E12-19-006 Physics Analysis Possibilities

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We have an amazing amount of data from the Pion-LT experiment over a wide kinematic range. These are likely to remain the world's highest quality L/T-separated data set for deep exclusive $\pi^{\pm}$ production for many decades, and will be of significant importance for the interpretation of unseparated exclusive $\pi^{\pm}$ data from the EIC.

Names are placed next to some items. However, many opportunities are still available for leading one of the analyses and publishing the results. These could be great projects for new students, postdoctoral researchers, or early-career faculty/research staff. If interested, please contact any of the spokespersons: Garth Huber, Tanja Horn, Dave Gaskell.

1 Introduction

Fig. 1 summarizes the PionLT kinematics. It is a "highly optimized" run plan, where most $W - Q^2$ points have multiple uses in different physics studies [see Table 1].

As a general analysis philosophy, we want efficient data analysis with various cross checks to verify validity and establish systematic uncertainties. Preferably, this means we want at least a few points to be analyzed by more than one person.

Ultimately, what this means is that we have to distinguish between which $W - Q^2$ points are assigned to a given person for analysis, and what physics topics they ultimately write up for thesis and publications. The best arrangement we can think of is to assign people to analyze different sets of points according to the columns in Fig. 1, and then as the different physics studies are written up, we combine together the different L/T-separated results by different people to make the larger physics conclusions. If you have a better idea, please let us know!

In the next sections, we summarize the different physics studies we would like to do with the PionLT data, and enumerate the different papers we hope to write in the next few years. Your ideas on to optimize the timely analysis of the data, and how best to divide up the necessary studies, are most welcome.

2 Physics from π^+ channels

2.1 Q^{-n} scaling tests at x=0.31, 0.39, 0.55

The upgraded JLab facilities enable a new representation of the proton's inner structure to be probed. In the past, our knowledge has been limited to one-dimensional spatial densities (form factors) and longitudinal momentum densities (parton distributions). These cannot fully describe the proton's inner structure, as it will, for instance, be impossible to describe orbital angular momentum, an important aspect for nucleon spin, for which we need to be able to

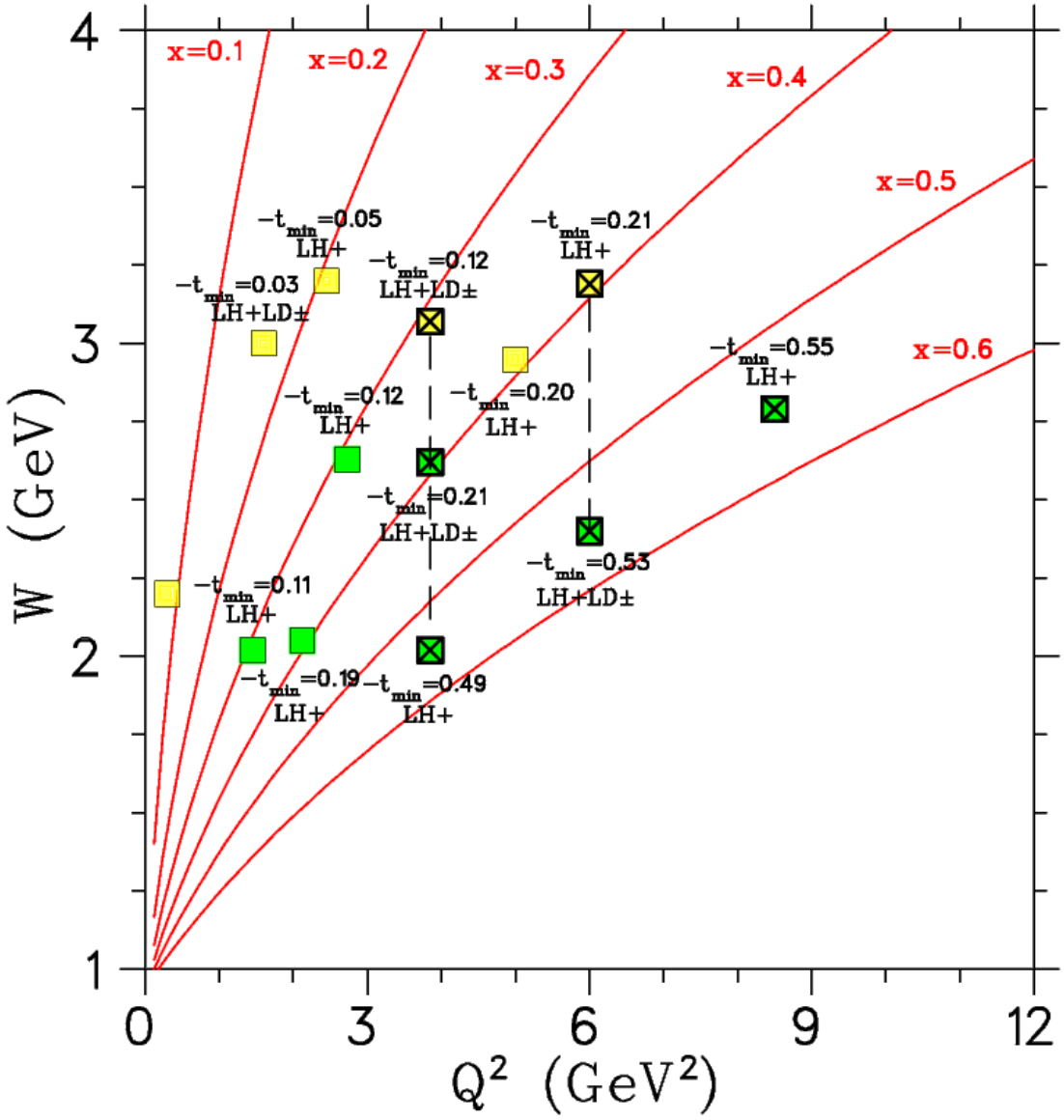

Figure 1: W versus Q^2 settings for the "F_π study" (yellow squares) and the "Pion Scaling" study (green squares). The points instrumental in the higher Q^2 F_π extraction are indicated with 'X'. The red lines indicate fixed x values from 0.1 to 0.6. The dashed vertical lines denote scans in t at fixed Q^2, which will be used to evaluate the dependence of the F_π extraction on t. The text indicates the $-t_{min}$ values and target/SHMS polarities used for each point.

Table 1: List of which studies each $W - Q^2$ point is part of. In addition to the studies listed in the table, it should be understood that points are also part of studies 2.5, 3 and 4. Regarding the π^-/π^+ studies, Jacob Murphy will do an initial check of unseparated ratios, but the final analysis, including L/T-separations, is not yet assigned. MJ=Muhammad Junaid; NH=Nathan Heinrich.

Setting	**Studies used in**	**Person**
Q^2 =1.45, W =2.02, $-t_{min}$=0.11	$x = 0.31$ scaling 2.1	MJ & NH
Q^2 =1.6, W=3.08, $-t_{min}$ =0.03	F_π studies 2.2, 2.4; π^-/π^+ 2.3	MJ
Q^2 =2.12, W=2.05, $-t_{min}$=0.19	$x = 0.39$ scaling 2.1	NH
Q^2=2.45, W=3.20, $-t_{min}$=0.05	F_π studies 2.2, 2.4	MJ
Q^2=2.73, W=2.63, $-t_{min}$=0.12	$x = 0.31$ scaling 2.1	NH
Q^2=3.85, W=2.02, $-t_{min}$=0.49	$x = 0.55$ scaling 2.1; F_π study 2.2	MJ & NH
Q^2=3.85, W=2.62, $-t_{min}$=0.21	$x = 0.39$ scaling 2.1; F_π study 2.2; π^-/π^+ 2.3	LH2: MJ; LD2: open
Q^2=3.85, W=3.07, $-t_{min}$=0.12	$x = 0.31$ scaling 2.1; F_π studies 2.2, 2.4; π^-/π^+ 2.3	LH2: NH; LD2: open
Q^2=5.0, W=2.95, $-t_{min}$=0.20	$x = 0.39$ scaling 2.1; F_π study 2.4	MJ & NH
Q^2=6.0, W=2.40, $-t_{min}$=0.53	$x = 0.55$ scaling 2.1; F_π study 2.2; π^-/π^+ 2.3	LH2: NH; LD2: open
Q^2=6.0, W=3.19, $-t_{min}$=0.21	$x = 0.39$ scaling 2.1; F_π studies 2.2, 2.4	MJ
Q^2=8.5, W=2.79, $-t_{min}$=0.55	$x = 0.55$ scaling 2.1; F_π study 2.4	MJ & NH

describe the correlation between the momentum and spatial coordinates. A three-dimensional description of the nucleon has been developed through the Generalized Parton Distributions (GPDs) and the Transverse Momentum-Dependent parton distributions (TMDs). GPDs can be viewed as spatial densities at different values of the longitudinal momentum of the quark, and due to the space-momentum correlation information encoded in the GPDs, can link through the so-called Ji sum rule to a parton's angular momentum. The TMDs are functions of both the longitudinal and transverse momentum of partons, and they offer a momentum tomography of the nucleon complementary to the spatial tomography of GPDs.

The scaling study is vitally important for establishing the dominance of the hard-soft factorization "handbag diagram", which is a pre-requisite for the extraction of GPD information from deep exclusive meson production reactions. Thus, the results are highly anticipated by the community as the studies have wide impact upon the JLab program. The longitudinal and transverse cross sections, truly separated from experiment, also contain essential information for studying GPDs. This has become even more important in recent years, and was acknowledged in 2019, when the JLab PAC stated *It has been shown only in recent years that the transverse part of the pion electroproduction is not to be regarded as a "nuisance" but could rather serve as a valuable source of information on transversity GPDs* and reaffirmed the high scientific importance of this study.

The scaling test involves the analysis of $p(e, e'\pi^+)n$ L/T ratios for the following points:

x=0.31	$Q^2 = 1.45$, $W = 2.02$	$Q^2 = 2.73$, $W = 2.63$	$Q^2 = 3.85$, $W = 3.07$
x=0.39	$Q^2 = 2.12$, $W = 2.05$	$Q^2 = 3.85$, $W = 2.62$	
	$Q^2 = 5.0$, $W = 2.95$	$Q^2 = 6.0$, $W = 3.19$	
x=0.55	$Q^2 = 3.85$, $W = 2.02$	$Q^2 = 6.0$, $W = 2.40$	$Q^2 = 8.5$, $W = 2.79$

Note that the low ϵ data for $Q^2 = 1.45$, 2.12 were acquired in Summer 2019.

The scaling tests will be done separately for σ_L and σ_T, at fixed t, x versus Q^2. See Horn et al. PRC **78** (2008) 058201 for the result of a pilot study which motivated this dedicated measurement. The factorization theorem predicts that σ_L scales to leading order as Q^{-6}. If what the theorem predicts is true, then it also follows that σ_T scales differently, with the expectation of Q^{-8} scaling; and $\sigma_L \gg \sigma_T$. Additional rules can be formed for LT and TT scaling.

Although the original idea was simply to do an acceptance-corrected integration over ϕ for the L/T-separation, we have taken sufficient quality data to enable a full L/T/LT/TT-separation for every point. A preliminary study result is possible using a selected consistent t-range for each scaling test, however, for the final result we would expect to extract separated cross sections over the full t-range of the data.

2.2 F_π extraction test: Different distances from the pole at fixed Q^2

In Fπ-2, we did this test at $Q^2 = 1.60$, 2.45, and the extracted form factor values agreed well within errors. See Huber et al. PRC **78** (2008) 045203. Here, we want to do a more extensive test, covering a wider range of $-t_{min}$. This would better establish the t-range for reliable pion form factor extraction and be vitally imporant for future high Q^2 form factor studies with JLab-20+ and EIC.

This involves the analysis of $p(e, e'\pi^+)n$ L/T/LT/TT ratios and pion form factor extraction for the following points:

Q^2=1.60	$W = 3.08$, $-t_{min} = 0.026$	Fπ-2: $W = 2.22$, $-t_{min} = 0.079$
	Fπ-1: $W = 1.95$, $-t_{min} = 0.135$	
Q^2=2.45	$W = 3.20$, $-t_{min} = 0.048$	Fπ-2: $W = 2.22$, $-t_{min} = 0.145$
Q^2=3.85	$W = 3.07$, $-t_{min} = 0.120$	$W = 2.62$, $-t_{min} = 0.208$
	$W = 2.02$, $-t_{min} = 0.487$	
Q^2=6.00	$W = 3.19$, $-t_{min} = 0.214$	$W = 2.40$, $-t_{min} = 0.531$

The Fπ-1,2 results are listed to indicate that they should be used in the overall study to gain wider dynamic range. It is not expected that the student will in any way re-analyze those data.

Because of its importance for establishing the validity of our pion form factor results, this study would have to be included in any full length papers we write on the F_π results from this experiment, just as was done in Huber et al., and at least a preliminary version of it would have to be performed before we publish a PRL on the form factor results (see Sec 2.6 for the list of possible papers).

2.3 π^-/π^+ ratios: L/T/LT/TT-separation of LD2 data

The $\sigma_L(\pi^-)/\sigma_L(\pi^+)$ ratio is intended as a second pion pole dominance test, as this ratio will unexpectedly deviate from unity if non-pole backgrounds are significant. This is a particularly important test for the $Q^2 = 8.5$ pion form factor extraction, which is at a higher $-t_{min}$. The $\sigma_T(\pi^-)/\sigma_T(\pi^+)$ ratio is a second way to probe the hard-soft factorization mechanism needed for GPD studies in deep exclusive meson production, as this ratio should converge to the square of the u/d quark charge ratio (i.e. 1/4) in the hard scattering limit. s-channel helicity conservation provides a confirmation of the factorization test, as the $\sigma_{TT}(\pi^-)/\sigma_T(\pi^-)$, $\sigma_{TT}(\pi^+)/\sigma_T(\pi^+)$ ratios should vanish in the hard-scattering limit. See Huber et al., PRC **91** (2015) 015202.

This study involves the analysis of L/T/LT/TT ratios for the following LD2 points:

Q^2=1.60	$W = 3.08$, $-t_{min} = 0.026$	Fπ-1: $W = 1.95$, $-t_{min} = 0.135$
Q^2=2.45	Fπ=2: $W = 2.22$, $-t_{min} = 0.145$	
Q^2=3.85	$W = 3.07$, $-t_{min} = 0.120$	Q^2=3.85, $W = 2.62$, $-t_{min} = 0.208$
Q^2=6.00	$W = 2.40$, $-t_{min} = 0.531$	

The Fπ-1,2 results are listed to indicate that they should be used in the overall study to gain wider dynamic range. It is not expected that the student will in any way re-analyze those data.

The full results from this study would be published in its own papers, but due to the importance of the π^-/π^+ ratios for confirming the role of the pion pole mechanism at the higher $-t_{min}$ of the $Q^2 = 8.5$ GeV^2 data set, at least a preliminary version of this study would have to be completed before we release any $Q^2 = 8.5$ pion form factor results.

Preliminary study of π^-/π^+ unseparated yield ratios: Jacob Murphy, including various rate and trigger blocking corrections, but not involving L/T-separations, since he has a graduation time deadline coming up. Final π^-/π^+ analysis, including L/T-separations, is not yet assigned.

2.4 F_π over a wide Q^2 range

This involves the extraction of the pion form factor from L/T/LT/TT-separated LH2 data at:

Q^2=1.60 $W = 3.08$, $-t_{min} = 0.026$	Also part of study 2.2
Q^2=2.45 $W = 3.20$, $-t_{min} = 0.048$	Also part of study 2.2
Q^2=3.85 $W = 3.07$, $-t_{min} = 0.120$	Also part of studies 2.1, 2.2
Q^2=5.00 $W = 2.95$, $-t_{min} = 0.201$	Also part of study 2.1
Q^2=6.00 $W = 3.19$, $-t_{min} = 0.214$	Also part of studies 2.1, 2.2
Q^2=8.50 $W = 2.79$, $-t_{min} = 0.55$	Also part of study 2.1

Given the need to really understand our systematic uncertainties before releasing such highly anticipated results, along with having at least preliminary results from tests 2.2, 2.3, along with the form factor values, this is not likely to be the first result we publish. As described in Sec 1, it seems highly likely that our publication will include data points from more than one student's thesis, as it draws in so many other aspects of our kinematic coverage.

2.5 $\mathbf{p}(e,e'\pi^+)n$ beam helicity asymmetry

This could be an extension of beam helicity analysis of π^+ and K^+ data from Kaon-LT. The results could be released in a short stand-alone paper, and might be one of our earliest published results since many experimental systematic uncertainties cancel in the asymmetry ratios.

Preliminary study: Alicia Postuma is looking at the π^+ asymmetries from KaonLT, as a "warm-up" analysis to get familiar with the Hall C setup. Analysis of beam helicity asymmetries from PionLT is not yet assigned.

2.6 Possible papers resulting from the $\pi^\pm$ channel analyses

I count up to 9 papers resulting from the 2021-22 pion data:

1. PRC on our experimental method, data analysis, and L/T-separation method
   Given the common experimental approach for all of the above studies, it would be really useful to publish a detailed paper on our methods fairly early on. I see this as a successor to the Blok et al. PRC **78** (2008) 045202 paper. It does not have to be our first paper, but preferably it is also not our last. It would be jointly written by all of the graduate students contributing to the analysis.

   Note that my writing of a very detailed Technical Report [HallC-DocDB-773] dramatically sped up the publication of the papers, and I recommend that for all of these studies you do the same.

2,3. Q^{-n} scaling results
   Depending on the results, I could see this as most likely two papers, a PRL giving the "headline results", followed a year later by a PRC with all of the details. Both papers would be written by the lead student on the scaling analysis (Nathan).

4,5. F_π results up to Q^2=6.0 GeV^2
   Following our previous path, this would almost certainly be two papers, the first being a PRL along the tradition of Volmer et al., PRL **86** (2001) 1713 and Horn et al., PRL **97** (2006) 192001, followed a year later by a full length paper giving also the extraction test 2.2 similar to Huber et al., PRC **78** (2008) 045203. Junaid.

6. F_π at 8.5 GeV^2
   I am least certain on this point, but given the tie-in to the π^-/π^+ tests versus $-t_{min}$, I see this at the moment as a stand-alone PRL. Of course that could change, if fast progress is made on these studies.

7,8. π^-/π^+ results
   The most likely scenario is two papers, a PRL followed a year later by a PRC giving full

details. See Huber et al., PRL **112** (2014) 182501 and Huber et al., PRC **91** (2015) 015202 for examples. Not yet assigned.

9. π beam spin asymmetry results
   This would most likely be a PRC Rapid Communication. It's not yet known whether this would also include results from KaonLT, or if that would be a separate paper coming out sooner. Partially assigned.

3 Physics from p channels

1. **$\mathbf{p}(e,e'p)\omega$ L/T/LT/TT separated cross sections for $\mathbf{Q^2 > 2}$ GeV^2**

   This is a study of hard-soft factorization in backward angle DEMP reactions, which can be described by an extension of t-channel (forward angle) collinear factorization to the u-channel (backward angle) regime. Here, the produced ω is emitted 180 degrees opposite to the virtual-photon momentum (at large momentum transfer), and is reconstructed in missing mass, while the energetic (recoil) proton is detected in the SHMS. While the forward-angle handbag diagram physics is encapsulated in reaction-independent Generalized Parton Distributions (GPDs), the backward-angle handbag diagram physics is encapsuled in Transition Distribution Amplitudes (TDAs).

   This ties nicely into study 2.1, as the Q^{-n} dependence at fixed x is an important probe of the beginning of the TDA factorization regime. Many of the motivations and expected results are similar to the GPD factorization study. If the backward angle factorization regime is reached, it is expected that $\sigma_T \propto Q^{-8}$ and $\sigma_T \gg \sigma_L$. The obtained separated cross sections would be compared to a variety of Regge and TDA-based models. It would be particularly helpful to combine these studies with the high statistics data from KaonLT at $x = 0.40$. For an example paper, see W. Li et al., PRL **123** (2019) 182501.

   Not yet assigned.

2. **$\mathbf{p}(e,e'p)\omega$ beam helicity asymmetry and comparison to TDA calculations**

   TDA-based models can make predictions for the beam spin asymmetries and we have been encouraged by B. Pire to analyze these data.

   Not yet assigned. Possibly this could be included as part of other beam asymmetry, or other u-channel studies.

3. **$\mathbf{p}(e,e'p)\phi/p(e,e'p)\omega$ ratios**

   While there is a lot of theoretical interest in publishing ratios of L/T/LT/TT separated cross sections for these two channels, this really depends on how many such events we have acquired. The KaonLT data have much higher statistics, but over a more limited kinematic range.

   Not yet assigned. Since it's a ratio, it might be less prone to systematic errors than the ω L/T-separation analysis.

4. **Possible papers resulting from the p channel analyses**

   Most likely, the $p(e,e'p)M$ results, where M is a reconstructed backward-angle meson, from both KaonLT and PionLT will be combined into a common set of papers. This would give the benefit of higher statistics from the KaonLT data set, and broader kinematic range of the PionLT data set.

I could see 3-4 papers resulting from these studies:

1,2. Similar to Sec 2.1, a PRL giving "headline results" on the Q^{-n} scaling analysis, followed a year later by a PRC with all of the details.

3. Possible paper on ω beam helicity results.

4. Possible paper on ϕ/ω L/T-separated ratios, presented in a manner similar to the π^-/π^+ ratios discussed in Sec 2.3.

4 Physics from K^+ channels

In principle, we have $p(e, e'K^+)\Lambda, \Sigma^0$ data from PionLT. While the kinematic range will be broader, the statistics will be poorer than from KaonLT. It remains to be seen how much effort should be put into the analysis of these data. However, if statistics are sufficient, in particular the Q^{-n} scaling studies and Σ^0/Λ ratios over a broad kinematic range would be of considerable interest, and have wide applicability to any JLab 20+ GeV program, and the EIC.

Of necessity, any results from this channel would come after the KaonLT $x = 0.40$ data set is published.

Depending on what is found, this could motivate a successor proposal to KaonLT, covering K^+ scaling studies over a larger kinematic range, led by one of the students or PDFs. Also note that not all of the KaonLT data have been acquired yet, with the approved $x = 0.25$ scaling study data not yet completed.

Preliminary study: A survey of Σ^0 channel statistics for the various settings, and the identification of which settings merit further study, would make a nice Honours or summer student project. Not yet assigned.