Overview Meson Form Factors

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PionLT Publications – based on two 6 GeV pion experiments

- 2000

  - Precision $F_{\pi}$ results between $Q^2=0.60$ and 1.60 GeV$^2$

  - Precision $F_{\pi}$ results at $Q^2=1.60$ and 2.45 GeV$^2$


  - Archival paper of precision $F_{\pi}$ measurements at JLab 6 GeV

  - Archival paper of precision LT separated pion cross sections at JLab 6 GeV

  - L/T cross sections and $F_{\pi}$ at $Q^2=2.15$ GeV$^2$, exploratory at $Q^2\sim4.0$ GeV$^2$

- Plus several spin-off papers on, e.g. L/T separations in $\pi^-$ and $\omega$ production, high-$t$, transverse charge density (2012-present)

6 GeV Pion Experiments:
- 1997 (phase 1)
- 2003 (phase 2)
The incomplete Hadron: Mass Puzzle

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

"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.

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*

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Pion and kaon form factors are sensitive experimental probes to the strength of EHM
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 $x \sim 0.5$

- 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

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

Experiment
- Capability to reliably access large $Q^2$ regime

Experimental Determination of the $\pi^+$ Form Factor

Through the Sullivan Process

- $F_{\pi^+}$ measured indirectly using the “pion cloud” of the proton via the $p(e,e'\pi^+)n$ process
  - At small $-t$, the pion pole process dominates the longitudinal cross section, $\sigma_L$
  - In the Born term model, $F_\pi^2$ 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 $\sigma_L$
- 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

- $\sigma_L$ 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 ($\phi_\pi$) allows for extracting $L$, $T$, $LT$, and $TT$

- Careful evaluation of the systematic uncertainties is important due to the $1/\varepsilon$ amplification in the $\sigma_L$ extraction
  - Spectrometer acceptance, kinematics, and efficiencies

- 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.

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

$\sigma_L$ will give us $F_\pi$
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
  - $F_\pi$ 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

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

[R. J. Perry et al., PRC 100 (2019) 2, 025206.]
The pion experiments L/T separation requirements greatly influenced design specs of the new SHMS
- Small forward-angle capabilities
- Good angular reproducibility
- 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)
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.
One of the most stringent tests of the reaction mechanism is the $Q^2$ dependence of the $\pi$ and $K$ electroproduction cross section

- $\sigma_L$ scales to leading order as $Q^{-6}$
- $\sigma_T$ 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 $\sigma_T$ is confirmed to be large, it could allow for detailed investigations of transversity GPDs. If, on the other hand, $\sigma_L$ 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 $F_\pi$ 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

![SHMS angles](image)

### Two/three beam energies

<table>
<thead>
<tr>
<th>( Q^2 ) (GeV(^2))</th>
<th>( x_B )</th>
<th>L/T complete</th>
<th>Purpose</th>
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<tr>
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<td>Reaction mechanism</td>
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<tr>
<td>2.12</td>
<td>0.4</td>
<td>No</td>
<td>Reaction mechanism</td>
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### Physics cross section

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

This gives \( F_\pi \)

![Physics cross section graph](image)
Low-$Q^2$ data taking for E12-19-006 completed in summer 2019 (3 PAC days)

- Enables measurements of the separated $\pi^+$ 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 $Q^2 = 6 \text{ GeV}^2$

- Combined allows for pion form factor extraction to the very largest $Q^2$ accessible at 12 GeV JLab, 8.5 GeV$^2$

<table>
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<th>Setting</th>
<th>Low $\epsilon$ data</th>
<th>High $\epsilon$ data</th>
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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

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


- >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 Σ⁰ cross sections, Q⁻ⁿ dependence, coupling constants g_{KΛ}, beam helicity asymmetry, Λ(1405), Λ(1115), Λ(1520) cross sections
  - **π⁺ channel**: L/T separated cross sections, beam helicity asymmetry, n/Δ⁰ ratios, Q⁻ⁿ dependence
  - **p channel**: p(e,e’p)ρ/p(e,e’p)ω, p(e,e’p)φ ratios, as possible, cross sections and p(e,e’p)η and p(e,e’p)η’, Q⁻ⁿ dependence

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Online data

Data collected

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<thead>
<tr>
<th>Q² (GeV²)</th>
<th>W (GeV)</th>
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</tr>
</tbody>
</table>
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

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:
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)

- 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!
1. VR model shows strong dominance of $\sigma_L$ at small $-t$ at large $Q^2$.
2. Assume $\sigma_L$ dominance
3. Measure the $\pi^-/\pi^+$ ratio to verify – it will be diluted (smaller than unity) if $\sigma_T$ is not small, or if non-pole backgrounds are large


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

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
  o Pion and kaon form factor extractions up to high $Q^2$ possible (~9 and ~6 GeV$^2$)
  o Kaon experiment completed in 2018/19
  o Pion experiment took low-$Q^2$ data in summer 2019
  o 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

Supported in part by NSF grant PHY1714133, 2012430