Update on KaonLT Experiment

Richard Trotta, Tanja Horn, Garth Huber, Pete Markowitz, Stephen Kay, Vijay Kumar, Vladimir Berdnikov, Ali Usman, and the KaonLT collaboration
L/T separated data for verifying reaction mechanism

- Jlab 6 GeV data demonstrated the technique of measuring the $Q^2$ dependence of L/T separated cross sections at fixed $x/t$ to test QCD Factorization
  - Consistent with expected scaling of $\sigma_L$ to leading order $Q^{-6}$ but with 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
  - Interpreting non-perturbative contributions in experimentally accessible kinematics

Meson Form Factors

- Pion and kaon form factors are of special interest in hadron structure studies
  - Pion - lightest QCD quark system and crucial in understanding dynamic generation of mass
  - Kaon - next simplest system containing strangeness

- Clearest case for studying transition from non-perturbative to perturbative regions

- Jlab 6 GeV data showed FF differs from hard QCD calculation
  - Evaluated with asymptotic valence-quark Distribution Amplitude (DA), but large uncertainties

- 12 GeV FF extraction data require:
  - measurements over a range of $t$, which allow for interpretation of kaon pole contribution

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

- At larger $Q^2$, $F_{\pi^+}^2$ 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 $\sigma_L$
  - In the Born term model, $F_{\pi^+}^2$ appears as

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

- 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

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

- Three SHMS angles for azimuthal (φ) coverage to determine the interference terms (LT, TT)
- Using the two beam energies (ε) to separate longitudinal (L) from transverse (T) cross section

Fit using measured ε and φ dependence
Review E12-09-011 (KaonLT) Goals

- $Q^2$ 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

- $t$-dependence allows for detailed studies of the reaction mechanism
  - Contributes to understanding of the non-pole contributions, which should reduce the model dependence
  - Bonus: if warranted by data, extract the kaon form factor
Kaon LT - Data Collected

- The $p(e, e'K^+)^\Lambda,\Sigma^0$ experiment ran in Hall C at Jefferson Lab over the fall 2018 and spring 2019.

<table>
<thead>
<tr>
<th>E (GeV)</th>
<th>$Q^2$ (GeV$^2$)</th>
<th>W (GeV)</th>
<th>x</th>
<th>$\varepsilon_{\text{high}}/\varepsilon_{\text{low}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.6/8.2</td>
<td>5.5</td>
<td>3.02</td>
<td>0.40</td>
<td>0.53/0.18</td>
</tr>
<tr>
<td>10.6/8.2</td>
<td>4.4</td>
<td>2.74</td>
<td>0.40</td>
<td>0.72/0.48</td>
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<tr>
<td>10.6/8.2</td>
<td>3.0</td>
<td>3.14</td>
<td>0.25</td>
<td>0.67/0.39</td>
</tr>
<tr>
<td>10.6/6.2</td>
<td>3.0</td>
<td>2.32</td>
<td>0.40</td>
<td>0.88/0.57</td>
</tr>
<tr>
<td>10.6/6.2</td>
<td>2.115</td>
<td>2.95</td>
<td>0.21</td>
<td>0.79/0.25</td>
</tr>
<tr>
<td>4.9/3.8</td>
<td>0.5</td>
<td>2.40</td>
<td>0.09</td>
<td>0.70/0.45</td>
</tr>
</tbody>
</table>
Experimental Details

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

- SHMS for kaon detection:
  - angles, 6 – 30 deg
  - momenta, 2.7 – 6.8 GeV/c

- HMS for electron detection:
  - angles, 10.7 – 31.7 deg
  - momenta, 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

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<table>
<thead>
<tr>
<th>$n$</th>
<th>$\pi_{\text{thr}}$ (GeV/c)</th>
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<th>$P_{\text{thr}}$ (GeV/c)</th>
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<td>1.015</td>
<td>0.81</td>
<td>2.84</td>
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</tr>
<tr>
<td>1.011</td>
<td>0.94</td>
<td>3.32</td>
<td>6.31</td>
</tr>
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</table>
Analysis Phases

1. **Calibrations**
   - Calorimeter, aerogel, HG cer, HMS cer, DC, Quartz plan of hodo
   - Assure we are replaying to optimize our physics settings

2. **Efficiencies and offsets**
   - Luminosity, elastics, Heeps, etc.
   - *Current Phase*

3. **First iteration of cross section**
   - Bring everything together

4. **Fine tune**
   - Fine tune values to minimize systematics

5. **Repeat previous step**
   - Repeat until acceptable cross sections are reached

6. **Possible attempt at form factor extraction**
   - Fit the data to a model and iterate
Phase 1: Timing Windows

- Applying cuts should be done only once reference time cuts are properly chosen.

- TDC coincidence spectra are the outputs from the L1ACC pre-triggers. The cuts are applied to the raw TDC spectra first.

- Remove all cuts to the raw spectra to see the entire raw spectrum including background.

- Then subtract the background surrounding the peaks in order to clean the spectrum up a bit.
Phase 1: Detector Calibrations

- The online calibrations of the HMS cherenkov, SHMS HGCer, aerogel, and HODO were determined to be satisfactory for our current analysis.
- Future calibrations will be completed on run by run basis.
Phase 1: Drift Chamber Calibrations

- Calibrating the chambers in each spectrometer is identical.

- Performance of the drift chambers is very sensitive to the gas mix within the chamber.
  - This gas mix is in turn dependent upon environmental conditions

- Purpose of the drift chamber calibration is to find the correct parameters to convert the recorded drift times to drift distances for each wire

- For the KaonLT and PionLT experiments, it was decided that a new calibration would be produced for every experimental shift
  - roughly every 8 hours
Phase 1: Calorimeter Calibrations

- Purpose of the calibration is to correctly convert the detected ADC signal from the calorimeter into an equivalent energy.

- Calibration script utilises electron events to perform the calibration.

- Many iterations were performed for all adequate runs

- There were tiny wiggles that can be seen in most runs
  - Vardan and others are aware. This is an ongoing issue.
Phase 2.1: Importance of Luminosity Runs

Careful evaluations of the systematic uncertainties is important due to the $1/\varepsilon$ amplification in the $\sigma_L$ extraction.

<table>
<thead>
<tr>
<th>Singles</th>
<th>$E$ (GeV)</th>
<th>$Q^2$ (GeV$^2$)</th>
<th>$W$ (GeV)</th>
<th>$x$</th>
<th>Target</th>
<th>Current (uA)</th>
<th>$\varepsilon_{\text{high}}$</th>
<th>$\varepsilon_{\text{low}}$</th>
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<tbody>
<tr>
<td></td>
<td>10.6</td>
<td>5.5</td>
<td>3.02</td>
<td>0.40</td>
<td>LH2,C</td>
<td>5,15,30,45,50,55</td>
<td>0.53</td>
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<tr>
<td></td>
<td>10.6</td>
<td>3.0</td>
<td>3.14</td>
<td>0.25</td>
<td>LH2,C</td>
<td>50,70</td>
<td>0.67</td>
<td></td>
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<tr>
<td></td>
<td>6.2</td>
<td>3.0</td>
<td>2.32</td>
<td>0.40</td>
<td>LH2,C</td>
<td>5,15,30,50,65,70</td>
<td>0.57</td>
<td></td>
</tr>
</tbody>
</table>

Spectrometer acceptance, kinematics, and efficiencies are the primary contributors.
Phase 2.1: Importance of Luminosity Runs

<table>
<thead>
<tr>
<th>COIN</th>
<th>E (GeV)</th>
<th>Q² (GeV²)</th>
<th>W (GeV)</th>
<th>x</th>
<th>Target</th>
<th>Current (uA)</th>
<th>ε high</th>
<th>ε low</th>
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<tbody>
<tr>
<td></td>
<td>10.6</td>
<td>5.5</td>
<td>3.02</td>
<td>0.40</td>
<td>LH²,C</td>
<td>5,15,30,45,50,55</td>
<td>0.53</td>
<td></td>
</tr>
<tr>
<td></td>
<td>8.2</td>
<td>5.5</td>
<td>3.02</td>
<td>0.40</td>
<td>LH²,C</td>
<td>10,25,40,45,60</td>
<td>0.18</td>
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</tr>
<tr>
<td></td>
<td>8.2</td>
<td>4.4</td>
<td>2.74</td>
<td>0.40</td>
<td>LH²,C</td>
<td>5,15,30,45,50,65</td>
<td>0.48</td>
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<tr>
<td></td>
<td>10.6</td>
<td>3.0</td>
<td>3.14</td>
<td>0.25</td>
<td>LH²,C</td>
<td>50,65,70</td>
<td>0.67</td>
<td></td>
</tr>
</tbody>
</table>

- Singles: 17 runs
- COIN: 50 runs (set singles+coin)
- Plus PionLT runs!
Previous luminosity/tracking analysis

- Singles luminosity scans has been previously looked out with online data

- Relative yield has been reduced to ~2% spread for carbon target

- Tracking efficiencies are a big contributor
  - At a given ¾ rate, 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%

Analysis by D. Mack and R. Trotta
Phase 2.1: HG Cer Challenges

- A hole in the HG Cer will allow unwanted pions and accidentals
- An in-depth analysis will be required for proper efficiency determination
- This hole is already causing visible issues

Stephen Kay analysis
https://logbooks.jlab.org/entry/3676623
## Phase 2.2: Heep Runs

<table>
<thead>
<tr>
<th>$E$ (GeV)</th>
<th>-$P_{SHMS}$ (GeV)</th>
<th>-$P_{HMS}$ (GeV)</th>
<th>Type</th>
<th>Target</th>
<th>Current (uA)</th>
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<tbody>
<tr>
<td>10.6</td>
<td>6.30-8.04</td>
<td>5.32-6.59</td>
<td>Single+ COIN</td>
<td>LH2</td>
<td>10,15,30,35,40</td>
</tr>
<tr>
<td>8.2</td>
<td>4.35-5.75</td>
<td>4.35-5.75</td>
<td>Single+ COIN</td>
<td>LH2</td>
<td>65,70</td>
</tr>
<tr>
<td>6.2</td>
<td>3.28-3.94</td>
<td>2.94-3.71</td>
<td>Single+ COIN</td>
<td>LH2</td>
<td>25,50,65,70</td>
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<tr>
<td>4.9</td>
<td>2.58-4.64</td>
<td>2.58-4.37</td>
<td>Single+ COIN</td>
<td>LH2</td>
<td>10,35,70</td>
</tr>
<tr>
<td>3.9</td>
<td>2.48-3.01</td>
<td>2.03-3.01</td>
<td>Single+ COIN</td>
<td>LH2</td>
<td>50</td>
</tr>
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</table>
Conclusion

● E12-09-011 ran Fall 2018, Spring 2019
  ○ Also includes PionLT data from Summer 2019

● Currently in the second phase of analysis

● The calibrations are complete for all detectors

● Studies of efficiencies from luminosity are the immediate future
  ○ Nailing down our efficiencies is critical in diminishing our uncertainties for eventual cross section extraction
  ○ The hole in the HGCer will be a unique challenge for us to overcome which we look forward to figuring out.

● Acceptances and Heep studies will be the focus once this is complete
Extra Slides
Phase 2: PID Efficiencies
L/T Separation Example

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

- \( \sigma_L \) is isolated using the Rosenbluth separation technique
- Measure the cross section at two beam energies and fixed \( W, Q^2, -t \)
- Simultaneous fit using measured azimuthal angle (\( \phi \)) 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
- Must have magnetic spectrometers for such precision cross section measurements
  - This is only possible in Hall C at JLab

\[ \sigma_L \text{ will give us } F_{K^+}^2 \]

SHMS small angle operation

- Some issues with opening and small angle settings at beginning of run
  - SHMS at 6.01°
  - HMS at 12.7°

[12/17/18]

Work of many people...
Aerogel Cherenkov detector in SHMS

- ~15 successful tray exchanges since Fall 2018
- Aerogel performance as expected
- Trays require some optimization before next use - prevent damage from crane operation
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

\[ \frac{\sigma_L(\gamma^* p \rightarrow K^+ \Sigma^0)}{\sigma_L(\gamma^* p \rightarrow K^+ \Lambda)} \]

  - Should be similar to ratio of coupling constants \( g^2_{pK\Sigma}/g^2_{pK\Lambda} \) in t-channel
Interesting Physics in the other channels

- Large difference in L/T ratio between $p(e,e'\pi^+)n$ and $p(e,e'\pi^+)^0\Delta$ final states – G. Huber
  hclog #3640187

- Large increase in neutron missing mass peak at high epsilon is evidence of the pion-pole process at low $Q^2$ and small $-t$, which suggests $\sigma_L >> \sigma_T$
- $^0\Delta$ exclusive longitudinal cross section expected to be at best $\sigma_L \sim \sigma_T$

Plots by R. Ambrose, S. Kay, R. Trotta
Comparison of high and low $\varepsilon$ [$Q^2=3.0$, $W=2.32$, $x=0.40$]

- [10.6 Gev (high $\varepsilon$), 6.2 Gev (low $\varepsilon$)]
- Left ($\theta_{\text{high}}=21.18, \theta_{\text{low}}=16.28$)
Comparison of high and low $\varepsilon$ [$Q^2=3.0$, $W=2.32$, $x=0.40$]

- [10.6 Gev (high $\varepsilon$), 6.2 Gev (low $\varepsilon$)]
- Left ($\theta_{\text{high}}=21.18, \theta_{\text{low}}=16.28$)

10.6 GeV (high $\varepsilon$)

![Graph of Kaon Missing mass with Cuts (Random Subtracted) for 10.6 GeV (high $\varepsilon$)]

- Pion leakthrough

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6.2 GeV (low $\varepsilon$)

![Graph of Kaon Missing mass with Cuts (Random Subtracted) for 6.2 GeV (low $\varepsilon$)]

- Pion leakthrough

Events: 9248

Events: 2696
Comparison of high and low $\varepsilon$ [$Q^2=3.0$, $W=3.14$, $x=0.25$]

- [10.6 Gev (high $\varepsilon$), 8.2 Gev (low $\varepsilon$)]
- Center ($\theta_{\text{high}}=9.42, \theta_{\text{low}}=6.89$)

10.6 GeV (high $\varepsilon$)

8.2 GeV (low $\varepsilon$)
Comparison of high and low $\varepsilon$ [$Q^2 = 3.0$, $W = 3.14$, $x = 0.25$]

- [10.6 GeV (high $\varepsilon$), 8.2 GeV (low $\varepsilon$)]
- Center ($\theta_{\text{high}} = 9.42, \theta_{\text{low}} = 6.89$)

10.6 GeV (high $\varepsilon$)

8.2 GeV (low $\varepsilon$)
Comparison of high and low $\varepsilon$ [$Q^2=3.0$, $W=3.14$, $x=0.25$]

- [10.6 GeV (high $\varepsilon$)]
- Right ($\theta_{\text{high}}=6.65$)

10.6 GeV (high $\varepsilon$)
Comparison of high and low $\varepsilon$ [$Q^2=0.5$, $W=2.40$, $x=0.09$]

- [4.9 GeV (high $\varepsilon$), 3.8 GeV (low $\varepsilon$)]
- Center ($\theta_{\text{high}}=8.86, \theta_{\text{low}}=6.79$)

4.9 GeV (high $\varepsilon$)

3.8 GeV (low $\varepsilon$)
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

*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 $F^2_\pi$ 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