Meson Form Factors and Deep Exclusive Meson Production Experiments

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Form factors are essential for our understanding of internal hadron structure and the dynamics that bind the most basic elements of nuclear physics.

- 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.
  - The kaon is of interest as it replaces one light quark with a heavier strange quark.

- Recent advances in experiments: last 5-10 years
  - Dramatically improved precision in $F_\pi$ measurements
  - Improved experimental understanding of the meson production/reaction mechanism

- Future approved measurements – JLab 12 GeV next 5-10 years
  - $F_\pi$ and exclusive meson studies up to highest possible $Q^2$ – potential to reach the regime in which hard QCD’s signatures will be quantitatively revealed
  - Exclusive kaon cross sections at low $t$ and possible $F_{K^+}$ extraction
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

Major progress on large $Q^2$ behavior of meson form factor
At low $Q^2$, $F_{\pi^+}$ can be measured directly via high energy elastic $\pi^+$ scattering from atomic electrons.

- CERN SPS used 300 GeV pions to measure form factor up to $Q^2 = 0.25 \text{ GeV}^2$ \[\text{(Amendolia et al, NPB277,168 (1986))}\]
- These data used to constrain the pion charge radius: $r_\pi = 0.657 \pm 0.012 \text{ fm}$

The maximum accessible $Q^2$ is roughly proportional to the pion beam energy.

- $Q^2 = 1 \text{ GeV}^2$ requires 1000 GeV pion beam
Experimental Determination of the $\pi^+$ Form Factor

Through pion electroproduction

- At larger $Q^2$, $F_{\pi^+}$ must be measured indirectly using the “pion cloud” of the proton via the $p(e,e'\pi^+)n$ 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
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

Magnetic spectrometers a must for such precision cross section measurements

- This is only possible in Hall C at JLab

\[ 2\pi \frac{d^2 \sigma}{dtd\phi} = s \frac{d\sigma_L}{dt} + \frac{d\sigma_T}{dt} + \sqrt{2s(1+1)} \frac{d\sigma_{LT}}{dt} \cos \phi + s \frac{d\sigma_{TT}}{dt} \cos 2\phi \]
Pion pole contribution to pion electroproduction data at low $t$

$L/T$ separated data from JLab 6 GeV (Hall C)

\[
\frac{d\sigma_{\text{pole}}}{dt} \left( \gamma_L^* \rightarrow \pi^+ \right) = \frac{1}{\kappa} \left( t - m_{\pi}^2 \right)^2 Q^2 \rho_{\pi}^2
\]

\[
\rho_{\pi} = \sqrt{2} e_0 F_\pi(Q^2) g_{\pi NN} F_{\pi NN}(t)
\]

\[
F_{\pi NN} = \frac{\Lambda_N^2 - m_{\pi}^2}{\Lambda_N^2 - t} \quad F_x = \frac{1}{1 + Q^2/\Lambda_x^2} \quad [\Lambda_x^2 = 0.53 \text{ GeV}^2]
\]

Band indicates calculated range of values for:

- $\Lambda_N = 0.4$ to $0.6 \text{ GeV}$
- $g_{\pi NN} = 13.1$ to $13.5$

- Longitudinal cross section at $W = 2.2 \text{ GeV}$ in good agreement with the pion pole calculation
- At $W = 1.95 \text{ GeV}$ the pole calculation seems to predict a different $Q^2$ dependence than the data

Note: the values of $W$ and $Q^2$ listed are the overall central values. Each $t$-bin has actually its own bin-centered $W$ and $Q^2$ values


Overall, $\sigma_L$ data demonstrate the important contribution from the pion pole at small $t$
Pion pole process in pion electroproduction data at larger $t$

Unseparated data from JLab 6 GeV (CLAS) [K. Park et al., EPJA 49 (2013)]

Cross section, $d\sigma/dt$ [μb/GeV²]

- $Q^2=2.35$ GeV², $W=2.47$ GeV
- $Q^2=3.85$ GeV², $W=2.44$ GeV

Band indicates calculated range of values for:

- $A_N=0.4-0.6$ GeV
- $g_{\pi NN}=13.1-13.5$

- At larger $t$ the pole contribution does not give a good description of the data


- In the unseparated cross section one cannot quantify the contribution of longitudinal and transverse photons
  - For $F_\pi$ extraction must fully separate cross section into longitudinal and transverse contributions

- Need to experimentally determine that $F_\pi$ extraction does not depend on the $t$-value of the data
Extraction of $F_\pi$ from $\sigma_L$ Jlab data

- JLab 6 GeV $F_\pi$ experiments used the VGL/Regge model as it has proven to give a reliable description of $\sigma_L$ across a wide kinematic domain
  
  
  - Feynman propagator replaced by $\pi$ and $\rho$ trajectories
  - Model parameters fixed by pion photoproduction data
  - Free parameters: $\Lambda_\pi^2$, $\Lambda_\rho^2$

$$F_\pi(Q^2) = \frac{1}{1 + Q^2 / \Lambda_\pi^2}$$

Fit of $\sigma_L$ to model gives $F_\pi$ at each $Q^2$

$\Lambda_\pi^2 = 0.513, 0.491 \text{ GeV}^2$

$\Lambda_\rho^2 = 1.7 \text{ GeV}^2$
Validation: Check of non-pole backgrounds in $\sigma_L$ with charged pion ratios in deuterium

- $\pi^+$ $t$-channel diagram is pure isovector (G-parity conservation)
- Measure (separated) $\pi^-/\pi^+$ ratio to test pole dominance

$$R_L = \frac{\sigma_L(\pi^-)}{\sigma_L(\pi^+)} = \left|\frac{A_V - A_S}{A_V + A_S}\right|^2$$

- Isoscalar backgrounds like $b_1(1235)$ contributions to $t$-channel will dilute the ratio from unity

- With increasing $t$, $R_T$ is expected to approach the ratio of quark charges

$R_L$ approaches unity at large $Q^2$ - consistent with pion-pole dominance

[Huber et al, PRL112 (2014)182501]

[O. Nachtman, NP B115 (1976) 61]

[$R_L = \frac{\sigma_L(\pi^-)}{\sigma_L(\pi^+)}$, $R_T = \frac{\sigma_T(\pi^-)}{\sigma_T(\pi^+)}$, $\sigma_L$, $\sigma_T$, $Q^2$, $t$ (GeV/c)$^2$]

- Goloskokov/Kroll, EPJA 47, 112 (2011)
- Kaskulov and Mosel, PRC 81, 045202 (2010)
- Vranckx and Ryckebusch, PRC 89, 025203 (2014)
- Vanderhaeghem, Guidal, Laget, PRC 57, (1998) 1454
Experimental studies over the last decade have given confidence in the electroproduction method yielding the physical pion form factor. 

- Experimental studies include:
  - Check consistency of model with data
    - $F_\pi$ values do not depend on the $t$-acceptance – 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
    - $R_L$ approaches the pion charge ratio, consistent with pion pole dominance
  - Extract $F_\pi$ at several values of $t_{\text{min}}$ for fixed $Q^2$ (next slide)

Validation: experimental considerations


[Huber et al, PRL112 (2014)182501]
Several effective models do a good job describing the data, e.g.,

- **LFQM**: C.-W. Hwang, PRD **64** (2001) 034011

- **Factor ~3** from hard QCD calculation evaluated with asymptotic wave function
  - Trend consistent with time like meson form factor data up to $Q^2=18$ GeV$^2$

  [Seth et al, PRL **110** (2013) 022002]

- **Recent efforts**:
  - Compare data with the QCD prediction calculated using the broad pion PDA predicted by modern analyses of continuum QCD

Provides an interpretation of EM form factors in terms of physical charge and magnetization densities

\[ \rho_\pi(b) = \frac{1}{\pi R^2} \sum_{n=1}^{\infty} F_\pi(Q_n^2) \frac{J_0(X_n \frac{b}{R})}{[J_1(X_n)]^2} \]

\[ Q_n = \frac{X_n}{R} \]

\[ \sum \frac{1}{n^2} \]

\[ (\sum \frac{1}{n^2}) \]

\[ (\sum \frac{1}{n^2}) \]

- Method: Finite Radius Approx. [S. Venkat et al., PRC 83 (2011) 015203]

- Uncertainty dominated by incompleteness error due to limited data range—estimated using models

- \( \rho_\pi \) and \( \rho_p \) coalesce for \( 0.3 \text{ fm} < b < 0.6 \text{ fm} \)

- Meson cloud only dominating at large impact parameter?

JLab 12 GeV data will allow further studies of transverse charge density and test for common confinement mechanism

[Insight from data: Pion Transverse Charge Density and the edge of hadrons]

Extension to systems containing strangeness: the $K^+$ Form Factor

- Similar to $\pi^+$, elastic $K^+$ scattering from electrons used to measure charged kaon for factor at low $Q^2$
  - CERN SPS used 250 GeV kaons to measure form factor up to $Q^2 = 0.13$ GeV$^2$ [Amendolia et al, PLB 178, 435 (1986)]
  - These data used to constrain the kaon RMS radius: $r_K = 0.58 \pm 0.04$ fm

Can “kaon cloud” of the proton be used in the same way as the pion to extract kaon form factor via $p(e,e'K^+)\Lambda$?

- Need to quantify the role of the kaon pole
**Kaon pole process in kaon electroproduction**

\[ W = 2.2 \text{ GeV}, Q^2 = 1.6 \text{ GeV}^2 \]

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### At large \( t \):
- **Unseparated** data: pion \( t \)-dependence is steeper than for kaons
  

- Due to experimental constraints most of existing kaon data fall into this category

Clearly, separated low-\( t \) data are needed in the deep inelastic regime

### At small \( t \):
- Kaon pole is *expected* to be strong enough to produce a maximum in \( \sigma_L \)
  
  [Kroll/Goloskokov EPJ A47 (2011), 112]

JLab 12 GeV will provide data to verify role of the kaon pole experimentally
JLab 6 GeV: $F_{K^+}$ extractions from kaon electroproduction data

- Analyze data with same techniques as used for pion analysis and extract $F_{K^+}$
  - L/T separation
  - Extract form factor using the VGL Regge model

- The $-t$ dependence of $K^+$ longitudinal cross section near $Q^2=1$ GeV$^2$ from experiment E93-018
  - Preliminary data analysis shows maybe some pole-like behavior
  - Data analysis ongoing – expect final results in a few months

![Graph showing $Q^2 = 1.00$ GeV$^2$, $W = 1.85$ GeV](image)

[Preliminary analysis](Analysis by Marco Carmignotto)
Kaon Transverse Charge Distribution

- Kaon space-like data sparse - evaluate transverse density based on a dispersion representation of the form factor
  
  \[ F_k(t) = \frac{1}{\pi} \int_0^\infty dt' \frac{\text{Im} F_k(t')}{t'-t+i\epsilon} \]

  - Dispersion relation uses \textit{time-like data}

  - Low \( t \) dominates except for very small values of \( b \) – use model for high \( t \) including recent data from CLEO

  \[ \rho(b) = \frac{1}{2\pi} \int_0^\infty dt K_0(\sqrt{t b}) \frac{\text{Im} F_k(t)}{\pi} \]

- Analytic continuation to spacelike region and studies of uncertainties ongoing

- [N. Mecholsky et al., 16+]
- [T. Pedlar et al., PRL 95 (2005), 261803]
- [K. Seth et al., PRL 110 (2013), 022002]
- [New analysis: N. Mecholsky, J. Meija-Ott, M. Carmignotto, TH, I. Pegg, L. Resca, 16+]
Based on a dispersion representation of the form factors

Pion

\[ \int_0^{\infty} \rho_{\pi}(b) \, db \approx 2 \]

Kaon

\[ \rho(b) = \frac{1}{2\pi} \int_{4m_k^2}^{\infty} dt \, K_0(\sqrt{t} \, b) \frac{\text{Im} F_K(t)}{\pi} \]

Perhaps pion and kaon transverse densities conform with expectation as the kaon is a heavier quark system.
JLab12: $F_\pi$ measurements

- CEBAF 10.9 GeV electron beam and SHMS small angle capability and controlled systematics are essential for extending precision measurements to higher $Q^2$

- The JLab 12 GeV $\pi^+$ experiments were optimized to extract $F_\pi$ up to highest possible $Q^2$ value
  - **E12-06-101**: determine $F_\pi$ up to $Q^2=6$ GeV$^2$ in a dedicated experiment
    - Require $t_{\min}<0.2$ GeV$^2$ and $\Delta\varepsilon>0.25$ for L/T separation
    
    *E12-06-101 spokespersons: G. Huber, D. Gaskell*

  - **E12-07-105**: probe conditions for factorization of deep exclusive measurements in $\pi^+$ data to highest possible $Q^2 \approx 9$ GeV$^2$ with SHMS/HMS
    - Potential to extract $F_\pi$ to the highest $Q^2 \approx 9$ GeV$^2$ achievable at Jlab 12 GeV
    
    *E12-07-105 spokespersons: T. Horn, G. Huber*
JLab12: $F_\pi$ kinematic reach

Measurement at $Q^2=8.5$ GeV$^2$ and $t_{\text{min}} \sim 0.5$ GeV$^2$

- Reliable $F_\pi$ extractions from existing data to the highest possible $Q^2$
- Validation of $F_\pi$ extraction at highest $Q^2$

Projected precision using $R=\sigma_\perp/\sigma_\parallel$ from VR model and assumes pole dominance – uncertainties are very sensitive to that value

JLab 12 GeV experiments have the potential to access the hard scattering scaling regime quantitatively for the first time – may also provide info on log corrections.

- These results would also have implications for nucleon structure interpretation.

E12-09-011: primary goal L/T separated kaon cross sections to investigate hard-soft factorization and non-pole contributions

E12-09-011 spokespersons: T. Horn, G. Huber, P. Markowitz

- scheduled to run in 2017/18

- Possible kaon form factor extraction to highest possible $Q^2$ value achievable at JLab
  - Extraction like in the pion case by studying the model dependence at small $t$
  - Comparative extractions of $F_\pi$ at small and larger $t$ show only modest model dependence, where larger $t$ data lie at a similar distance from pole as kaon data

Transition to Deep Exclusive Meson Electroproduction

- In the limit of small $-t$, meson production can be described by the $t$-channel meson exchange (pole term)
  - Spatial distribution described by form factor

- At sufficiently high $Q^2$, the process should be understandable in terms of the “handbag” diagram – can be verified experimentally
  - The non-perturbative (soft) physics is represented by the GPDs
    - Shown to factorize from QCD perturbative processes for longitudinal photons [Collins, Frankfurt, Strikman, 1997]
JLab 12 GeV: Relative L/T contribution to the meson cross section

Important for nucleon structure studies


- Data from JLab 6 GeV demonstrated the technique of measuring the $Q^2$ dependence of L/T separated cross sections at fixed $x/t$
  

- Separated cross sections over a large range in $Q^2$ are essential for:
  
  - testing factorization required for studies of transverse spatial structure
  - understanding dynamical effects in both $Q^2$ and $-t$ kinematics
  - interpretation of non-perturbative contributions in experimentally accessible kinematics

JLab 12 GeV provides separated (Hall C only) data up to $Q^2 \sim 10$ GeV$^2$ and 5 GeV$^2$ for $\pi$ (E12-07-105) and $K$ (E12-09-011), respectively

- $Q^2$ dependence of $\sigma_L$ relevant towards an interpretation in a GPD-based framework
Transverse Contributions may allow for probing a new set of GPDs

Recent data suggest that transversely polarized photons play an important role in charged and neutral pion electroproduction

- Model predictions based on handbag in good agreement with data

For pion and kaon production the relative contribution of longitudinal and transverse photons in JLab 12 GeV kinematics this has to be verified

- A large transverse cross section in meson production may allow for accessing helicity flip GPDs

JLab 12 GeV will provide relative $\sigma_L$ and $\sigma_T$ contributions to the $\pi^0$ cross section up $Q^2 \sim 6\text{ GeV}^2$

- Exclusive $\pi^0$ data may also be helpful for constraining non-pole contributions in $F_\pi$ extraction

Goloskokov, Kroll, EPJ C65, 137 (2010); EPJ A45, 112 (2011)
[Ahmad, Goldstein, Liuti, PRD 79 (2009)]
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

- Meson form factor measurements in the space-like region at $Q^2 \sim 0.3$ GeV$^2$
  - In general, require a model to extract the form factor at physical meson mass – experimental validation of the extraction is essential
  - $K^+$ requires experimental verification of pole dominance in $\sigma_L$
  - $\pi^+$ form factor: reliable measurements up to $Q^2=2.45$ GeV$^2$ from JLab 6 GeV

- 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 ($\sim 9$ and $\sim 6$ GeV$^2$)
  - Kaon experiment scheduled to run in 2017/18
  - 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 – in progress…