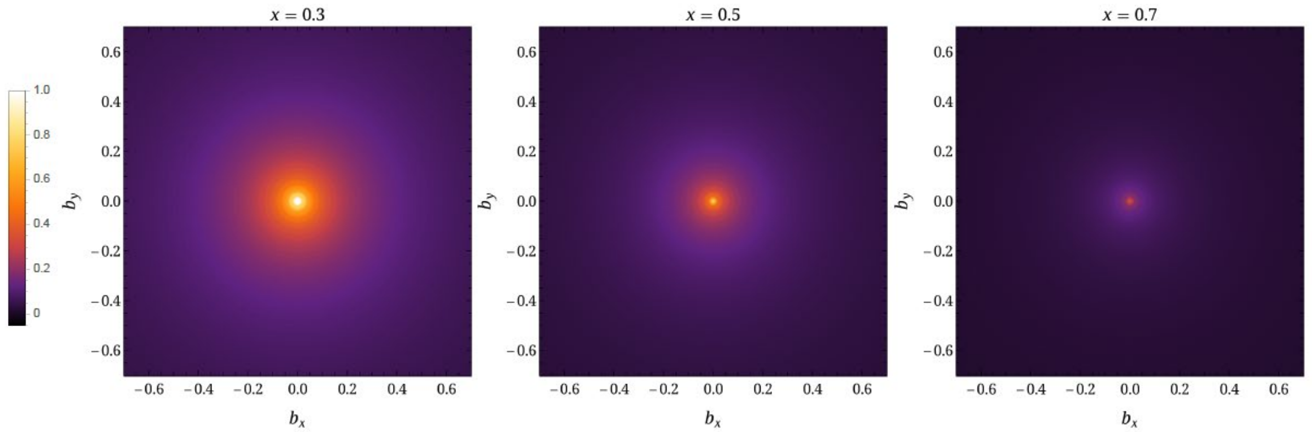
- Valence quarks carry 52% of the pion's momentum at the light front, at the scale used for Lattice QCD calculations, or ~65% at the perturbative hadronic scale
- At the same scale, valence-quarks carry ⅔ of the kaon's light-front momentum, or roughly 95% at the perturbative hadronic scale



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

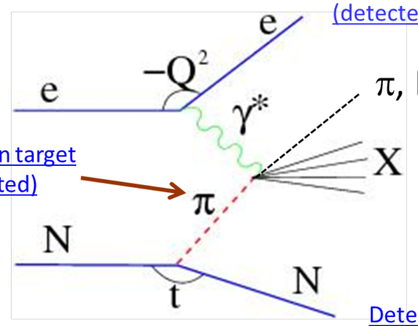
- heavier quarks radiate less readily than lighter quarks
- heavier quarks radiate softer gluons than do lighter quarks
- Landau-Pomeranchuk effect: softer gluons have longer wavelength and multiple scatterings are suppressed by interference.
- Momentum conservation communicates these effects to the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

EIC Meson Structure Questions



Science Question	Key Measurement[1]	Key Requirements[2]
Are transverse momentum distributions universal in pions and protons?	Hadron multiplicities in SIDIS off a pion target as defined with Sullivan process.	• Need to uniquely determine SIDIS off pion $e + p \rightarrow e' + h + X + n$ (low $-t$) • High luminosity (10^{34} cm^{-2} sec^{-1}) • $e + p$ and $e + D$ at similar energies desirable • CM energy ∼10-100 GeV

Can we even do SIDIS or DES off meson target?



Studies ongoing – stay tuned!

Summary

- Pion and kaon structure is vital for EHM topics and understanding of visible Universe
- Pion and kaon structure is non-trivial – experimental data for pion and kaon structure is extremely sparse
- New facilities provide exciting imminent opportunities to collect data on pion and kaon structure functions
    - Pion and kaon form factors at JLab
        - Two experiments have been completed in the last few years – analysis ongoing
    - Pion and kaon structure functions at JLab
        - Conditionally approved experiments – offer important data for resolving and cross-checking pion PDF issues at high-x; provide essentially the first kaon SF world data set
    - Pion and kaon form factors and SFs at EIC
        - Potential game changer with a large CM range (20-140 GeV) and access to wide x-Q^2 landscape
        - Potential to provide definite answers on different gluon distributions in pion/kaons
- A coherent and global effort is required among theory, phenomenology, computing, and experiments to further our understanding of hadron structure