Charged meson production - status and perspectives

Tanja Horn

THE
CATHOLIC UNIVERSITY
of AMERICA

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Meson Reaction Dynamics

• Meson production can be described by the t-channel exchange meson pole term in the limit of small \(-t\) and large \(W\)
  – Pole term is dominated by longitudinally polarized photons
  – Meson form factor describes the spatial distribution

• At sufficiently high \(Q^2\), the process should be understandable in terms of the “handbag” diagram
  – The non-perturbative (soft) physics is represented by the GPDs

• Shown to factorize from QCD perturbative processes for longitudinal photons [Collins, Frankfurt, Strikman, 1997]
GPDs and Meson Form Factors

- Form factors and GPDs are essential to understand the structure of hadrons

- In exclusive reactions we can study both nucleon GPDs and meson form factors
  - shedding light on quark-antiquark interaction in QCD

- But measurements of form factors and GPDs have certain prerequisites:
  - Before we can start looking at form factors, we must make sure that $\sigma_L$ is dominated by the meson pole term at low -$t$
  - Before we can learn about GPDs, we must demonstrate that factorization applies
**Q^2 dependence of σ_L and σ_T**

- Measurements of GPDs are limited to kinematics where *hard-soft factorization* applies.

- A test is the Q^2 dependence of the polarized cross section:
  - σ_L ~ Q^{-6}
  - σ_T ~ Q^{-8}
  - For large Q^2: σ_L >> σ_T

- The QCD scaling prediction is reasonably consistent with recent 6 GeV JLab π^+ σ_L data, *but* σ_T does not follow the scaling expectation.

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**Hall C π^+ production data at 6 GeV**

- Q^2 = 1.4 - 2.2 GeV^2
- Q^2 = 2.7 - 3.9 GeV^2

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**Full understanding of the onset of factorization requires an extension of the kinematic reach**
Pion Form Factor - a similar puzzle?

- $Q^2$ dependence of the pion form factor ($F_\pi$) follows prediction from perturbative QCD
  - Factorization condition seems to hold

- Different magnitudes imply that
  - Factorization condition does not hold
  - Or something else is missing in the calculation

Further information on the pion puzzle through varying the system
Jefferson Lab 12 GeV Upgrade

Add new hall

Upgrade magnets and power supplies

Add 5 cryomodules

20 cryomodules

Add arc

Enhance equipment in existing halls

Hall C

Super High Momentum Spectrometer (SHMS)

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12 GeV pion and kaon experiments

Phase space for L/T separations with SHMS+HMS

- **E12-07-105**: extends the kinematic reach of current data
  - To fully understand the onset of factorization

- **E12-09-011**: provides the first L/T separated kaon data above the resonance region
  - Quasi-model independent comparison of pions and kaons
Factorization Tests in $\pi^+$ Electroproduction

- JLab experiment E12-07-105 [T. Horn et al.] will search for the onset of factorization
- $Q^2$ coverage is 2-3 times larger than at 6 GeV at smaller $t$
- Factorization essential for reliable interpretation of results from the JLab GPD program at both 6 GeV and 12 GeV

Is the partonic description applicable at JLab?
Can we extract GPDs from pion production?
\( \sigma_L \) without explicit L/T?

- If \( \sigma_L \) is small, GPD flavor studies may be limited to focusing spectrometers
  - L/T separations required

- But data suggest that \( \sigma_L \) is larger for \( \pi^- \) than for \( \pi^+ \) production
  - If this holds, one can extract \( \sigma_L \) from unseparated cross sections

\[
\sigma = \sigma_T + \varepsilon \sigma_L \xrightarrow{\sigma_T \rightarrow 0} \varepsilon \sigma_L
\]

E12-07-105 will compare \( \pi^+ \) and \( \pi^- \) production to check possibilities of extracting GPDs without explicit L/T

JLab 6 GeV \( \pi^+ \) data

JLab 6 GeV \( \pi^- \) data
Transverse Contributions: $\pi^+$

- In $\pi^+$ production, $\sigma_T$ is much larger than predicted by the VGL/Regge model [PRL 97:192001 (2006)]

- To understand the reaction mechanism, one should compare with a different yet similar system

Hall C 6 GeV $\pi^+$ data at $W=2.2$ GeV

Transverse Contributions: $K^+$

- For $K^+$ production in the resonance region $\sigma_T$ is also not small at $Q^2=2$ GeV$^2$

- Unfortunately, available kaon data are limited
  - No separated data above the resonance region
  - Limited $W$ and $Q^2$ range
  - Significant uncertainty due to scaling in $x_B$ and $-t$

Kaon cross section: $\sigma_L$ and $\sigma_T$

- Approved experiment E12-09-011 [T. Horn et al.] will provide first L/T separated kaon data above the resonance region
- Onset of factorization
- Understanding of hard exclusive reactions
  - QCD model building
  - Coupling constants

**E12-09-011:** Precision data for $W > 2.5$ GeV
$R = \sigma_L / \sigma_T$: Form Factor Prerequisite

- To reliably extract meson ff, the influence of non-pole $t$-channel contributions must be modest in comparison to pole contributions.

- For kaons, current knowledge of $\sigma_L$ and $\sigma_T$ above the resonance region is insufficient.

\[ R = \frac{\sigma_L}{\sigma_T} : \text{Form Factor Prerequisite} \]

- To reliably extract meson ff, the influence of non-pole $t$-channel contributions must be modest in comparison to pole contributions.

- For kaons, current knowledge of $\sigma_L$ and $\sigma_T$ above the resonance region is insufficient.

- Experiment E12-09-011 will provide a better understanding of the $t$-channel kaon exchange in the amplitude.
F_{\pi, K} - can kaons shed light on the puzzle?

- Compare the observed $Q^2$ dependence and magnitude of $\pi^+$ and $K^+$ form factors
- Will the analogy between pion cross section and form factor also manifest itself for kaons?

Projected uncertainties for kaon experiment at 12 GeV

Is onset of scaling different for kaons than pions?
Kaons and pions together provide quasi model-independent study

Relations between Pole and Non-Pole

• Can be addressed with an experiment comparing $\pi^+$ (pole) with $\pi^0$ (no pole) production

• First step is taken by E12-07-105

• One can also do this in a more strange way [Strikman, Weiss 2008]

Example comparison in a GPD framework
F_{\pi} Backgrounds

- Size of non-pole backgrounds not well known above the resonance region
  - $-t_{\text{min}} < 0.2$ GeV$^2$ constraint limits $Q^2$ reach of $F_{\pi}$ measurements
- A 6 GeV proposal for the measurement of $\pi^0$ longitudinal cross sections to constrain pQCD backgrounds was submitted – can also be done at 12 GeV
- $\pi^+$ and $\pi^0$ cross sections involve different combinations of same GPDs

$$A_{p\pi^+} \sim (\tilde{H}^u - \tilde{H}^d)(e_u + e_d)$$
$$B_{p\pi^+} \sim (\tilde{E}^u - \tilde{E}^d)(e_u + e_d)$$

$$A_{p\pi^0} \sim (e_u \tilde{H}^u - e_d \tilde{H}^d)$$
$$B_{p\pi^0} \sim (e_u \tilde{E}^u - e_d \tilde{E}^d)$$

$\pi^0$ has no pole contribution!
Feasibility ↔ Measurement

• Exclusive meson production adds flavor to quark imaging studies
  – But one needs to test various pre-requisites
  – Demonstrate that, e.g., QCD factorization applies

• What about other exclusive processes like Compton scattering?
  – Factorization easier to achieve
Compton Scattering

\[ \gamma^* + p \rightarrow \gamma^* + p \]

- **Real Compton Scattering**
  - Both photons are real

- **Deeply Virtual Compton Scattering (DVCS)**
  - Outgoing photon is real
  - Simplest and cleanest process probing GPDs

- **Timelike Compton Scattering (TCS)**
  - Incoming photon is real
  - Complementary to DVCS. Allows more reliable GPD extraction, and interesting model comparisons.

- **Double DVCS**
  - Both photons are virtual
  - The general Compton process can provide most information
  - Experimentally challenging
Why TCS in addition to DVCS?

Pros:

- Real part of amplitude can be measured with better systematics
- TCS and DVCS amplitudes are equivalent only to leading order
  - at finite $Q^2$, data on both reduces model dependence of GPD extraction
- TCS asymmetries are easy to compare directly with GPD models
  - Polyakov-Weiss D-term

Cons:

- Cross section smaller than for DVCS
  - enhancement through interference with Bethe-Heitler always needed
- Resonances in timelike final state limit $Q^2$ coverage
Photoproduction of lepton pairs

- TCS cross section is small compared with Bethe-Heitler for all kinematics
  - cannot be measured directly

- The interference term is, however, larger and easy to isolate

- In TCS, the hard scale is given by the virtuality of the final state photon ($Q^2$)
  - experimentally accessed as the invariant mass of the produced lepton pair
TCS-BH Interference

\[ \gamma p \rightarrow p l^+ l^- \]

\( l = e, \mu \)

\[ \frac{d^4\sigma}{dx_b dQ^2 dt d\varphi} \approx |T^{BH}|^2 + 2T^{BH} \cdot \text{Re}(T^{VCS}) + |T^{VCS}|^2 \]

- Under reversal of the lepton charge:
  - Compton and BH amplitudes are even
  - Interference term is odd
  - Observables that change sign project out only the interference term

- Example: azimuthal angular distribution of the lepton pair
The CLAS g12 experiment

- Carried out between March 29 and June 8, 2008.
- Tagged real photons with energies of 3.6 – 5.4 GeV on LH2 target.
- CLAS Cerenkovs and calorimeter allow good pion rejection
  - $10^{-7}$ with two leptons detected, $10^{-4}$ with one lepton detected
- 25 billion two- and three-track events collected (mostly hadron triggers)
- Calibrations are almost ready!

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Production of lepton pairs with quasi-real photons

- Several CLAS data sets with 6 GeV electron beams available
- Circular photon polarization

Analysis of e1-6 and e1f data is underway
At JLab 12 GeV we study the three valence quarks of the nucleon.

The next step is to extend this to the sea of virtual quarks and gluons that surround them, and carry a large fraction of the momentum and spin.
Electron Ion Collider (EIC)

- A next-generation facility aimed at providing unprecedented access to gluon imaging in nucleons and nuclei

  We recommend the allocation of resources to develop accelerator and detector technology necessary to lay the foundation for a polarized Electron-Ion Collider. The EIC would explore the new QCD frontier of strong color fields in nuclei and precisely image the gluons in the proton. [NSAC Long Range Plan 2007]

- Two possible physics goals:
  - QCD at high gluon densities
  - Precision imaging of sea-quarks and gluons to determine spin, flavor, and spatial structure of the nucleon

- Candidates for the EIC are BNL and JLab
# Mapping the Virtual Sea

<table>
<thead>
<tr>
<th>Channel</th>
<th>“diffractive” (vacuum exchange)</th>
<th>“non-diffractive” (quantum number exchange)</th>
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</thead>
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<td><img src="image2.png" alt="Image" /></td>
</tr>
<tr>
<td>Cross section</td>
<td>rises with energy</td>
<td>drops with energy</td>
</tr>
<tr>
<td>Interest</td>
<td>gluon imaging of nucleon</td>
<td>spin/flavor structure of quark GPDs</td>
</tr>
</tbody>
</table>

- $\gamma p, \rho^0 p, J/\psi p, \ldots$
- $\pi^+ p, \pi^0 p, K\Lambda, p^+ n, \ldots$

- Non-singlet quark
Simulations for Detector Design

- Exclusive reactions have the most stringent requirements and drive the detector design
  - Illustrated are $\rho^-$ simulations that I did with summer students in 2008

Summer students (2008): D. Cooper, K. Henderson, B. Pollack, and E. van der Goetz

Summer students (2009): J. Castilow, T. Jones

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Summary

• Meson production data play an important role in our understanding of nucleon structure

• JLab 12 GeV will allow rigorous tests of factorization in meson production
  – Extended kinematic reach and studies of additional systems
  – Essential prerequisite for studies of valence quark spin/flavor/spatial distributions

• Beyond JLab 12 GeV: meson production at an electron-ion collider allows for imaging of sea quarks and gluons
  – Consistent description of kinematic dependences of all channels?
Backup
Probing GPDs through Compton scattering

(Im, x=ξ)
DVCS: spin asymmetries
HERMES, CLAS, Hall A

DIS: PDFs at ξ = 0

(|Re|)
TCS: azimuthal asymmetry
CLAS
DVCS: charge asymmetry
HERMES

H(x, ξ, 0)

(|Im, x ≠ ξ, x < |ξ| )
DDVCS, CLAS12?

(|Re|^2)
DVCS: cross sections
H1, Hall A
To leading order, in terms of helicity amplitudes:

\[
\frac{d\sigma_{\text{INT}}}{dQ'^2 \, dt \, d(cos \, \theta) \, d\varphi} = -\frac{\alpha^3_{\text{em}}}{4\pi s^2} \frac{1}{-t \, Q'} \frac{M}{\tau \sqrt{1 - \tau}} \frac{1}{L} \left[ \cos \varphi \, \frac{1 + \cos^2 \theta}{\sin \theta} \Re \tilde{M}^- \right. \\
- \cos 2\varphi \, \sqrt{2} \cos \theta \Re \tilde{M}^0 + \cos 3\varphi \, \sin \theta \Re \tilde{M}^+ + O \left( \frac{1}{Q'} \right) \\
\left. - \frac{\nu}{\alpha^3_{\text{em}} \, L} \frac{1}{-t \, Q'} \frac{M}{\tau \sqrt{1 - \tau}} \frac{1}{L} \left[ \sin \varphi \, \frac{1 + \cos^2 \theta}{\sin \theta} \Im \tilde{M}^- \right. \\
- \sin 2\varphi \, \sqrt{2} \cos \theta \Im \tilde{M}^0 + \sin 3\varphi \, \sin \theta \Im \tilde{M}^+ \right] + O \left( \frac{1}{Q'} \right)
\]

Circular polarization of incoming photon

\[
\frac{1}{2} \sum_{\lambda, \lambda'} |M^{\lambda', \lambda'}|^2 = \left( 1 - \eta^2 \right) \left( |H_1|^2 + |\tilde{H}_1|^2 \right) - 2\eta^2 \Re \left( H_1^* E_1 + \tilde{H}_1^* \tilde{E}_1 \right) \\
- \left( \eta^2 + \frac{t}{4M^2} \right) |E_1|^2 - \eta^2 \frac{t}{4M^2} |\tilde{E}_1|^2.
\]
Azimuthal e^+e^- asymmetries in TCS

- Example:

\[ R = \frac{2\int_0^{2\pi} d\varphi \cos \varphi \frac{dS}{dQ'^2} dtd\varphi}{\int_0^{2\pi} d\varphi \frac{dS}{dQ'^2} dtd\varphi} \]

- Numerator is proportional to M^--
- R can be compared directly with GPD models
- Sensitive to Polyakov-Weiss D-term in the ERBL region (-\eta<\kappa<\eta), where the \gamma^* is formed from a qq-bar pair
Other Implications for GPDs

• $\sigma_L(\pi)$ : (model-dependent) power corrections in the framework of GPD models like VGG allow good agreement

• May provide information on big features of GPDs

• Important to provide consistent description of all channels ($\pi^{+/0},K^{+/0},\ldots$), $Q^2$, $x_B$, $t$, dependences, etc… (ratio, polarization observables,…)