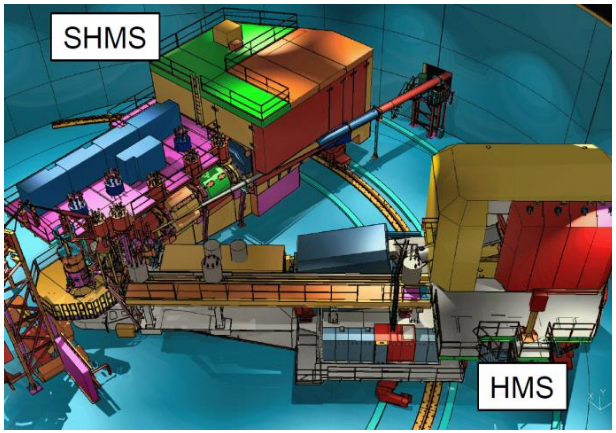
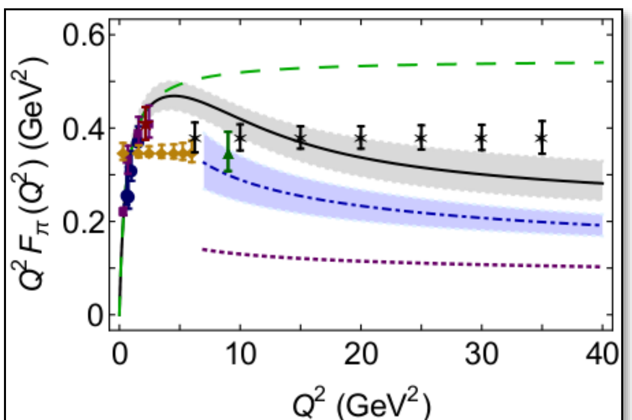
Overview Meson Form Factors





Tanja Horn

The Catholic University of America

Jefferson Lab
Thomas Jefferson National Accelerator Facility

2020 JLUO Annual Meeting

online, 22-24 June 2020

PionLT Publications – based on two 6 GeV pion experiments

6 GeV Pion Experiments:
1997 (phase 1)
2003 (phase 2)

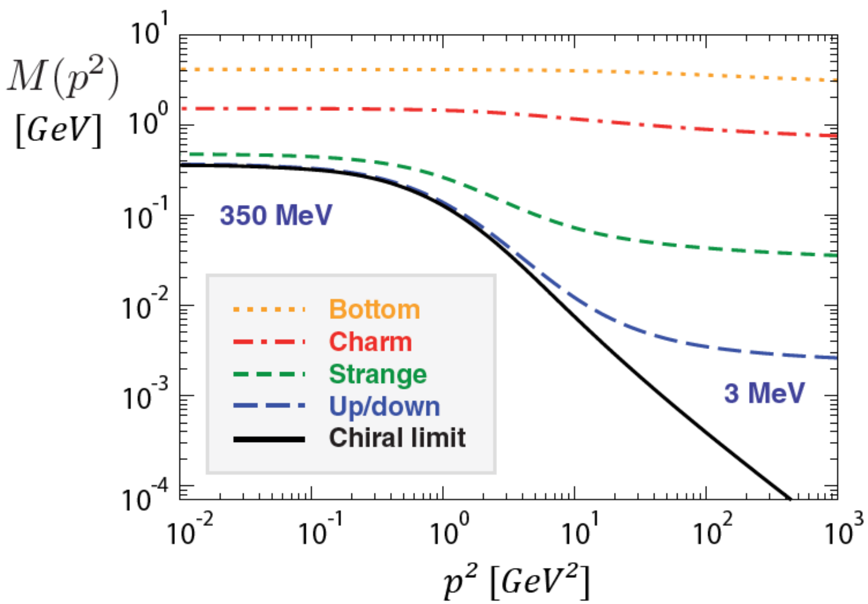
~2000

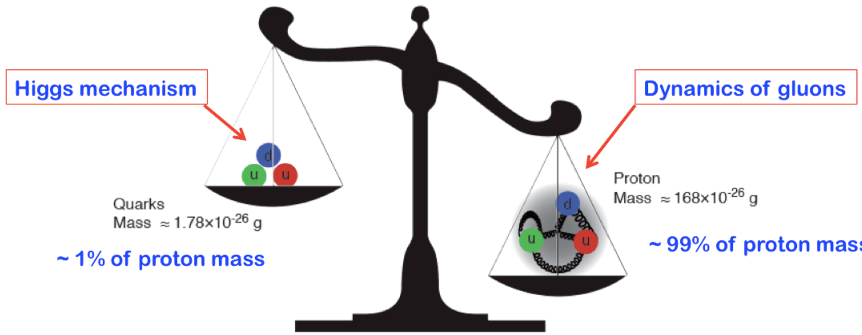
- J. Volmer, et al., Phys. Rev. Lett. **86** (2001) 1713 – **319 citations**
  - Precision F_π results between Q^2=0.60 and 1.60 GeV^2
- T. Horn, D. Gaskell, G. Huber, et al., Phys. Rev. Lett. **97** (2006) 192001 – **255 citations**
  - Precision F_π results at Q^2=1.60 and 2.45 GeV^2
- V. Tadevosyan, et al., Phys. Rev. C**75** (2007) 055205 – **212 citations**
- G. Huber, T. Horn, D. Gaskell, et al., Phys. Rev. C**78** (2008) 045203 – **194 citations**
  - Archival paper of precision F_π measurements at JLab 6 GeV
- H. P. Blok, T. Horn, G. Huber, et al., Phys. Rev. C**78** (2008) 045202 – **112 citations**
  - Archival paper of precision LT separated pion cross sections at JLab 6 GeV
- T. Horn, D. Gaskell, G. Huber, et al., Phys. Rev. C**78** (2008) 058201 – **73 citations**
  - L/T cross sections and F_π at Q^2=2.15 GeV^2 ,exploratory at Q^2~4.0 GeV^2
- Plus several spin-off papers on, e.g. L/T separations in π^- and ω production, high-t, transverse charge density (2012-present)

2020

The incomplete Hadron: Mass Puzzle

"Mass without mass!"





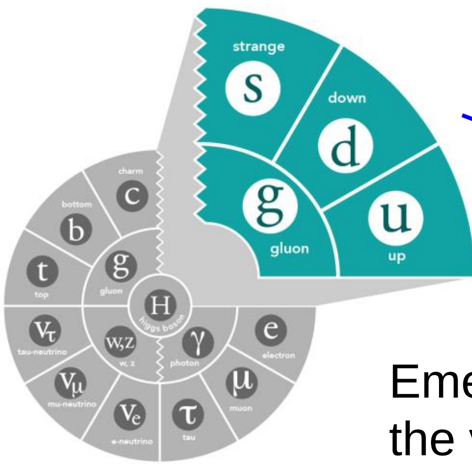
The light quarks acquire (most of) their masses as effect of the gluon cloud.

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

Measurements connected to the origin of hadron mass

- ***Pion and kaon form factors*** are of special interest in hadron structure studies

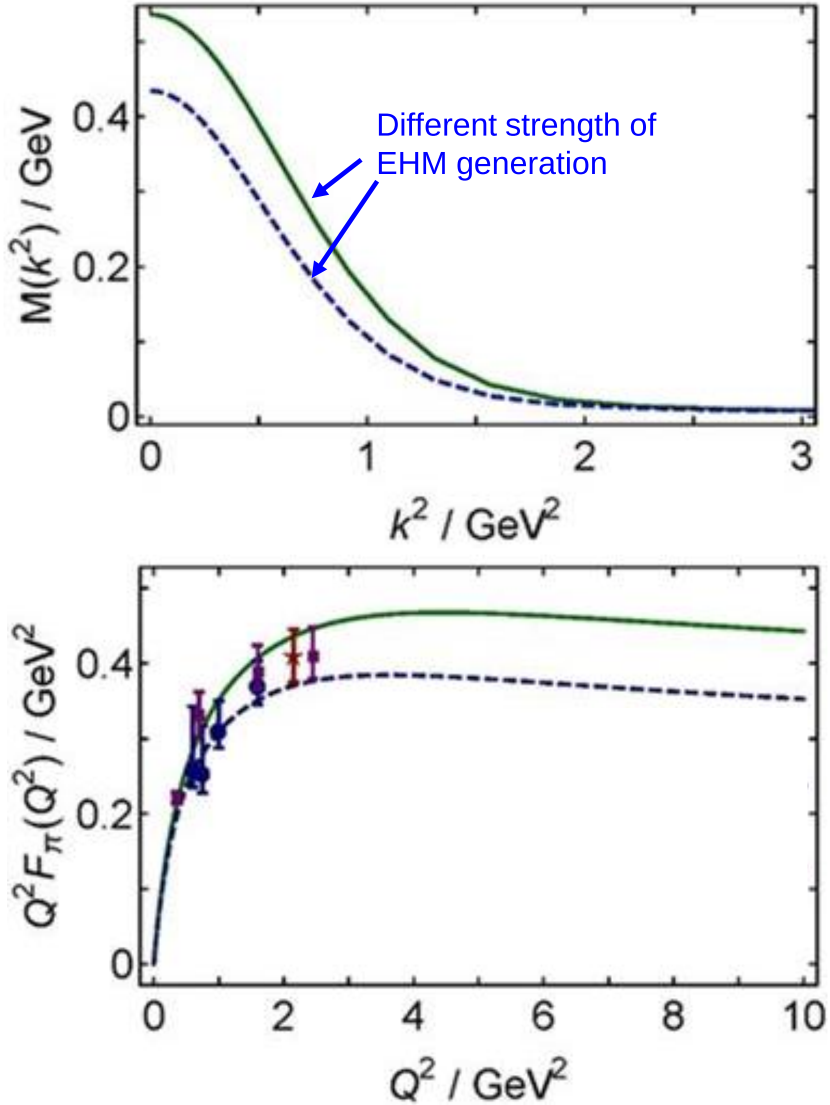
  Clearest test case for studies of the transition from non-perturbative to perturbative regions

- Continuum and lattice QCD connect the data to emergent hadron mass (EHM)

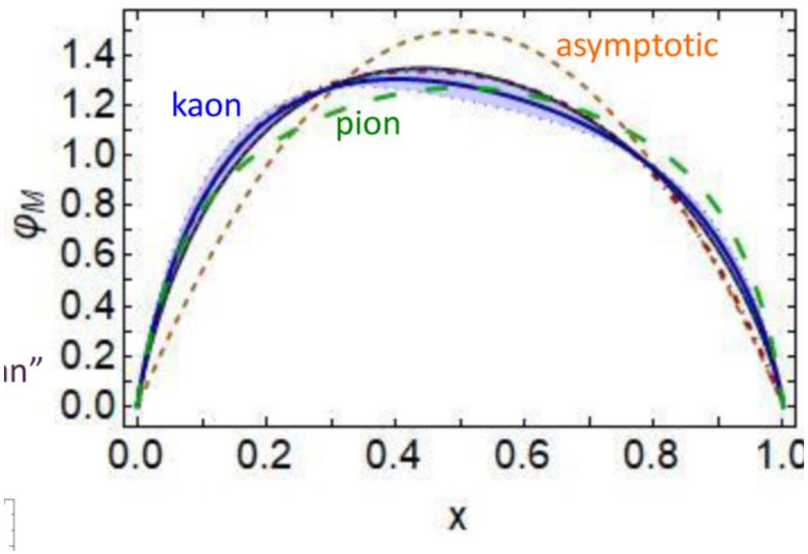
  Normalization of the form factor curve is a measure of the size of EHM

Pion and kaon form factors are sensitive experimental probes to the strength of EHM

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

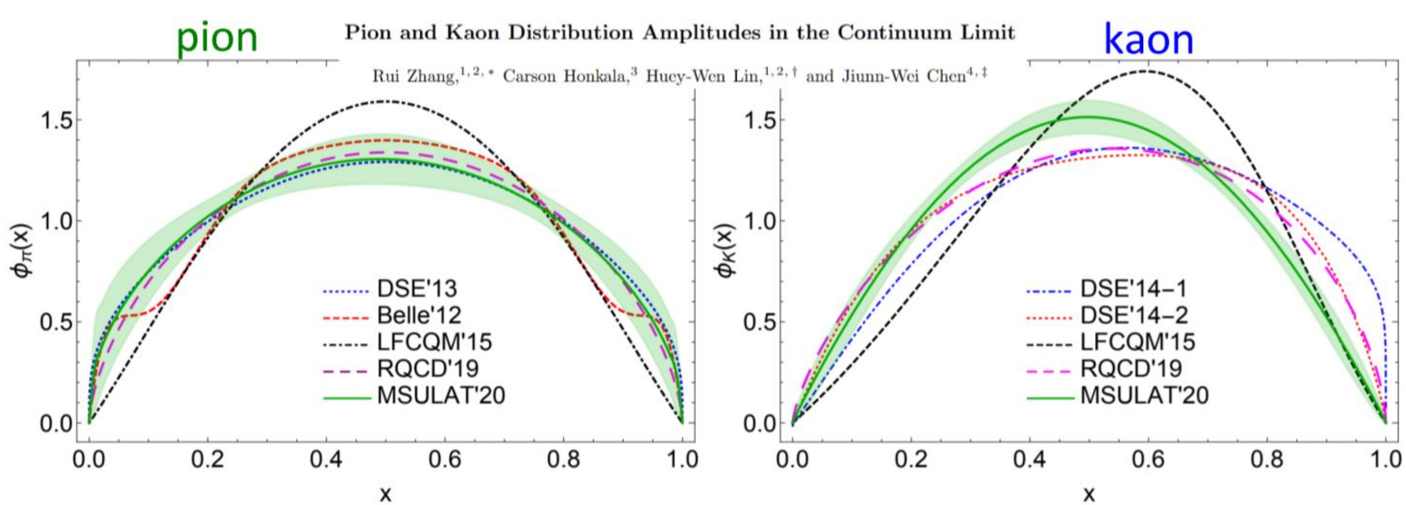


Meson Leading-Twist DA



- The shape of the meson DA including EHM is broader than asymptotic
  - Kaon DA is almost as broad and peak is shifted with respect to x~0.5
- No differences between pion and kaon if EHM is all there is
  - Differences arise from Higgs-modulation of EHM mechanism

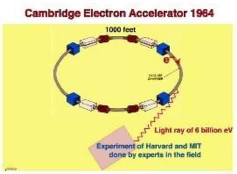
Recent progress: Continuum results exist and lattice QCD results are arriving



Meson Form Factor Data Evolution

Experiment

Capability to reliably access large Q^2 regime



DESY

Jefferson Lab

JLab 6 GeV

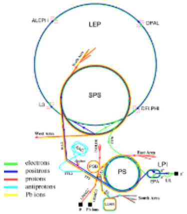
JLab 12 GeV

EIC

1959 | 1971 | 1976 | 1979 | 1981 | 1984 | 1986 | 1997 | 2003 | 2004 | 2017+ | 2025+

Cornell University

Fermilab



Theory

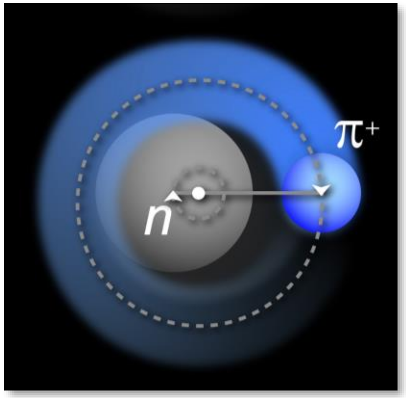
- Accessing the form factor through electroproduction
- Extraction of meson form factor from data
- Electroproduction formalism

Theory

Major progress on large Q^2 behavior of meson form factor

Experimental Determination of the π^+ Form Factor

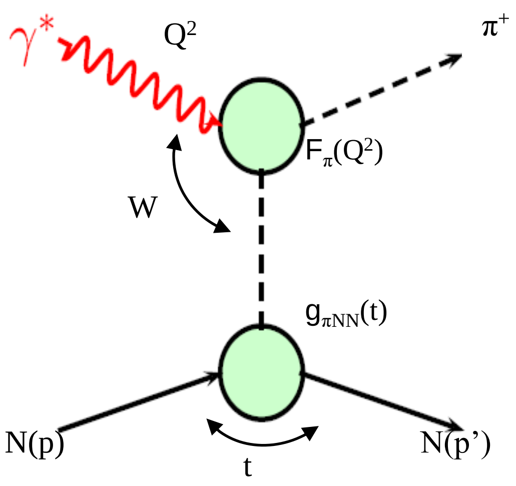
Through the Sullivan Process



- ❑ $F_{\pi+}$ 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

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

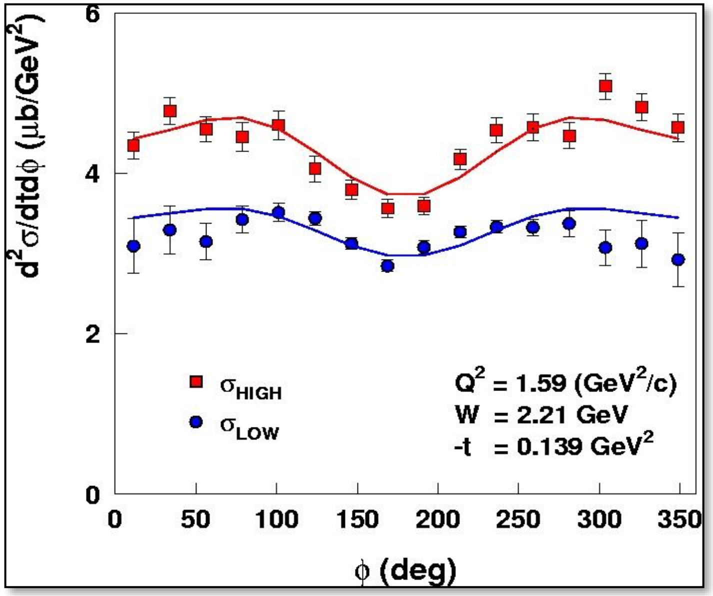
[In practice one uses a more sophisticated model]



- ❑ 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

- 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/ε 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

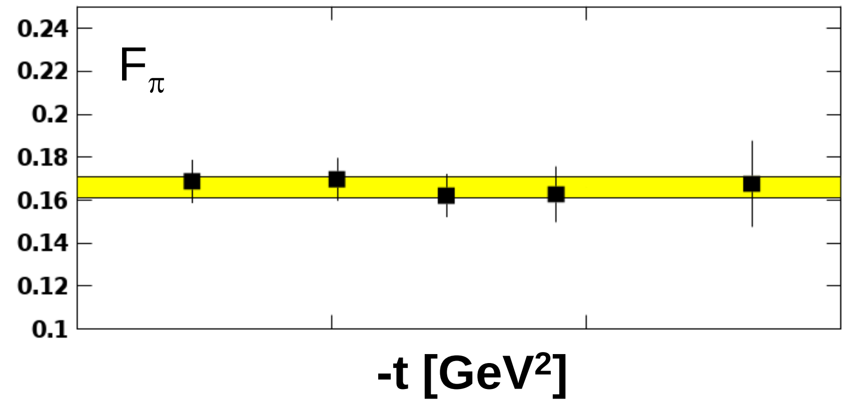
- This is only possible in Hall C at JLab
- SHMS was built to meet these exp. req.

Experimental Validation (Pion Form Factor example)

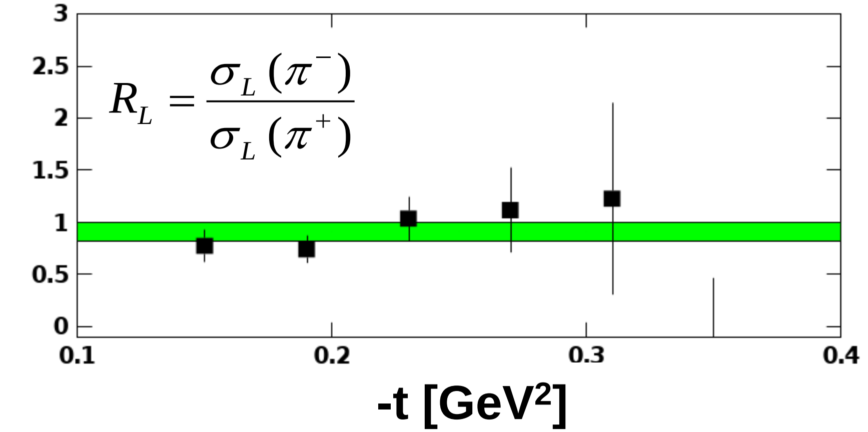
Experimental studies over the last decade have given ***confidence*** in the electroproduction method yielding the physical pion form factor

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



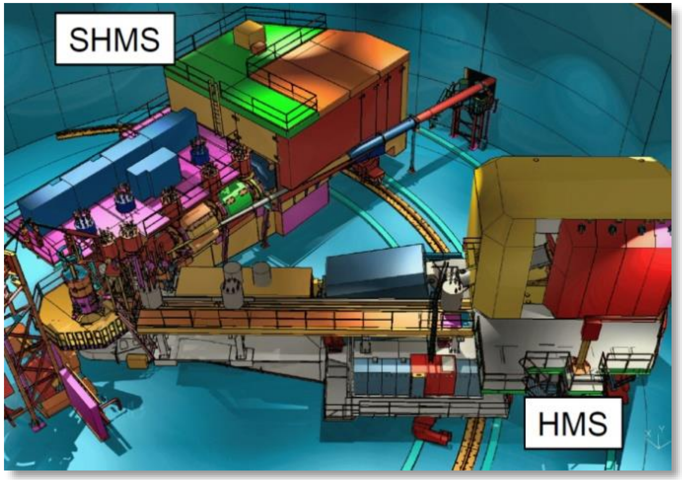
*[G. Huber et al, PRL**112** (**2014**)182501]*

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

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

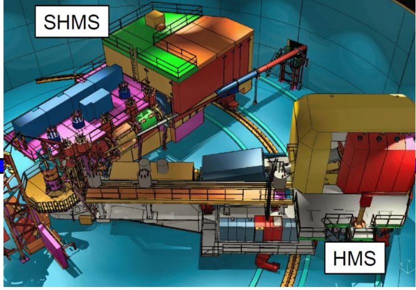
Exclusive Pion and Kaon Experiments in Hall C @ 12 GeV

- The pion experiments L/T separation requirements greatly influenced design specs of the new SHMS
  - Small forward-angle capabilities
  - Good angular reproducibilty
  - Missing mass resolution



- The pion and kaon experiment proponents built (and are maintaining) key SHMS detectors for the experiments
  - Aerogel Cherenkov – funded by NSF MRI (CUA)
  - Heavy gas Cherenkov – partially funded by NSERC (U Regina)

JLab12: E12-19-006 (PionLT)



Spokespersons: D. Gaskell (JLab), T. Horn (CUA), G. Huber (URegina)

Grad. Students: V. Kumar (URegina), A. Usman (URegina), R. Trotta (CUA)

Goals

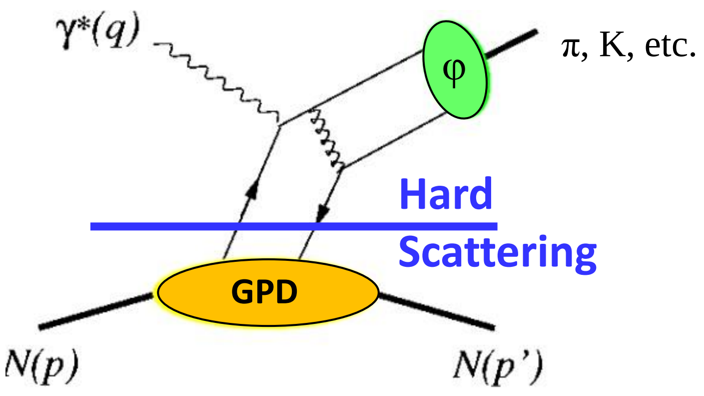
- ❑ Separated cross sections as a function of Q^2 at fixed x=0.3, 0.4, 0.55 to investigate the reaction mechanism towards 3D imaging studies
- ❑ Reliable pion form factor extractions up to the largest Q^2 accessible until the EIC

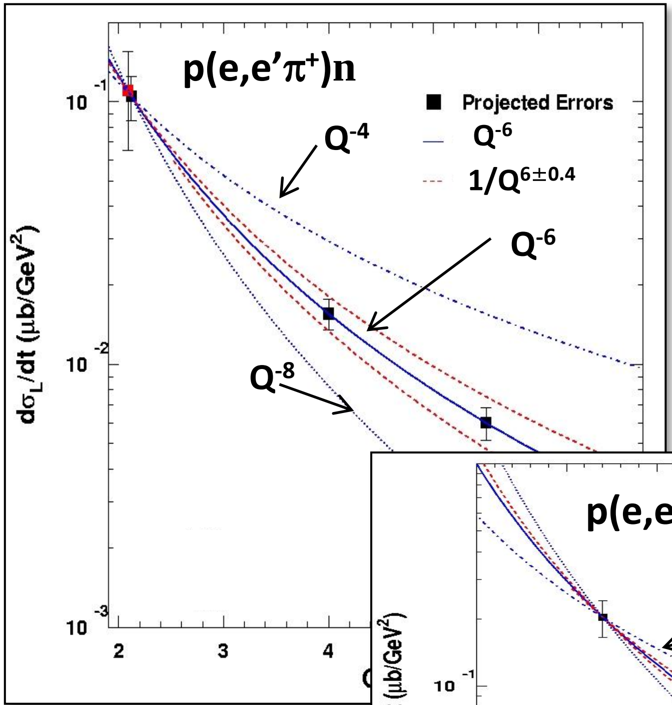
A comprehensive and coherent program of charged pion electroproduction, L/T-separated cross section measurements

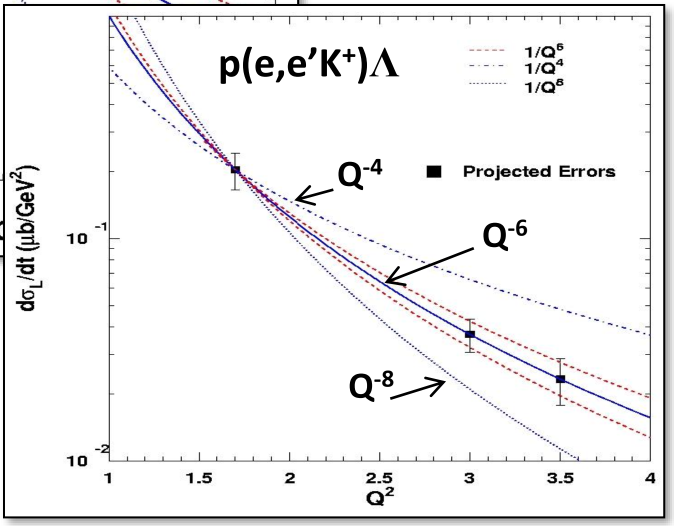
Motivation

- ❑ Pion structure is the clearest test case for studies of the transition from the nonperturbative to perturbative region
- ❑ Need to validate the hard-exclusive reaction mechanism – key are precision longitudinal-transverse (L/T) separated data over a range of Q^2 at fixed x/t
- ❑ L/T separated pion electroproduction is the clearest test case for studies of the transition from the nonperturbative to perturbative region beyond DVCS
- ❑ Pion electroproduction could allow access to transversity and regular GPDs

PionLT Scientific Motivation: Reaction Mechanism







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 the π and K electroproduction cross section
  - –σ_L scales to leading order as Q^{-6}
  - –σ_T does not
- ❑ Experimental validation of reaction mechanism is essential for reliable interpretation of results from the JLab GPD program at 12 GeV for meson electroproduction
  - ➢ **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**

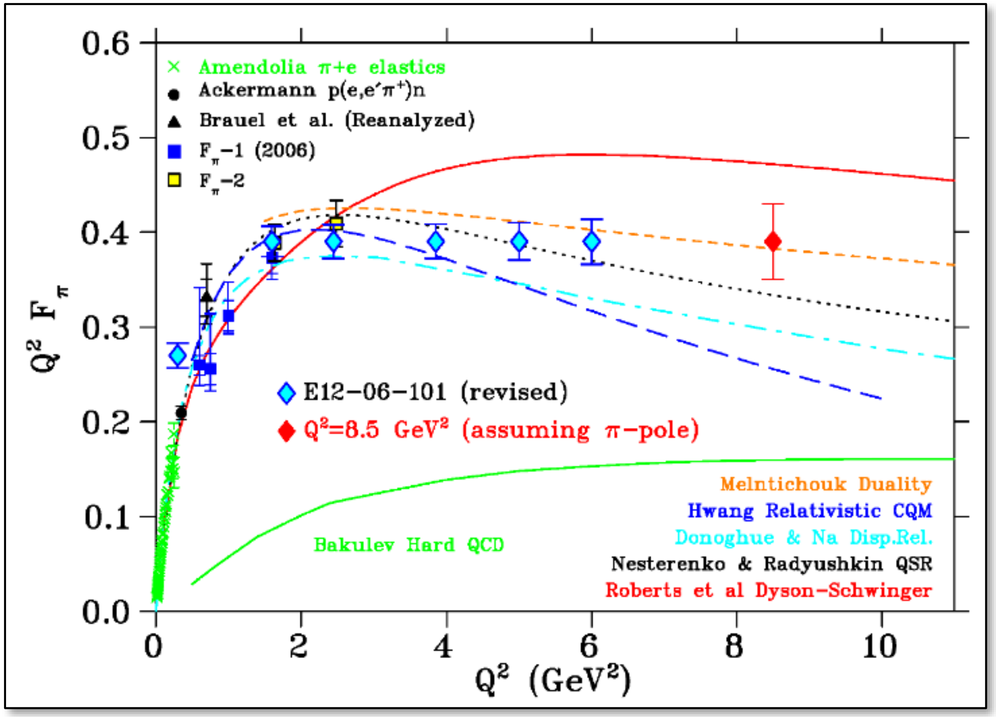
PionLT Scientific Motivation: Form Factors

- ❑ ***Pion and kaon form factors*** are of special interest in hadron structure studies
  - ➢ The *pion* is the lightest QCD quark system and also has a central role in our understanding of the dynamic generation of mass

Clearest test case for studies of the transition from non-perturbative to perturbative regions

- ❑ Completed Hall C experiments have established JLab's capability for reliable F_π measurements and are among the top-cited works from JLab

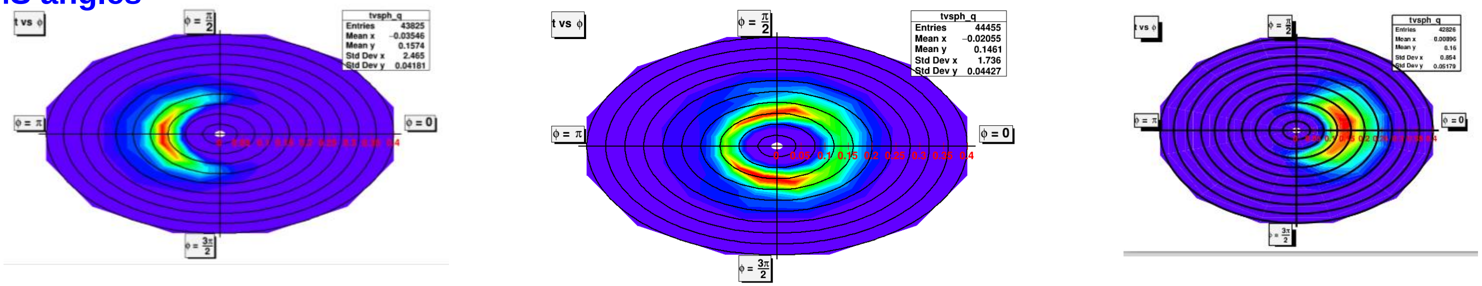
- ❑ New higher Q^2 data would challenge QCD-based models in the most rigorous way and provide a real advance in our understanding of light quark systems



PionLT: Low energy kinematic run summer 2019

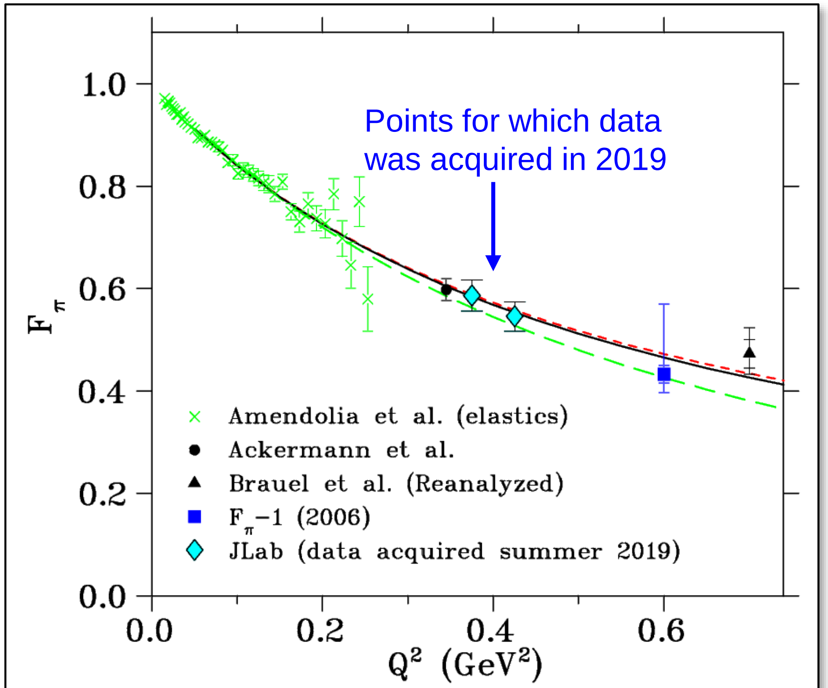
With combined and optimized run plan completed 2 L/T separations at low Q^2 and took data for the low epsilon points for two more settings, which also required these beam energies

Three SHMS angles



Two/three beam energies

Q^2 (GeV^2)	x_B	L/T complete	Purpos`e
0.375	0.09	Yes ✓	Form Factor
0.425	0.1	Yes ✓	Form Factor
1.45	0.3	No	Reaction mechanism
2.12	0.4	No	Reaction mechanism



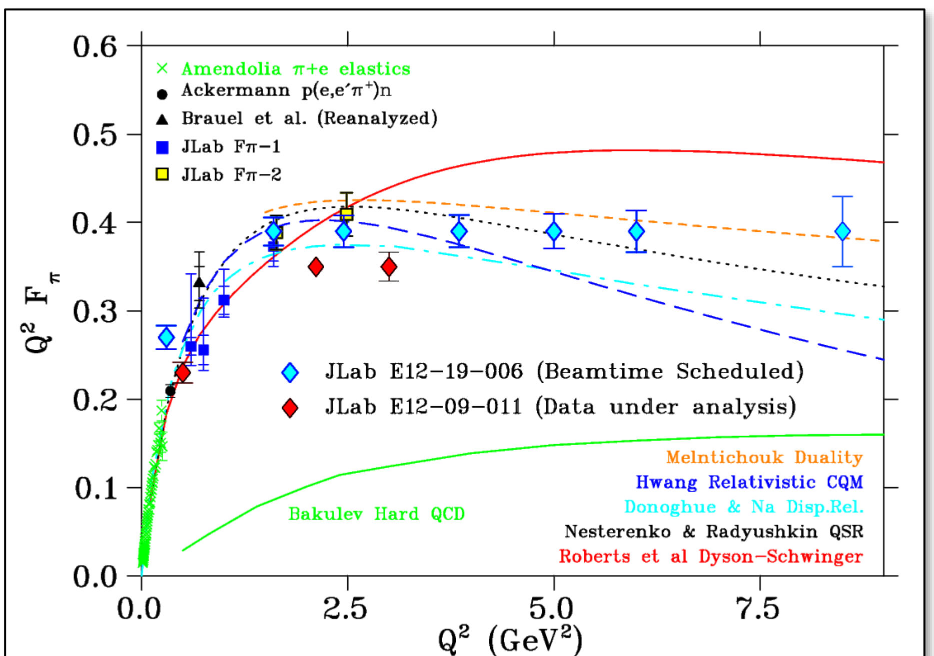
Physics cross section

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

This gives F_π

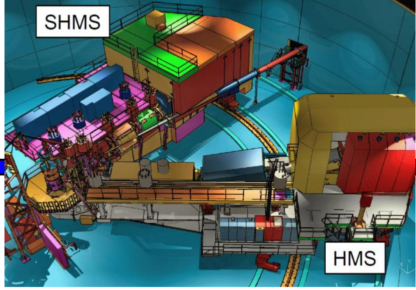
PionLT Program at 12 GeV: Outlook

- Low-Q^2 data taking for E12-19-006 completed in summer 2019 (3 PAC days)
- Enables measurements of the separated π^+ cross sections as function of Q^2 at x=0.3, 0.4, 0.55
- Enables measurements of pion form factor at low t up to Q^2 = 6 GeV^2
- Combined allows for pion form factor extraction to the very largest Q^2 accessible at 12 GeV JLab, 8.5 GeV^2



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	✗	✗

JLab12: E12-09-011 (KaonLT)



Spokespersons: T. Horn (CUA), G. Huber (URegina), P. Markowitz (FIU)

Grad. Students: V. Kumar (URegina), A. Usman (URegina), R. Trotta (CUA)

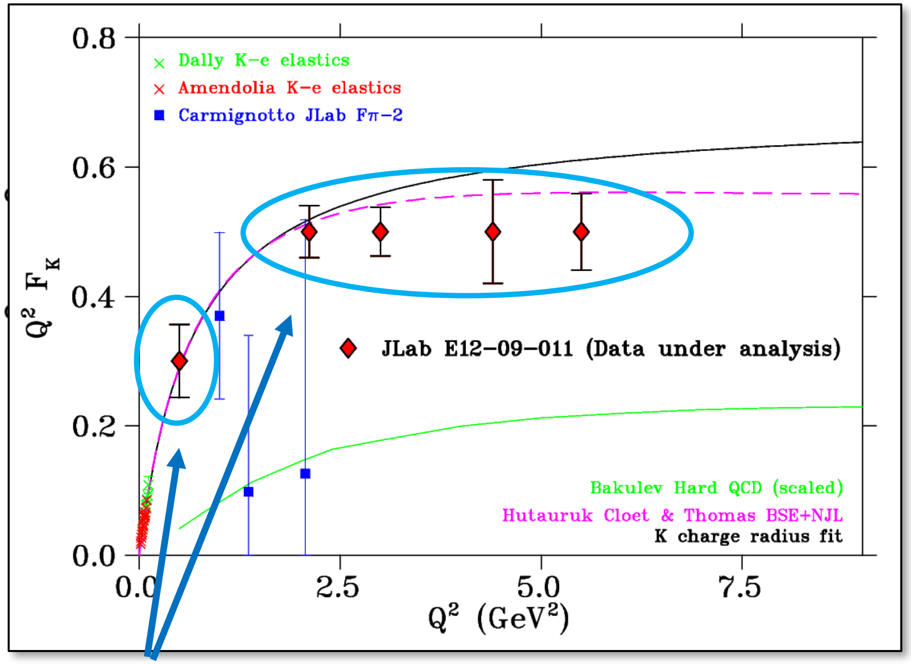
Goals

- ❑ Separated cross sections as a function of Q^2 at x_B=0.1, 0.25, 0.4
- ❑ Separated cross sections as a function of –t for kaon pole studies and possible kaon form factor extractions

Motivation

- ❑ Q^2 dependence for validating the hard exclusive reaction mechanism
  - ➢ First cross section data for Q^2 scaling tests with kaons
  - ➢ Highest Q^2 for L/T separated kaon electroproduction cross section
- ❑ t-dependence for validating the reaction mechanism
  - ➢ if warranted by data, extract the kaon form factor

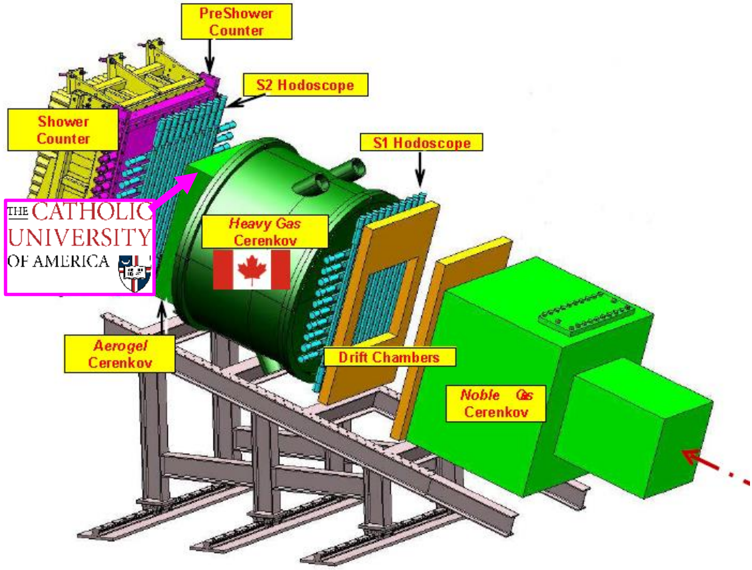
[M. Carmignotto et al., Phys. Rev. C97 (2018) no.2, 025204]



Possible extractions from 2018/19 run

KaonLT (PionLT) Setup in Hall C

- ❑ SHMS for kaon (pion) detection :
  - ➢ Kaon angles between **6** – 30 deg
  - ➢ Kaon momenta between 2.7 – 6.8 GeV/c

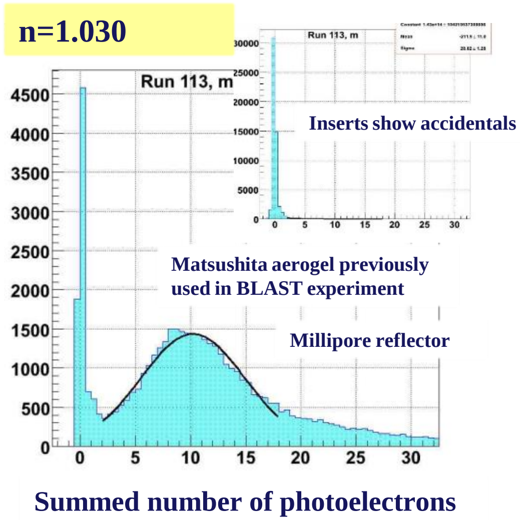


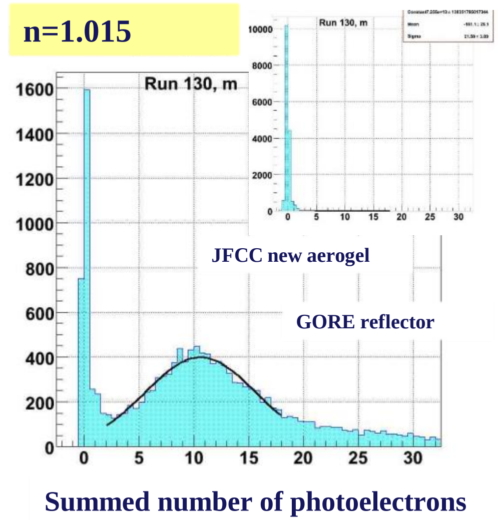
- ❑ HMS for electron detection :
  - ➢ angles between 10.7 – 31.7 deg
  - ➢ momenta between 0.86 – 5.1 GeV/c
- ❑ Particle identification:
  - ➢ Dedicated Aerogel Cherenkov detector for kaon/proton separation
    - ○ Four refractive indices to cover the dynamic range required by experiments
  - ➢ Heavy gas Cherenkov detector for kaon/pion separation

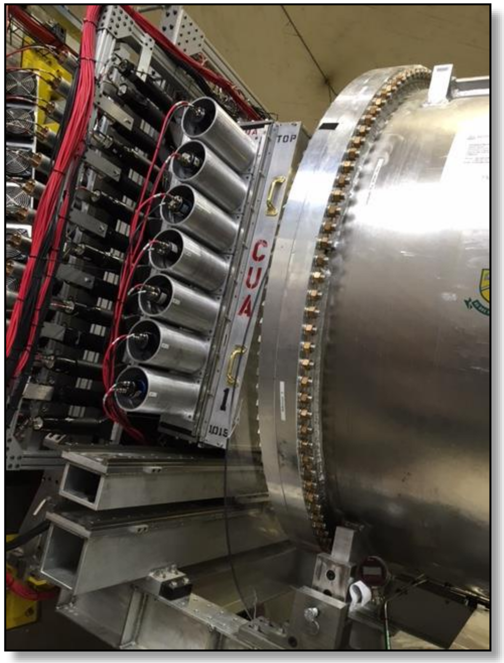
Dedicated equipment: SHMS Aerogel Cherenkov Detector

NSF MRI PHY-1039446

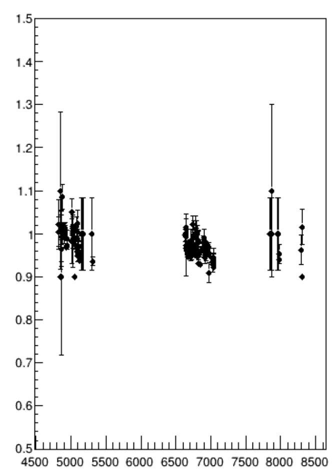
*T. Horn, V. Berdnikov, et al., Nucl.Instrum.Meth.A **842** (**2017**) 28-47*

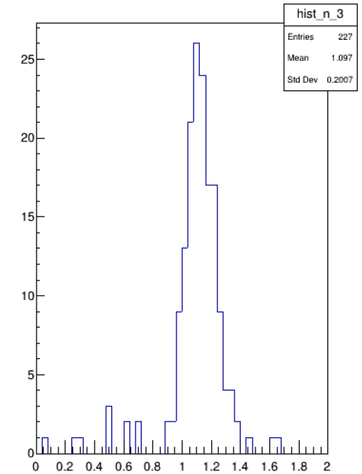






- >15(!) successful tray exchanges since Fall 2018
- Aerogel performance as expected
- Trays require optimization before next use – make more robust against damage due to crane movement during installation



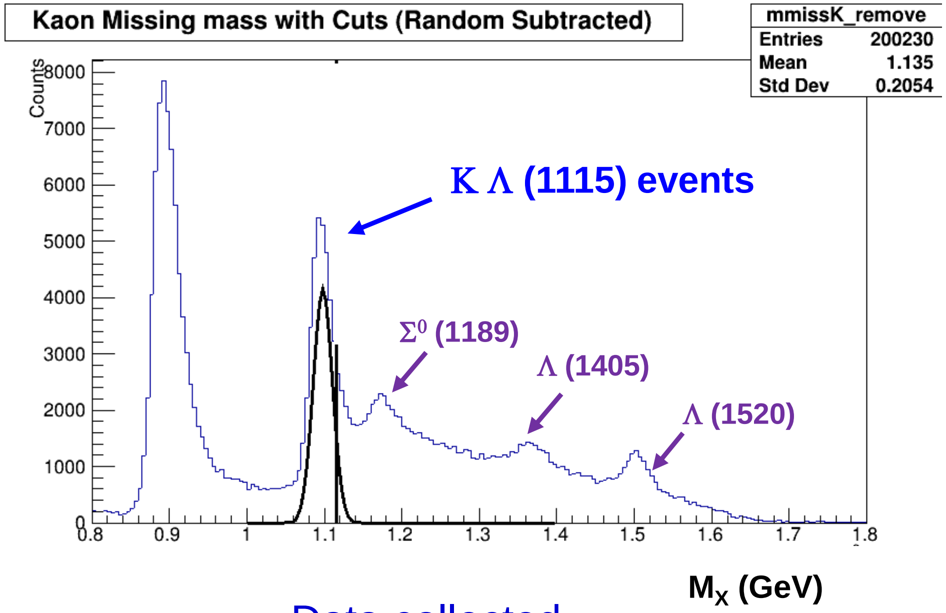


KaonLT took data in 2018/2019

- Data taking completed end of Spring 2019

- Physics analyses may include:
  - **K⁺ channel**: L/T separated Λ and Σ^0 cross sections, Q^{-n} dependence, coupling constants $g_{KN\Lambda}$, beam helicity asymmetry, $\Lambda(1405)$, $\Lambda(1115)$, $\Lambda(1520)$ cross sections
  - **π^+ channel**: L/T separated cross sections, beam helicity asymmetry, n/Δ^0 ratios, Q^{-n} dependence
  - **p channel**: $p(e,e'p)\rho/p(e,e'p)\omega$, $p(e,e'p)\phi$ ratios, as possible, cross sections and $p(e,e'p)\eta$ and $p(e,e'p)\eta'$, Q^{-n} dependence

Online data

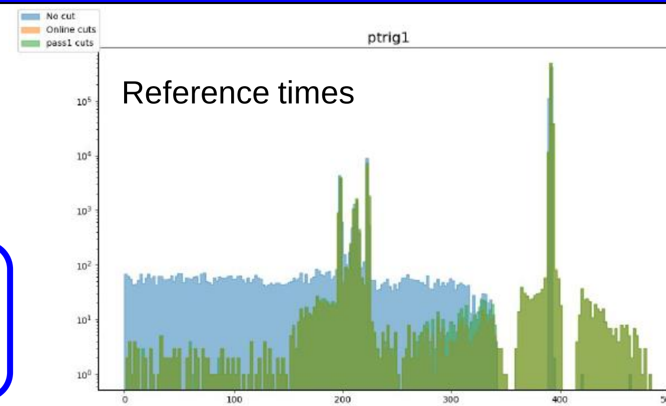


Data collected

Q^2 (GeV^2)	W (GeV)	LT complete
5.5	3.02	✔
4.4	2.74	✔
3.0	3.14	✔
3.0	2.32	✔
2.115	2.95	✔
0.5	2.40	✔

KaonLT: Data Analysis ongoing

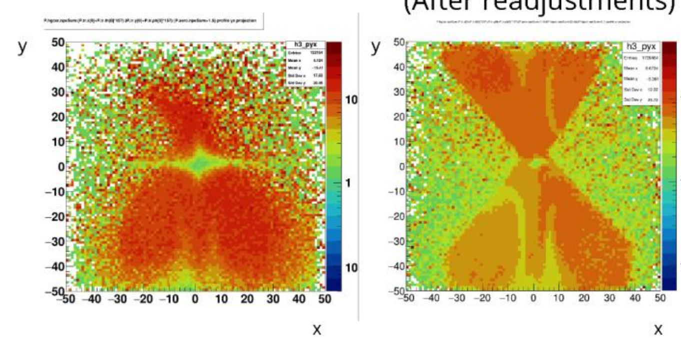
- ✔ Calibrations
  - ➢ Calorimeter, aerogel, HGC, HMS cer, DC, hodo
  - ➢ Optimize replay for all physics settings
- ❑ Efficiencies, deadtimes, kinematic offsets
  - ➢ Special runs, e.g. luminosity scans and elastics
- ❑ First iteration of cross section
  - ➢ Bring everything together
- ❑ Fine tune
  - ➢ Fine tune fits and study systematics
- ❑ Repeat previous step
  - ➢ Repeat until stable cross sections are reached
- ❑ Possible attempt at form factor extraction
  - ➢ Fit data to a model and iterate, study systematics



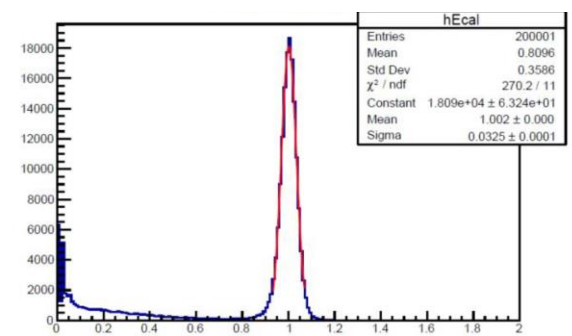
HGC – interesting challenges

Fall

Spring
(After readjustments)



Example of hodoscope calibration



Analysis by: N. Heinrich, V. Kumar, R. Trotta, A. Usman, S. Kay, V. Berdnikov

Meson Structure Function Studies at the EIC

The Meson SF Working Group:
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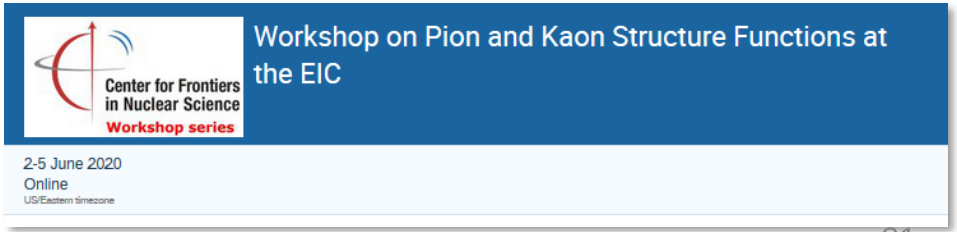
- Includes researchers from experiment, phenomenology, theory, lattice
- Working on development of science, projections, detector requirements for structure function studies at the EIC
- Recent CFNS Workshop on Pion and Kaon Structure Functions at the EIC had large participation: 139 registered participants
- Everyone welcome to join the WG!



Outlook: Meson Form Factors at an EIC

1. VR model shows strong dominance of σ_L at small –t at large Q^2.
2. Assume σ_L dominance
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

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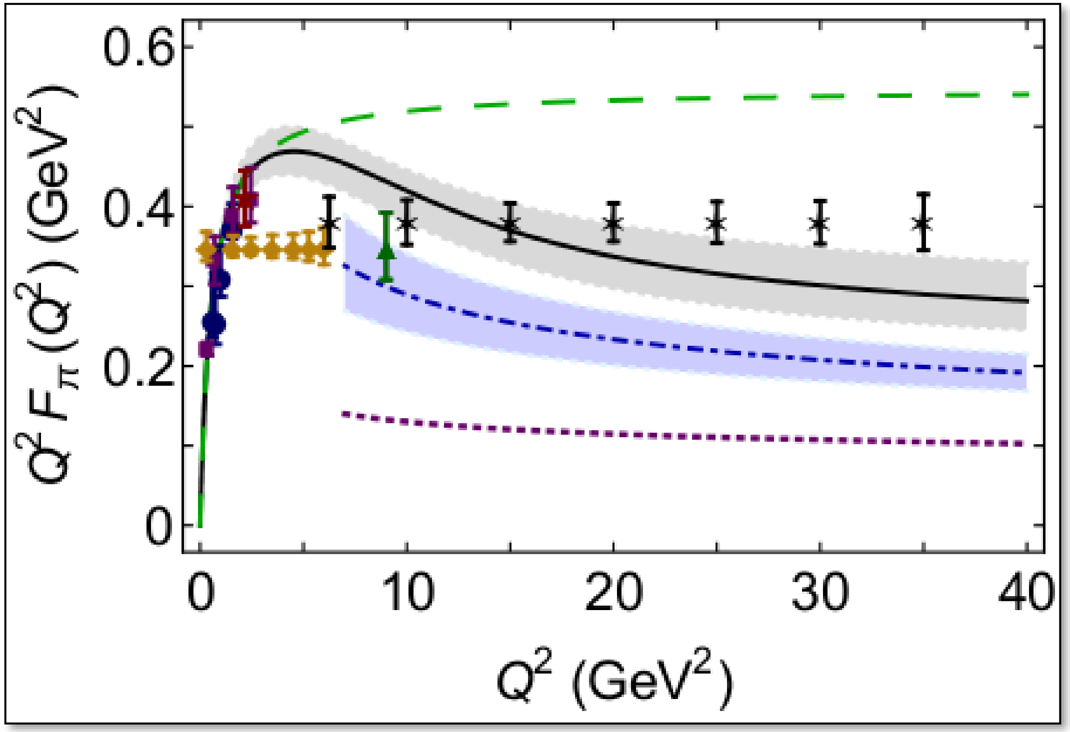

- ❑ 5 GeV(e^-) x 100 GeV(p)
- ❑ Integrated luminosity: L=20 fb^{-1}/yr
- ❑ Identification of exclusive $p(e,e'\pi^+)n$ events
- ❑ 10% exp. syst. unc.
- ❑ $R=\sigma_L/\sigma_T$ from VR model, and π pole dominance at small t confirmed in ^2H π^-/π^+ ratios
- ❑ 100% syst. unc. in model subtraction to isolate σ_L

Can we measure kaon form factor at EIC?

Summary

- Meson form factor measurements play an important role in our understanding of the structure and interactions of hadrons based on the principles of QCD

- Much recent progress in continuum and lattice-QCD calculations

- JLab 12 GeV will dramatically improve the $\pi^+/K^+/\pi^0$ electroproduction data set
  - Pion and kaon form factor extractions up to high Q^2 possible (~9 and ~6 GeV^2)
  - Kaon experiment completed in 2018/19
  - Pion experiment took low-Q^2 data in summer 2019
  - L/T separated cross sections important for transverse nucleon structure studies – may allow for accessing new type of GPDs

- Beyond 12 GeV, EIC provides interesting opportunities to map pion and kaon structure functions over a large (x, Q^2) landscape

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