Deep Exclusive $p(e,e'\pi^+)n$ Studies at Jefferson Lab
Deep Exclusive Meson Production (DEMP)

• In Deep Exclusive Scattering, all final state particles are either detected or inferred via missing mass.

• Experiments are demanding, since exclusive cross sections are small, and multiple particles must be detected in coincidence with sufficient resolution to ensure exclusivity.

Deep Exclusive Scattering allows some simplifications at sufficiently high $Q^2$, where the Soft-Hard factorization theorem applies.

[Collins, Frankfurt, Strikman, 1997]
Two Motivations for Studying DEMP

1) Determine the Pion Form Factor at $Q^2 > 0.3$ GeV$^2$:

- Indirectly measure $F_\pi$ using the “pion cloud” of the proton via $p(e,e'\pi^+)n$

$$|p\rangle = |p\rangle_0 + |n\pi^+\rangle + \ldots$$

- Pion pole pole process dominates $\sigma_L$ in forward kinematics.

2) Study the Hard-Soft Factorization Regime:

Implications for GPD studies, as they can only be extracted from hard exclusive data where hard-soft factorization applies.

- Investigate if the $p(e,e'\pi^+)n$ cross section at fixed $x$ behaves according to the $Q^{-n}$ expectations of hard QCD.

$$\frac{\sigma_T[n(e,e'\pi^-)p]}{\sigma_T[p(e,e'\pi^+)n]}$$

- Form ratios where soft contributions may cancel, yielding insight to factorization at modest $Q^2$. 

Garth Huber, huberg@uregina.ca
Meson Form Factors

Simple $q\bar{q}$ valence structure of mesons presents the ideal testing ground for our understanding of bound quark systems.

In quantum field theory, the form factor is the overlap integral:

$$F_\pi (Q^2) = \int \phi_\pi^* (p) \phi_\pi (p+q) dp$$

The meson wave function can be separated into $\phi_\pi^{\text{soft}}$ with only low momentum contributions ($k<k_0$) and a hard tail $\phi_\pi^{\text{hard}}$.

While $\phi_\pi^{\text{hard}}$ can be treated in pQCD, $\phi_\pi^{\text{soft}}$ cannot.

**From a theoretical standpoint, the study of the $Q^2$-dependence of the form factor focuses on finding a description for the hard and soft contributions of the meson wave-function.**
Charged Pion Form Factor

- The pion is attractive as a QCD laboratory:
  - Simple, 2 quark system

- Electromagnetic form factor can be calculated exactly at very large momentum transfer (small distances).
- For moderate $Q^2$, it remains a theoretical challenge.
  - “the positronium atom of QCD”

Downside for experimentalists:
- No “free” pion targets.
- Measurements at large momentum transfer difficult.
At large $Q^2$, perturbative QCD (pQCD) can be used

$$F_\pi(Q^2) = \frac{4\pi C_F \alpha_s(Q^2)}{Q^2} \sum_{n=0}^{\infty} a_n \left( \log \left( \frac{Q^2}{\Lambda^2} \right) \right)^{-\gamma_n} \left[ 1 + O(\alpha_s(Q^2), \frac{m}{Q}) \right]$$

at asymptotically high $Q^2$, only the hardest portion of the wave function remains

$$\phi_\pi(x) \rightarrow \frac{3 f_\pi}{Q^2 \sqrt{n_c}} x (1 - x)$$

and $F_\pi$ takes the very simple form

$$F_\pi(Q^2) \rightarrow \frac{16\pi \alpha_s(Q^2) f_\pi^2}{Q^2}$$

where $f_\pi = 92.4$ MeV is the $\pi^+ \rightarrow \mu^+\nu$ decay constant.

Pion Form Factor at Finite $Q^2$

- At finite momentum transfer, higher order terms contribute
- Calculation of higher order, “hard” (short distance) processes difficult, but tractable

There are “soft” (long distance) contributions that cannot be calculated in the perturbative expansion
- **Understanding the interplay of these hard and soft processes is a key goal**
Measurement of $\pi^+$ Form Factor – Low $Q^2$

At low $Q^2$, $F_{\pi}$ can be measured model-independently via high energy elastic $\pi^-$ scattering from atomic electrons in Hydrogen

- CERN SPS used 300 GeV pions to measure form factor up to $Q^2 = 0.25$ GeV$^2$ [Amendolia et al, NPB277, 168 (1986)]

- Data used to extract pion charge radius $r_{\pi} = 0.657 \pm 0.012$ fm

Maximum accessible $Q^2$ roughly proportional to pion beam energy

$Q^2 = 1$ GeV$^2$ requires 1 TeV pion beam
At larger $Q^2$, $F_{\pi}$ must be measured indirectly using the “pion cloud” of the proton via pion electroproduction $p(e,e'\pi^+)n$

\[ |p\rangle = |p\rangle_0 + |n\pi^+\rangle + \ldots \]

- At small $-t$, the pion pole process dominates the longitudinal cross section, $\sigma_L$
- In Born term model, $F_{\pi}^2$ appears as,

\[
\frac{d\sigma_L}{dt} \propto \frac{-tQ^2}{(t-m_{\pi}^2)} g_{\pi NN}^2(t) F_{\pi}^2(Q^2, t)
\]

Drawbacks of this technique
1. Isolating $\sigma_L$ experimentally challenging
2. Theoretical uncertainty in form factor extraction.
$F_\pi$ Program at JLab Hall C

- 2 $F_\pi$ experiments have been carried out at JLab
  (spokespersons H. Blok, G. Huber, D. Mack)
  - $F_\pi$ -1: $Q^2=0.6-1.6$ GeV$^2$ with 4 GeV beam, 1997-2001.
\[ 2\pi \frac{d^2\sigma}{dtd\phi} = \varepsilon \frac{d\sigma_L}{dt} + \frac{d\sigma_T}{dt} + \sqrt{2\varepsilon (\varepsilon + 1)} \frac{d\sigma_{LT}}{dt} \cos\phi + \varepsilon \frac{d\sigma_{TT}}{dt} \cos 2\phi \]

**Virtual-photon polarization:**

\[ \varepsilon = \left( 1 + 2 \left( \frac{E_e - E_{e'}}{Q^2} \right)^2 + Q^2 \tan^2 \frac{\theta_{e'}}{2} \right)^{-1} \]

- **L-T separation required to separate** \( \sigma_L \) **from** \( \sigma_T \).
- **Need to take data at smallest available** \(-t\), **so** \( \sigma_L \) **has maximum contribution from the** \( \pi^+ \) **pole.**
Measuring $d\sigma_L/dt$

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

- Rosenbluth separation required to isolate $\sigma_L$
  - Measure cross section at fixed ($W,Q^2,-t$) at 2 beam energies
  - Simultaneous fit at 2 $\varepsilon$ values to determine $\sigma_L$, $\sigma_T$, and interference terms

- Control of point-to-point systematic uncertainties crucial due to $1/\Delta\varepsilon$ error amplification in $\sigma_L$
- Careful attention must be paid to spectrometer acceptance, kinematics, efficiencies, ...

Horn et al, PRL97, 192001, 2006
\(p(e,e'\pi^+)n\) data are obtained some distance from the \(t=m_{\pi}^2\) pole.

→ "Chew Low" extrapolation method requires knowing the analytic dependence of \(d\sigma_L/dt\) through the unphysical region.

Extrapolation method last used in 1972 by Devnish & Lyth

- Very large systematic uncertainties.
- Failed to produce reliable result.

→ Different polynomial fits equally likely in physical region gave divergent form factor values when extrapolated to \(t=m_{\pi}^2\).

The Chew-Low Method was subsequently abandoned.
Chew-Low Method Check with PseudoData

Plot \[ F^2 = \frac{N}{4\hbar c \left( \pi \right) g_{\pi NN}^2} \frac{(t - m^2_{\pi})^2}{-Q^2 m^2_{\pi}} \frac{d\sigma_L}{dt} \] \textbf{vs.} \(-t\).

- Pure pole cross section gives straight line through origin with value \( F^2_{\pi}(Q^2) \) at pole.

- Other contributions introduce non-linearities since don’t contain \((t-m^2_{\pi})^2\) factor, but don’t influence \(F^2\) value at pole.
  → Do not know if behavior of \(F^2\) with \(-t\) is linear, quadratic, or higher order.

**All fits missed the input \(F_{\pi}\).**
  → no consistent trend on order of polynomial best able to reproduce input value
    (6-15% deviation, \(Q^2=0.6-2.45\) GeV²).

- Experimental \(\sigma_L\) data have only 4-6 \(t\)-bins and statistical and systematic uncertainties of 5-10%.
  → Extrapolation with real data will be even more uncertain.

For details see: G.M. Huber et al., PRC 78(2008)045203.
Only reliable approach is to use a model incorporating the $\pi^+$ production mechanism and the `spectator’ nucleon to extract $F_\pi$ from $\sigma_L$.

- JLab $F_\pi$ experiments use the Vanderhaeghen-Guidal-Laget (VGL) Regge model as it has proven to give a reliable description of $\sigma_L$ across a wide kinematic domain. 
  [Vanderhaeghen, Guidal, Laget, PRC 57(1998)1454]

- More models would allow a better understanding of the model dependence of the $F_\pi$ result. There has been considerable recent interest:

Our philosophy remains to publish our experimentally measured $d\sigma_L/dt$, so that updated values of $F_\pi(Q^2)$ can be extracted as better models become available.
Extract $F_\pi(Q^2)$ from $\sigma_L$ data via VGL Regge Model

- Feynman propagator $\left(1 \over t - m_\pi^2\right)$ replaced by $\pi$ and $\rho$ Regge propagators.
- Free parameters: $\Lambda_\pi$, $\Lambda_\rho$ (trajectory cutoff).
- At small $-t$, $\sigma_L$ only sensitive to $F_\pi$

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

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

The JLab 6 GeV experiments were limited to $Q^2=2.45$ GeV$^2$ by $-t_{min}<0.2$ GeV$^2$ and $\Delta\varepsilon>0.25$ needed for reliable L/T separation.

Error bars indicate statistical and random (pt-pt) systematic uncertainties in quadrature. Yellow band indicates the correlated (scale) and partly correlated (t-corr) systematic uncertainties.

$\Lambda_\pi^2=0.513, 0.491$ GeV$^2$, $\Lambda_\rho^2=1.7$ GeV$^2$. 
Current Experimental Status

JLab results in a region of $Q^2$ where model calculations begin to diverge.

**Bethe-Salpeter/Dyson-Schwinger:**

  - B-S equation is conventional formalism for relativistic bound states.
  - D-S expansion in terms of dressed quark propagators, consistent w/ confinement.
  - Model parameters fixed from $f_\pi$ and $m_\pi$, then $r_\pi$ and $F_\pi$ predicted.

**Constituent Quark Model:**

- [C-W. Hwang, Phys.Rev.D 64(2001)034001]
  - Relativistic constituent quarks and effective interaction on the light front
  - Consistent treatment of quark spins.
  - Wave function parameters determined from $f_\pi$ and $\pi^0 \rightarrow \gamma\gamma$ decay width, then charge and transition FF's and $\pi^0$ branching ratios predicted.

Dispersion Relation with QCD Constraint:

  - Uses constraints posed by *causality* and *analyticity* to relate the timelike and spacelike domains of the pion form factor on the complex plane.
  - Additional constraints, such as behavior of $F_\pi$ in asymptotic region, imposed.

For details see: G.M. Huber et al., PRC 78(2008)045203.
12 GeV Upgrade

Add new hall

Upgrade magnets and power supplies

Add 5 cryomodules

20 cryomodules

Add arc

20 cryomodules

Add 5 cryomodules

CHL-2

Enhance equipment in existing halls

Accelerator upgrade completed: August 2014

12 GeV Era has begun!
Jefferson Lab 12 GeV Era – Hall C Configuration

Hall C will provide 2 moderate acceptance, magnetic focusing spectrometers:

**High Momentum Spectrometer:**
\[ d\Omega \sim 6 \text{ msr}, \quad P_{\text{max}} = 7 \text{ GeV/c} \]
\[ \Theta = 10.5 \text{ to } 80 \text{ degrees} \]

**Super-HMS:**
\[ d\Omega \sim 4 \text{ msr}, \quad P_{\text{max}} = 11 \text{ GeV/c} \]
\[ \Theta = 5.5 \text{ to } 40 \text{ degrees} \]

- Both spectrometers provide excellent control of systematic uncertainties
- Kinematic reproducibility, well-understood acceptance

**Ideal for:**
- precision cross section measurements and response function separations,
  - in single arm or coincidence,
  - at high luminosity \((>10^{38}/\text{cm}^2\text{sec})\).
Interest in Higher $Q^2$ Measurements

Section 2.1.1: The Quark Structure of Hadrons

- The pion is seen as key to confirm the mechanisms that dynamically generate nearly all of the mass of hadrons and central to the effort to understand hadron structure.
- With such strong theoretical motivation, the study of the pion form factor is one of the flagship goals of the JLab 12-GeV Upgrade.
- The SHMS (in Hall C) will nearly quadruple the momentum transfer over which the pion form factor is known.
- These measurements will probe a broad regime in which the phenomenology of QCD begins to transition from large- to small-distance-scale behavior.

What do we have to do to enable reliable $F_\pi$ measurements at high $Q^2$?
A common criticism of the electroproduction technique is the difficulty to be certain one is measuring the "physical" form factor.

"What is at best measured in electroproduction is the transition amplitude between a mesonic state with an effective space-like mass \( m^2 = t < 0 \) and the physical pion. It is theoretically possible that the off-shell form factor \( F_\pi(Q^2, t) \) is significantly larger than the physical form factor because of its bias towards more point-like \( q\bar{q} \) valence configurations within its Fock state structure."


What tests/studies can we do to give confidence in the result?

- Check consistency of model with data.
- Extract form factor at several values of \(-t_{\text{min}}\) for fixed \( Q^2 \).
- Test that the pole diagram is really the dominant contribution to the reaction mechanism.
- Verify that electroproduction technique yields results consistent with \( \pi\)-e elastic scattering at same \( Q^2 \).
Check of Pion Electroproduction Technique

Directly compare $F_\pi(Q^2)$ values extracted from very low -$t$ electroproduction with the exact values measured in elastic e-$\pi$ scattering.

**METHOD PASSES CHECKS:**

- $Q^2=0.35$ GeV$^2$ data from DESY consistent with limit of elastic scattering data within uncertainties.
  
  *H. Ackermann, et al., NP B137(1978)294*

- A much better check is planned in E12–06–101 by taking $Q^2=0.30$ GeV$^2$ data at 50% lower -$t$ (0.005 GeV$^2$).

E12-06-101 Proposal:
G.M. Huber, D. Gaskell, spokespersons
**F$_\pi$-2 VGL $p(e,e'\pi^+)n$ model check**

- To check whether VGL Regge model properly accounts for:
  - $\pi^+$ production mechanism.
  - spectator nucleon.
  - other off-shell ($t$-dependent) effects.
  - extract $F_{\pi}$ values for each $t$-bin separately, instead of one value from fit to all $t$-bins.

  Error band based on fit to all $t$-bins.

- Deficiencies in model may show up as $t$-dependence in extracted $F_{\pi}(Q^2)$ values.
- Resulting $F_{\pi}$ values are insensitive (<2%) to $t$-bin used.
- Lends confidence in applicability of VGL model to the kinematical regime of the JLab data, and the validity of the extracted $F_{\pi}(Q^2)$ values.

Only statistical and $t$-uncorrelated systematic uncertainties shown.
Possible effect of resonances at $W \approx 1.95$ GeV

- Our earlier $F_\pi$-1 data were obtained when only 4 GeV electron beam was available.
- Measurements limited to $W \approx 1.95$ GeV, which is above the region of most (but not all??) $\sigma_L$ resonances.

We found some anomalies in the fit of the $F_\pi$-1 data by the VGL model

$\rightarrow$ Likely due to contributions from resonances, which are not included in the Regge model

- The deficiency in the VGL fit is reflected in the non-constant $\Lambda_\pi^2$ fit to each $-t$ bin
- Dependence strongest at the low $Q^2$
- At higher $Q^2$, the resonance form factor is expected to reduce resonance contributions

We needed to apply corrections to determine $F_\pi$ from these data

| Expt  | $Q^2$ (GeV/c)$^2$ | $W$ (GeV) | $|t_{\text{min}}|$ (GeV/c)$^2$ | $E_e$ (GeV) |
|-------|------------------|----------|-------------------------------|------------|
| $F_\pi$-1 | 0.6-1.6 | 1.95 | 0.03-0.150 | 2.445-4.045 |
| $F_\pi$-2  | 1.6,2.5 | 2.22 | 0.093,0.189 | 3.779-5.246 |

For details see: G.M. Huber et al., PRC 78(2008)045203.
\( \pi^-/\pi^+ \) data to check \( t \)-channel dominance

- \( \pi^+ \) \( t \)-channel diagram is purely isovector (G-parity conservation).

\[ R_L = \frac{\sigma_L[(e,e'\pi^-)]}{\sigma_L[(e,e'\pi^+)]} = \frac{|A_V - A_S|^2}{|A_V + A_S|^2} \]

- Isoscalar backgrounds (such as \( b_1(1235) \) contributions to \( t \)-channel) will dilute ratio.

- Qualitatively in agreement with our \( F_{\pi^{-}}-1 \) analysis:
  - We found evidence for small additional contribution to \( \sigma_L \) at \( W=1.95 \text{ GeV} \) not taken into account by the VGL model.
  - We found no evidence for this contribution at \( W=2.2 \text{ GeV} \).

Vranckx-Ryckebusch Model:
- VR extend VGL with hard DIS process of virtual photons off nucleons.
  - [PRC 89(2014)025203]

\( R_L = 0.8 \) consistent with \( |A_S/A_V| < 6\% \).
Anticipated E12-06-101 $d\sigma_L/dt$ Data

Achievable errors are limited by $R=\sigma_T/\sigma_L$ ratio and $1/\Delta\varepsilon$ error magnification.
Limits experimental kinematics.

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

$$
\frac{\Delta \sigma_L}{\sigma_L} = \frac{1}{(\varepsilon_1 - \varepsilon_2)} \left( \frac{\Delta \sigma}{\sigma} \right) \sqrt{(R + \varepsilon_1)^2 + (R + \varepsilon_2)^2}
$$

where $R = \frac{\sigma_T}{\sigma_L}$

$$
\frac{\Delta \sigma_T}{\sigma_T} = \frac{1}{(\varepsilon_1 - \varepsilon_2)} \left( \frac{\Delta \sigma}{\sigma} \right) \sqrt{\varepsilon_1^2 \left( 1 + \frac{\varepsilon_2}{R} \right)^2 + \varepsilon_2^2 \left( 1 + \frac{\varepsilon_1}{R} \right)^2}
$$

Note: $\sigma_T < \sigma_L$ at small $-t$

$R=\sigma_T/\sigma_L$ values taken from best available model:

Error Assumptions from PAC proposal:
• 1.3% stat. unc. per un-sep. t-bin
• 1.7% t-correl. & pt-pt syst. unc. which are magnified by $\Delta\varepsilon>0.25$
Extending $F_\pi(Q^2)$ to $Q^2=8.5$ GeV$^2$ in Hall C

- $E_{\text{beam}}=10.9$ GeV and $\Delta\varepsilon>0.25$ with the SHMS+HMS spectrometers allows L/T separations up to $Q^2\approx8.5$ GeV$^2$.

- Note the less favorable $R=\sigma_T/\sigma_L$ predicted by VR model for these kinematics.

- For these $Q^2$, $-t_{\text{min}}>0.5$ GeV$^2$, and the pion pole contributions to $\sigma_L$ will be significantly smaller.

- Will need to understand non-pole background to reliably extract $F_\pi$ from these $\sigma_L$ data.

Assumptions same as E12-06-101:
- 1.3% stat. unc. per un-sep. t-bin
- 1.7% t-correl. & pt-pt syst. unc.
Magnified by $\Delta\varepsilon>0.25$
$R=\sigma_T/\sigma_L$ values from:
Vrancx & Ryckebusch, PRC 89, 025203 (2014)
Extending $F_\pi(Q^2)$ to $Q^2=8.5$ GeV$^2$ in Hall C

- Efficiently combine settings from both $p(e,e'\pi^+)n$ experiments so extra information can be obtained on non-pole backgrounds contributing to $Q^2=8.5$ GeV$^2$.

- Data-driven approach to better ensure a reliable extraction of the pion form factor value from these data.
One way to understand non-pole to $\sigma_L$

**Data–driven approach to better understand non–pole backgrounds at higher $-t$.**

- Exclusive $^2\text{H}(e,e'\pi^+)nn$ and $^2\text{H}(e,e'\pi^-)pp$ L/T-separations.
- $\pi^+$ $t$–channel diagram is purely isovector (G-parity conservation).

$$R_L = \frac{\sigma_L[n(e,e'\pi^-)p]}{\sigma_L[p(e,e'\pi^+)n]} = \frac{|A_V - A_S|^2}{|A_V + A_S|^2}$$

- Isoscalar backgrounds would distort ratio (e.g. $b_1(1235)$ in $t$–channel).

**Significant $R_L$ deviation predicted**

---

**E12-06-101**  $R_L \approx 1.0$ at $-t_{\text{min}}$

<table>
<thead>
<tr>
<th>$Q^2$</th>
<th>$W$</th>
<th>Deviation of data from $R_L=1.0$ could confirm large non-pole contributions estimated by model.</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.50 GeV$^2$</td>
<td>3.10 GeV</td>
<td></td>
</tr>
<tr>
<td>6.0 GeV$^2$</td>
<td>3.20 GeV</td>
<td></td>
</tr>
<tr>
<td>8.3 GeV$^2$</td>
<td>2.77 GeV</td>
<td></td>
</tr>
</tbody>
</table>
Another way to understand non-pole to $\sigma_L$

Test by extracting $F_\pi$ at different distances from pole.
Expt: $F_\pi$-2, $-t_{\text{min}} = 0.093$ GeV$^2$
$W = 2.22$ GeV.
$F_\pi$-1, $-t_{\text{min}} = 0.15$ GeV$^2$
$W = 1.95$ GeV.

$W = 2.22$ point 30% closer to pole.
→ Agreement ~4%.

We plan further tests:

<table>
<thead>
<tr>
<th>$Q^2$ (GeV$^2$)</th>
<th>$-t_{\text{min}}$ (GeV$^2$)</th>
<th>$W$ (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.6</td>
<td>0.029</td>
<td>3.00</td>
</tr>
<tr>
<td>2.45</td>
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<tr>
<td>3.85</td>
<td>0.12, 0.21, 0.49</td>
<td>3.07, 2.62, 2.02</td>
</tr>
<tr>
<td>6.0</td>
<td>0.21, 0.53</td>
<td>3.19, 2.40</td>
</tr>
</tbody>
</table>
JLab 12 GeV upgrade will allow measurement of $F_\pi$ to much higher $Q^2$.

**No other facility worldwide can perform this measurement.**

New overlap points at $Q^2=1.6, 2.45$ will be closer to pole to constrain $-t_{min}$ dependence.

New low $Q^2$ point will provide best comparison of the electroproduction extraction of $F_\pi$ vs elastic $\pi^0 e$ data.

- If the $\pi$-pole contribution to $\sigma_L$ can be cleanly identified, a $\sim$10% measurement of $F_\pi$ at $Q^2=8.5$ GeV$^2$ would require about 6 days of additional beam. $\rightarrow \Delta \varepsilon=0.27$, Expected $R=\sigma_T/\sigma_L=1.7$ at $-t_{min}=0.544$ GeV$^2$. 
GPDs – A Unified View of Hadron Structure

- Elastic form factors
- Parton momentum distributions
- Real Compton Scattering at high t
- Deeply Virtual Compton Scattering
- Deep Exclusive Meson Production

Garth Huber, huber@uregina.ca
Leading Twist GPD Parameterization

- GPDs are universal quantities and reflect nucleon structure independently of the probing reaction.
  - GPDs provide 3D spatial information on the distributions of quarks and gluons in a nucleon.
  - GPDs inter-relate the longitudinal and transverse momentum structure of partons within a fast moving hadron.

- At leading twist-2, four quark chirality conserving GPDs for each quark, gluon type.
- Because quark helicity is conserved in the hard scattering regime, the produced meson acts as a helicity filter.
First moments of GPDs are related to nucleon elastic form factors through model-independent sum rules:

\[
\begin{align*}
\sum_{q} e_q \int_{-1}^{+1} dx \ H^q(x, \xi, t) &= F_1(t) \\
\sum_{q} e_q \int_{-1}^{+1} dx \ E^q(x, \xi, t) &= F_2(t)
\end{align*}
\]

Dirac and Pauli elastic form factors. \(t\) -dependence fairly well known.

Isovector axial form factor. \(t\) –dep. poorly known.

Pseudoscalar form factor. Very poorly known.

\[
\begin{align*}
\sum_{q} e_q \int_{-1}^{+1} dx \ \tilde{H}^q(x, \xi, t) &= G_A(t) \\
\sum_{q} e_q \int_{-1}^{+1} dx \ \tilde{E}^q(x, \xi, t) &= G_P(t)
\end{align*}
\]
Deep Exclusive Meson Production:
- Vector mesons sensitive to spin average $H, E$.
- Pseudoscalar mesons sensitive to spin difference $\tilde{H}, \tilde{E}$.

Deeply Virtual Compton Scattering:
- Sensitive to all four GPDs.

- Need a variety of Hard Exclusive Measurements to disentangle the different GPDs.
GPDs require Hard Exclusive Reactions

- In order to access the physics contained in GPDs, one is restricted to the hard scattering regime.

- **Factorization property of hard reactions:**
  - Hard probe creates a small size $qar{q}$ and gluon configuration,
    - interactions can be described by pQCD.
  - Non-perturbative part describes how hadron reacts to this configuration, or how the probe is transformed into hadrons (parameterized by GPDs).

- Hard Exclusive Meson Electroproduction first shown to be factorizable by Collins, Frankfurt & Strikman [PRD 56(1997)2982].
- Factorization applies when the $\gamma^*$ is longitudinally polarized.
  - corresponds to small size configuration compared to transversely polarized $\gamma^*$. 
We will perform the most detailed study to determine whether or not meson electroproduction can provide information on GPDs.

As it is not known how high $Q^2$ is needed for the factorization theorem to apply, it is necessary to first test that the regime of validity has been reached.

This can be done by comparing the $Q^2$ variation of the cross section against the prediction of Hard QCD.

We will study both $\pi^+$ and $K^+$ electroproduction. Virtually nothing is known concerning QCD factorization when strangeness is in play.
Scaling Experiment Goals

- Measure the $Q^2$ dependence of the $p(e,e'\pi^+)n$, $p(e,e'K^+)\Lambda$, $p(e,e'K^+)^\Sigma$ cross sections at fixed $x_B$ and $-t$ to search for evidence of hard-soft factorization
  - Separate the cross section components: $L$, $T$, $LT$, $TT$
  - Highest $Q^2$ for any $L/T$ separation in $\pi^+,K^+$ electroproduction
  - Can only learn about GPDs if soft-hard factorization applies
  - If transverse contributions are large, the accessible phase space may be limited

- A stringent test is the $Q^2$-dependence of the $p(e,e'\pi^+)n$, $p(e,e'K^+)\Lambda$ cross sections:
  - $\sigma_L$ scales to leading order as $Q^{-6}$.
  - $\sigma_T$ scales as $Q^{-8}$.
  - As $Q^2$ becomes large: $\sigma_L >> \sigma_T$. 

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**p(e,e’π⁺)n Scaling Experiment Overview**

- Measure separated cross sections for the \( p(e,e’\pi^+)n \), \( p(e,e’K^+)\Lambda \), and \( p(e,e’K^+)\Sigma \) reactions at three values of \( x_B \).

- **Q² coverage** is a factor of 3-4 larger compared to 6 GeV.
  - Facilitates tests of the \( Q^2 \) dependence even if L/T is less favorable than predicted.

<table>
<thead>
<tr>
<th>( x )</th>
<th>( Q^2 ) (GeV/c)^2</th>
<th>( W ) (GeV)</th>
<th>-t (GeV/c)^2</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.31</td>
<td>1.5-4.0</td>
<td>2.0-3.1</td>
<td>0.1</td>
</tr>
<tr>
<td>0.40</td>
<td>2.1-5.5</td>
<td>2.0-3.0</td>
<td>0.2</td>
</tr>
<tr>
<td>0.55</td>
<td>4.0-9.1</td>
<td>2.0-2.9</td>
<td>0.5</td>
</tr>
</tbody>
</table>

**Phase space for L/T separations with SHMS+HMS**

- Pion scaling: E12-07-105
- Fπ: E12-06-101

**Kinematics for \( \pi \) measurements**
π⁻/π⁺ Separated Response Function Ratios

- Transverse Ratios tend to ¼ as −t increases:
  → Is this an indication of Nachtmann’s quark charge scaling?
- −t=0.3 GeV² seems too low for this to apply. Might indicate the partial cancellation of soft QCD corrections in the formation of the ratio.

\[ R_T \rightarrow \frac{2Q_d^2}{2Q_u^2} = \frac{1}{4} \]

- Another prediction of quark-parton mechanism is the suppression of σ_{TT}/σ_T due to s-channel helicity conservation.
- Data qualitatively consistent with this, since σ_{TT} decreases more rapidly than σ_T with increasing Q².
Projected $\pi^-/\pi^+$ Data from F$\pi$-12 Experiment

- $^2$H data to determine $R_L$ $\pi^-/\pi^+$ ratio to constrain modeling of non–pole backgrounds in $\sigma_L$, relevant for extraction of pion form factor

- If $R_T$ is $\sim$1/4 at higher $Q^2$ and similar $x_B$, the hypothesis of a quark knockout mechanism will be strengthened.

Predictions of Vrancx-Ryckebusch Regge+DIS Model
[PRC 89(2014)025203]
12 GeV era – Hall C with SHMS and HMS

**SHMS:**
- 11 GeV/c Spectrometer
- Partner of existing 7 GeV/c HMS

**MAGNETIC OPTICS:**
- Point-to-Point QQQD for easy calibration and wide acceptance.
- Horizontal bend magnet allows acceptance at forward angles (5.5°)

**Detector Package:**
- Drift Chambers
- Hodoscopes
- Cerenkovs
- Calorimeter
- All derived from existing HMS/SOS detector designs

**Well-Shielded Detector Enclosure**

**Rigid Support Structure**
- Rapid & Remote Rotation
- Provides Pointing Accuracy & Reproducibility demonstrated in HMS

**SHMS = Super High Momentum Spectrometer**
**HMS = High Momentum Spectrometer**
SHMS Detector System

<table>
<thead>
<tr>
<th>DETECTOR</th>
<th>PURPOSE</th>
<th>NOTES</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1XY, S2XY Hodoscopes</td>
<td>Lowest-level Trigger. Time reference</td>
<td></td>
</tr>
<tr>
<td>Drift Chambers</td>
<td>Momentum Measurement. Tracking.</td>
<td>5mm max. drift 300 micron resolution</td>
</tr>
<tr>
<td>Noble-Gas Cerenkov</td>
<td>Particle ID, Trigger. e⁺/π⁺ at high momentum (replace by vacuum at low p)</td>
<td>Vary Ar/Ne mixture to set index at π⁺ threshold.</td>
</tr>
<tr>
<td>Heavy-Gas Cerenkov</td>
<td>Particle ID, Trigger. π⁺/K⁺ discrimination</td>
<td>C₄F₉O – Vary pressure to set index at K⁺ threshold</td>
</tr>
<tr>
<td>Preshower / Shower Counters</td>
<td>Particle ID, Trigger. Electron tag</td>
<td></td>
</tr>
</tbody>
</table>
SHMS Dipole Progress

- **Coil Progress**
  - Coils Joined Together and Entire Assembly Potted.
  - Coil Machined. Collars Machined.
  - Dipole Coil Collared 17-JUN-2015.
  - Coil sealed within its Helium Vessel.
  - Leak & Pressure tested successfully.
  - Thermal shields fabricated. Fitted around coil.
  - Vacuum Vessel Barrel Section is in Place.

**Images:**
- **NOV-2014: Coil Potting**
- **Collars going on Coil**
- **14-JAN-2016: Coil Insulated and Surrounded by Thermal Screen and Vacuum Vessel Can**
SHMS Q2 & Q3 Progress

- Q2 and Q3 Magnets
  - Coil winding completed.
  - Coils Joined, Spliced, Wrapped & the Assemblies Potted.
  - Coils inserted in their Helium Vessels. Vessels welded closed.
  - All of the Q2 Parts are ready for shipment to SigmaPhi.
    - Waiting on dipole assembly so that floor space is available.
  - Q3 Parts are undergoing QA tests.
SHMS Detector Construction is Complete
SHMS Rear Detector Installation
Hall C Deep Exclusive Mesons Timeline

<table>
<thead>
<tr>
<th>Event</th>
<th>Timeline</th>
</tr>
</thead>
<tbody>
<tr>
<td>SHMS rear detector installation</td>
<td>Feb – Aug, 2015</td>
</tr>
<tr>
<td>SHMS superconducting magnet installation</td>
<td>Until Sept, 2016</td>
</tr>
<tr>
<td>SHMS superconducting magnet testing</td>
<td>Until Sept, 2016</td>
</tr>
<tr>
<td>SHMS front detector installation</td>
<td>July – Aug, 2016</td>
</tr>
<tr>
<td>SHMS commissioning with beam</td>
<td>Dec, 2016</td>
</tr>
<tr>
<td>First physics-quality run in Hall C</td>
<td>Feb – June, 2017</td>
</tr>
</tbody>
</table>

Data Reconstruction Software (hcana)
- Z. Ahmed (PDF), completed

SHMS Detector Checkout & Commissioning
- W. Li (Ph.D.), S. Basnet (M.Sc.), work underway

p(e,e’K+)Λ Kaon Form Factor
- L/T commissioning experiment (2017)

Pion Form Factor and π+ QCD-Scaling Experiments
- Interleaved run-plans (2018 – 2019)