KaonLT: LT Separated Kaon Production Cross Sections and Form Factor

Spokespersons: Tanja Horn (CUA), Garth Huber (U. Regina), Pete Markowitz (FIU)

Graduate Students: Ryan Ambrose (U. Regina, M.Sc. 2018), Vijay Kumar (U. Regina), Mireille Muhoza (CUA), Richard Trotta (CUA)

Hall C Winter Meeting
Newport News, VA, 28-29 January 2019
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]
Meson 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. The kaon is the next simplest system containing strangeness.

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

- Recent advances and future prospects in experiments
  - Dramatically improved precision in $F_\pi$ measurements
    - 12 GeV JLab data have the potential to quantitatively reveal hard QCD's signatures
    - EIC data have the potential to quantitatively reveal DCSB emergent mass generation

---

**Notes:**

**Graph:**
- Off-shell pion = on-shell pion
- Off-shell meson = On-shell meson for $t<0.6$ GeV$^2$ ($\nu=30$) for pions and $t<0.9$ GeV$^2$ ($\nu_s=3$) for kaons
At sufficiently high $Q^2$, the process should be understandable in terms of the “handbag” diagram – can be verified experimentally

- Spatial distribution described by form factor

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

- The non-perturbative (soft) physics is represented by the GPDs
  - Shown to factorize from QCD perturbative processes for longitudinal photons \[\text{[Collins, Frankfurt, Strikman, 1997]}\]
The 3D Nucleon Structure

Generalized Parton and Transverse Momentum Distributions are essential for our understanding of internal hadron structure and the dynamics that bind the most basic elements of Nuclear Physics.

- **TMDs**
  - Confined motion in a nucleon (semi-inclusive DIS)

- **GPDs**
  - Spatial imaging (exclusive DIS)

- Requires
  - High luminosity
  - Polarized beams and targets

Major new capability with JLab12
QCD Factorization - Results from 6 GeV JLab

- Data demonstrate the technique of measuring the $Q^2$ dependence of L/T separated cross sections at fixed $x/t$ to test QCD Factorization (or perhaps, a precocious description)
  - Consistent with expected factorization, but small lever arm and relatively large uncertainties

Separated cross sections over a large range in $Q^2$ are essential for:
  - Testing factorization and understanding dynamical effects in both $Q^2$ and $-t$ kinematics
  - Interpretation of non-perturbative contributions in experimentally accessible kinematics


[π⁺]


Here, compare with P. Kroll’s GPD model \((\text{circles}=\sigma_L, \text{diamonds}=\sigma_T)\)

- Solid symbols are data
  - \(\sigma_L\) is comparable to \(\sigma_T\) at \(Q^2=2.4\ \text{GeV}^2\)

- Open symbols model calculations
  - Model overpredicts \(\sigma_T\)
  - Model underpredicts \(\sigma_L\)

- Separated cross section data over a large range in \(Q^2\) are essential for:
  - Testing factorization and understanding dynamical effects in both \(Q^2\) and \(-t\) kinematics
  - Interpretation of non-perturbative contributions in experimentally accessible kinematics
Reaction mechanism in systems containing strangeness: the $K^+$ Form Factor

- Similar to $\pi^+$ form factor, elastic $K^+$ scattering from electrons used to measure charged kaon for factor at low $Q^2$  
  \[\text{[Amendolia et al, PLB 178, 435 (1986)]}\]

- Can “kaon cloud” of the proton be used in the same way as the pion to extract kaon form factor via $p(e,e'K^+)_L$? – need to quantify the role of the kaon pole

- Unseparated data: pion $t$-dependence is steeper at low $t$ than for kaons  

- However, the kaon pole is expected to be strong enough to produce a maximum in $\sigma_L$  
  \[\text{[Kroll/Goloskokov EPJ A47 (2011), 112]}\]

JLab12 GeV essential for measurements at low $t$, which would allow for interpretation of the kaon pole contribution
Recent developments: when comparing the hard QCD prediction with a valence-quark DA of a form appropriate to the scale accessible in experiments, magnitude is in better agreement with the data.

- Differs from hard QCD calculation evaluated with asymptotic valence-quark Distribution Amplitude (DA)

  \[ L.\ Chang,\ et\ al.,\ PRL\ 111\ (2013)\ 141802;\ PRL\ 110\ (2013)\ 1322001 \]

  - Trend consistent with time like meson form factor data up to \( Q^2 = 18 \text{ GeV}^2 \)  

  \[ \text{Seth et al, PRL 110 (2013) 022002} \]

- Recent developments: when comparing the hard QCD prediction with a valence-quark DA of a form appropriate to the scale accessible in experiments, magnitude is in better agreement with the data.

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

  \[ F.\ Gao\ et\ al.,\ Phys.\ Rev.\ D 96\ (2017)\ no. 3,\ 034024 \]
**E12-09-011 (KaonLT) Goals**

Measure the separated cross section of $K^+$ production above the resonance region
- Separated cross sections: $L$, $T$, $LT$, $TT$ over a wide range of $Q^2$, $t$-dependence

- *The $Q^2$ dependence will allow studying the scaling behavior of the separated cross sections*
  - 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

- *The $t$-dependence allows for detailed studies of the reaction mechanism*
  - Contributes to understanding of the non-pole contributions, which should reduce the model dependence in interpreting the data
  - Bonus: if warranted by data, extract the kaon form factor
KaonLT Sample Projections

- **E12-09-011**: Separated L/T/LT/TT cross section over a wide range of $Q^2$ and $t$

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

**JLab 12 GeV Kaon Program features:**

- 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

Approved for 40 PAC days and scheduled to run in 2018/19

<table>
<thead>
<tr>
<th>$x$</th>
<th>$Q^2$ (GeV$^2$)</th>
<th>$W$ (GeV)</th>
<th>$-t$ (GeV/c)$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1-0.2</td>
<td>0.5-3.0</td>
<td>2.5-3.1</td>
<td>0.06-0.2</td>
</tr>
<tr>
<td>0.25</td>
<td>1.7-3.5</td>
<td>2.5-3.4</td>
<td>0.2</td>
</tr>
<tr>
<td>0.40</td>
<td>3.0-5.5</td>
<td>2.3-3.0</td>
<td>0.5</td>
</tr>
</tbody>
</table>

[blue points from M. Carmignotto, PhD thesis (2017)]
KaonLT: Projections for $F_{K^+}(Q^2)$ Measurements

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

- Possible $K^+$ form factor extraction to highest possible $Q^2$ 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
    - larger $t$ data lie at a similar distance from pole as kaon data

**Possible extractions from 2018/19 run**
Kinematic Coverage

- Measure the separated cross sections at varying $-t$ and $x_B$

- Measure separated cross sections for the $p(e,e'K^+)\Lambda(\Sigma^0)$ reaction at two fixed values of $-t$ and $x_B$
  - $Q^2$ coverage is a factor of 2-3 larger compared to 6 GeV at much smaller $-t$

<table>
<thead>
<tr>
<th>$x$</th>
<th>$Q^2$ (GeV$^2$)</th>
<th>$W$ (GeV)</th>
<th>$-t$ (GeV/c$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1-0.2</td>
<td>0.4-3.0</td>
<td>2.5-3.1</td>
<td>0.06-0.2</td>
</tr>
<tr>
<td>0.25</td>
<td>1.7-3.5</td>
<td>2.5-3.4</td>
<td>0.2</td>
</tr>
<tr>
<td>0.40</td>
<td>3.0-5.5</td>
<td>2.3-3.0</td>
<td>0.5</td>
</tr>
</tbody>
</table>

$Q^2=3.0$ GeV$^2$ was optimized to be used for both $t$-channel and $Q^{-n}$ scaling tests.
Experimental Constraints

- Hall C: $k_e = 3.8, 4.9, 6.4, 8.5, 9.4, 10.6$ GeV

- SHMS for kaon 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

<table>
<thead>
<tr>
<th>$n$</th>
<th>$\pi_{thr}$ (GeV/c)</th>
<th>$K_{thr}$ (GeV/c)</th>
<th>$P_{thr}$ (GeV/c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.030</td>
<td>0.57</td>
<td>2.00</td>
<td>3.80</td>
</tr>
<tr>
<td>1.020</td>
<td>0.67</td>
<td>2.46</td>
<td>4.67</td>
</tr>
<tr>
<td>1.015</td>
<td>0.81</td>
<td>2.84</td>
<td>5.40</td>
</tr>
<tr>
<td>1.011</td>
<td>0.94</td>
<td>3.32</td>
<td>6.31</td>
</tr>
</tbody>
</table>
Both spectrometers at 15 degrees here - go to even smaller angles for KaonLT…
Some issues with opening and small angle settings at beginning of run, but SHMS at 6.01° and HMS at 12.7° on 12/17/18

Work of many people…
Dedicated equipment: Aerogel Cherenkov detector in SHMS

- 5 successful tray exchanges since Fall 2018
- Aerogel performance as expected
- SP-15 tray requires some fixing before next use

Analysis by V. Berdnikov
KaonLT Event Selection

- Isolate Exclusive Final States through missing mass
  \[ M_X = \sqrt{(E_{det} - E_{init})^2 - (p_{det} - p_{init})^2} \]

- Coincidence measurement between kaons in SHMS and electrons in HMS
  - simultaneous studies of \( K\Lambda \) and \( K\Sigma^0 \) channels…and a few others…

- Kaon pole dominance tests through
  \[ \frac{\sigma_L(\gamma^*p \to K^+\Sigma^0)}{\sigma_L(\gamma^*p \to K^+\Lambda)} \]
  - Should be similar to ratio of coupling constants \( g^2_{pK\Lambda}/g^2_{pK\Sigma} \) if t-channel exchange dominates

Online data

Plots from: R. Ambrose, S. Kay, R. Trotta

Kaon Missing mass with Cuts (Random Subtracted)

<table>
<thead>
<tr>
<th>( M_X ) (GeV)</th>
<th>Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.8</td>
<td>1000</td>
</tr>
<tr>
<td>0.9</td>
<td>2000</td>
</tr>
<tr>
<td>1.0</td>
<td>3000</td>
</tr>
<tr>
<td>1.1</td>
<td>4000</td>
</tr>
<tr>
<td>1.2</td>
<td>5000</td>
</tr>
<tr>
<td>1.3</td>
<td>6000</td>
</tr>
<tr>
<td>1.4</td>
<td>7000</td>
</tr>
<tr>
<td>1.5</td>
<td>8000</td>
</tr>
<tr>
<td>1.6</td>
<td>9000</td>
</tr>
<tr>
<td>1.7</td>
<td>10000</td>
</tr>
<tr>
<td>1.8</td>
<td>11000</td>
</tr>
</tbody>
</table>

Entries: 200230
Mean: 1.135
Std Dev: 0.2054
**L/T Separation Example**

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

**Physics cross section**

- Three SHMS angles for azimuthal (\(\phi\)) coverage to determine the interference terms (LT, TT)
- Two beam energies (\(\varepsilon\)) to separate longitudinal (L) from transverse (T) cross section
- Careful evaluation of the systematic uncertainties is important due to the \(1/\varepsilon\) amplification in the \(\sigma_L\) extraction
  - spectrometer acceptance, kinematics, efficiencies…

Plots from: R. Ambrose, S. Kay, R. Trotta
Data Analysis – tracking

- Results are largely independent of target

- At a given ¾ rate, the HMS tracking efficiency is ~4% higher than that of the SHMS

- HMS tracking efficiency is mostly independent of kinematic setting – not the case for the SHMS

- SHMS tracking efficiency extrapolates to ~95% at 0 KHz – hadron tracking efficiency low by 4-6%

*From hcllog 3625806 – analysis based on tracking efficiencies in KaonLT report files*
Data Analysis – Luminosity scans

From Kaon_LT log [3645294] and [3645391]

Most up to date plots (Carbon)

\[ Y = \frac{N \times PS}{Q \times \varepsilon \times cpuLT} \]

N = number of reconstructed events passing cuts on calo, cer, and SHMS aerogel
PS = prescale
cpuLT calculated separately for HMS and SHMS
\( \varepsilon \) = tracking efficiency (HMS=electron, SHMS=hadron)
Interesting Physics in the other channels

- Large difference in L/T ratio between $p(e,e'\pi^+)n$ and $p(e,e'\pi^+)^0$ final states – G. Huber

  **KaonLT: $Q^2=0.50$ GeV$^2$**

- Large increase in neutron missing mass at high epsilon is evidence of the pion-pole process at low $Q^2$ and small $-t$ – suggests $\sigma_L >> \sigma_T$

- $^0$ exclusive longitudinal cross section expected to be at best $\sigma_L \sim \sigma_T$
Physics Insight: Beam Single Spin Asymmetry

Analysis by S. Wood – see also his talk in the Monday session

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

Additional term if beam polarized

\[
h \frac{d\sigma_{LT}}{dt} \sin \phi
\]

Measure

\[
A(\phi) = \frac{\sigma^+(\phi) - \sigma^-(\phi)}{\sigma^+(\phi) + \sigma^-(\phi)}
\]

Pion Asymmetry

<table>
<thead>
<tr>
<th>A, π</th>
<th>Entries</th>
<th>Mean</th>
<th>Std Dev</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>25</td>
<td>-18.5</td>
<td>16.54</td>
</tr>
</tbody>
</table>

Kaon Asymmetry

<table>
<thead>
<tr>
<th>A, K</th>
<th>Entries</th>
<th>Mean</th>
<th>Std Dev</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>25</td>
<td>-1.114</td>
<td>0.421</td>
</tr>
</tbody>
</table>
KaonLT Current Status

KaonLT experiment – status of completion

<table>
<thead>
<tr>
<th>Setting</th>
<th>Low $\varepsilon$ data</th>
<th>High $\varepsilon$ data</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q^2=0.50$</td>
<td>✔️</td>
<td>✔️</td>
</tr>
<tr>
<td>$W=2.40$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$Q^2=2.1$</td>
<td>❌</td>
<td>✔️</td>
</tr>
<tr>
<td>$W=2.95$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$Q^2=3.0$</td>
<td>❌</td>
<td>✔️</td>
</tr>
<tr>
<td>$W=2.32$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$Q^2=3.0$</td>
<td>❌</td>
<td>✔️</td>
</tr>
<tr>
<td>$W=3.14$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$Q^2=4.4$</td>
<td>❌</td>
<td>✔️</td>
</tr>
<tr>
<td>$W=2.74$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$Q^2=5.5$</td>
<td>❌</td>
<td>✔️</td>
</tr>
<tr>
<td>$W=3.02$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Experiment is ~60% done
  - Accelerator difficulties delayed the start of the experiment by ~5 weeks - most low $\varepsilon$ settings had to be cancelled and are now rescheduled for March/April 2019
  - Additional difficulties with reaching desired beam currents and stability, in particular during Sept-Oct part of the run

- Some KaonLT requirements for March/April Run:
  - Small angle beam pipe
  - Aerogel $n=1.011$ tray
  - Prefer no NGC installed

From RC report 11 Oct. 2018 – beam current
Summary and Outlook

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

- About 60% of data were taken in fall 2018 – almost all at high epsilon.
  - For physics goal (L/T separations) require both, low and high $\varepsilon$ data.

- Remaining kinematic settings scheduled to run in March/April 2019 – standard beam energies: 6.4 and 8.5 GeV.
  - Requires small angle beam pipe and has all the other challenges from last fall.

- Initial data analysis ongoing.

Thanks to the Hall A/C team for excellent support!