Exclusive Photon and Meson Production at HERMES

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on behalf of the HERMES Collaboration

EDS 2007  DESY, 22 May 2007

✧ Exclusive Reactions and GPDs
✧ The HERMES Experiment
✧ Exclusive Photon Production (DVCS)
✧ Exclusive Meson Production
✧ Summary and Outlook
GPDs offer most complete description of quark-gluon structure of hadrons
GPDs offer most complete description of quark-gluon structure of hadrons.

Ji sum rule:

\[ J_q = \lim_{t \to 0} \int_{-1}^{+1} x dx \left[ H_q(x, \xi, t) + E_q(x, \xi, t) \right] \]
Hard Exclusive Processes
interpreted in GPD framework!

large $Q^2$, small $t$
The HERMES Experiment at DESY

Gas storage target cell: Polarized/Unpolarized gas. $P_T \approx 88-97\%$

Forward spectrometer: $40 \text{ mrad} < \theta < 220 \text{ mrad}$

Tracking chambers: $\Rightarrow \delta p/p \approx 2\%, \delta \theta \leq 1 \text{ mrad}$

PIDs: $e/h$ separation efficiency $> 98\%$, $\pi^\pm / K^\pm / p$ ID: $2 < p < 15 \text{ GeV}$
Deeply Virtual Compton Scattering

\[ ep \rightarrow e'p'\gamma \]

DVCS

- In principle, \( H, E, \tilde{H}, \tilde{E} \) all participate in describing the target
- Final photon observables directly interpreted in terms of four \( GPDs \)
Deeply Virtual Compton Scattering

\[ e p \rightarrow e' p' \gamma \]

\[ d\sigma \propto |A_{DVCS}|^2 + |A_{BH}|^2 + |A_{DVCS}^* A_{BH} + A_{DVCS} A_{BH}^*|^2 \]

✦ At HERMES kinematics \( BH \) contribution dominates
✦ DVCS-BH interference gives rise to non-zero azimuthal asymmetry
⇒ still possible to access quark information
Deeply Virtual Compton Scattering

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

Choosing specific Beam/Target polarization asymmetries:

\[ \implies \text{gives access to different combinations of } GPDs \]

HERMES kinematics:

\[ \langle x_{Bj} \rangle \approx 0.1, \langle -t \rangle \approx 0.1 \]

\[ \implies \text{inside the selected combination, certain } GPDs \text{ suppressed} \]
DVCS: Asymmetries

✦ Beam-charge asymmetry $A_C(\phi)$ (BCA):
\[ d\sigma(e^+; \phi) - d\sigma(e^-; \phi) \propto Re[H] \cdot \cos(\phi) \]

✦ Beam-spin asymmetry $A_{LU}(\phi)$ (BSA):
\[ d\sigma(\vec{e}; \phi) - d\sigma(\vec{e}; \phi) \propto Im[H] \cdot \sin(\phi) \]

✦ Longitudinal target-spin asymmetry $A_{UL}(\phi)$ (LTSA):
\[ d\sigma(\vec{P}; \phi) - d\sigma(\vec{P}; \phi) \propto Im[\tilde{H}] \cdot \sin(\phi) \]

✦ Observables sensitive to convolution of GPDs with hard-scattering kernel (as for others hard exclusive processes):
\[ H, E, \tilde{H}, \tilde{E} \rightarrow H, E, \tilde{H}, \tilde{E} \]

(For simplicity: $F_1$ & $F_2$ FF from BH amplitude not shown)
Background Subtraction

- Recoiling nucleon not detected
- Exclusive events selected via “missing mass” technique:

\[ M_X^2 = (e_\mu + p_\mu - P_{\mu}^{\text{detected}})^2 \]
Background Subtraction

- Recoiling nucleon not detected
- Exclusive events selected via
  “missing mass” technique:

\[ M_X^2 = (e_\mu + p_\mu - P_{\mu\text{detected}})^2 \]

- Bg contamination estimated with non-exclusive MC (and data)
**DVCS: sensitivity to $H$ via BCA**

**BCA:** $A_C(\phi) \propto Re[H] \cdot \cos(\phi)$

**GPD calculations for $H$**
[Vanderhaegen et. al. (1999)]

**Different ways to model GPDs in non-forward region**
- **D-term:** included OR not-included

**$t$-dependence:**
- Regge-inspired OR factorized (e.g. $F(t, x, \xi) = g(t) \cdot h(x, \xi)$)
DVCS: sensitivity to $\mathcal{H}$ via BCA

**BCA:** $A_C(\phi) \propto \text{Re}[\mathcal{H}] \cdot \cos(\phi)$

- **Unique measurement:**
  - First kinematical dependence of DVCS
- **On publishing**
- **Analyzed data set:** 1998/2000
- **Additional data are being analyzed**

- **GPD calculations for $H$**
  - [Vanderhaegen et. al. (1999)]

- **Different ways to model GPDs in non-forward region**
  - D-term: included OR not-included

- **$t$-dependence:**
  - Regge-inspired OR factorized (e.g. $F(t, x, \xi) = g(t) \cdot h(x, \xi)$)
DVCS: sensitivity to $\mathcal{H}$ via BSA

**BSA:** $A_{LU}(\phi) \propto \text{Im}[\mathcal{H}] \cdot \sin(\phi)$

\[
\begin{align*}
\text{e}^+ p &\rightarrow e^+ \gamma X \ (M_x < 1.7 \text{ GeV}) \\
\text{HERMES PREL. 2000} &\text{ (refined)} \\
\text{- P1 + P2 sin }\phi + \text{ P3 sin }2\phi
\end{align*}
\]

- $P1 = -0.04 \pm 0.02 \text{ (stat)}$
- $P2 = -0.18 \pm 0.03 \text{ (stat)}$
- $P3 = 0.00 \pm 0.03 \text{ (stat)}$

$<t> = 0.18 \text{ GeV}^2$, $<x_B> = 0.12$, $<Q^2> = 2.5 \text{ GeV}^2$

**Non-zero $\sin \phi$ moment:**

...a \text{Im}[\mathcal{H}] signature
DVCS: sensitivity to $\mathcal{H}$ via BSA

**BSA:** $A_{LU}(\phi) \propto \text{Im}[\mathcal{H}] \cdot \sin(\phi)$

**Versatility of HERMES target:**

BSA off nuclei: H, D, He, N, Ne, Kr, Xe

**Non-zero $\sin \phi$ moment:**

...a $\text{Im}[\mathcal{H}]$ signature

**In coherent region, ratio off unity:** qualitatively in agreement with


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Exclusive Processes at HERMES
DVCS: sensitivity to $\tilde{H}$ via LTSA

- **LTSA:** $A_{UL}(\phi) \propto \text{Im}[\tilde{H}] \cdot \sin(\phi)$

- Final statistics of H and D
DVCS: sensitivity to $\tilde{H}$ via LTSA

✧ **LTSA:** $A_{UL}(\phi) \propto Im[\tilde{H}] \cdot \sin(\phi)$

✧ **Final statistics of H and D**

✧ **expected** $\sin \phi$ behaviour

✧ **unexpected** $\sin 2\phi$ moment

$\implies > 3\sigma (1.7\sigma)$ on proton (deuteron)

Twist-3 effect?

**HERMES PRELIMINARY**

$e^+ p \rightarrow e^+ \gamma X \ (M_x<1.7 \text{ GeV})$

(in HERMES acceptance)

$A = s_0 + s_1 \sin \phi + s_2 \sin 2\phi$

$\chi^2/\text{ndf}: 8.5/7$

$s_0: -0.009 \pm 0.024 \text{ (stat.)}$

$s_1: -0.071 \pm 0.034 \text{ (stat.)}$

$s_2: -0.113 \pm 0.034 \text{ (stat.)}$

$<t>=0.12 \text{ GeV}^2, <x_B>=0.10, <Q^2>=2.5 \text{ GeV}^2$
DVCS: sensitivity to $\mathcal{E}, \mathcal{H}, \tilde{\mathcal{H}}$ via TTSA

✦ Sofar, measured asymmetries insensitive to GPD $E$, and $\tilde{E}$ suppressed by HERMES kinematics!
DVCS: sensitivity to $E, H, \tilde{H}$ via TTSA

Transverse target-spin asymmetry $A_{UT}(\phi, \phi_S)$:

$$d\sigma(\phi, \phi_S) - d\sigma(\phi, \phi_S + \pi) \propto Im[F_2H - F_1E] \cdot \sin(\phi - \phi_S) \cdot \cos(\phi) +$$

$$\xi = \frac{x_{Bj}}{2 - x_{Bj}}$$

$$Im[F_2\tilde{H} - \xi F_1\tilde{E}] \cdot \cos(\phi - \phi_S) \cdot \sin(\phi)$$

Now we have sensitivity to $E$
DVCS: sensitivity to $\mathcal{E}$, $\mathcal{H}$, $\tilde{\mathcal{H}}$ via TTSA

✦ **TTSA:** 

$$A_{UT}(\phi) \propto A_{UT}^{\sin(\phi-\phi_S)\cos(\phi)} \cdot \sin(\phi - \phi_S) \cdot \cos(\phi) + A_{UT}^{\cos(\phi-\phi_S)\sin(\phi)} \cdot \cos(\phi - \phi_S) \cdot \sin(\phi)$$

✦ **Analyzed data sample:** 50% [2002-2004]
DVCS: sensitivity to $E, H, \tilde{H}$ via TTSA

\[ A_{UT}(\phi) \propto A_{UT}^{\sin(\phi-\phi_S)\cdot\cos(\phi)} \cdot \sin(\phi - \phi_S) \cdot \cos(\phi) + A_{UT}^{\cos(\phi-\phi_S)\cdot\sin(\phi)} \cdot \cos(\phi - \phi_S) \cdot \sin(\phi) \]

\begin{itemize}
  \item **TTSA:**
  \item **Analyzed data sample:** 50% [2002-2004]
  \item **Predictions:**
  \item **Model GPD $E$ via unkown $J$**
  \item $J_d = 0$ assumed here
  \item **Sensitivity to $J_u$:**
  - expected for $A_{UT}^{\sin(\phi-\phi_S)\cdot\cos(\phi)}$
  - NOT-expected for $A_{UT}^{\cos(\phi-\phi_S)\cdot\sin(\phi)}$
  \item Minor sensitivity found to other GPDs parameters:
  - profile / $t$-dependence
\end{itemize}
TTSA: ...exploiting sensitivity to $J_q$

\[ \chi^2_{exp}(J_u, J_d) = \sum_{i}^{kin bins} \frac{A_{UT,i}^{\sin(\phi-\phi_S) \cdot \cos(\phi)} |_{exp} - A_{UT,i}^{\sin(\phi-\phi_S) \cdot \cos(\phi)} |_{VGG(J_u, J_d)}^2}{\delta A^2_{stat,i} + \delta A^2_{syst,i} + \delta A^2_{accept,i}} \]

- Calculate $A^{\sin(\phi-\phi_S) \cdot \cos(\phi)}_{UT}$ within VGG-based model
- $J_u, J_d$ kept free in fit
- Via $\chi^2$ minimization determine $1\sigma$ area for $(J_u, J_d)$
TTSA: ...exploiting sensitivity to $J_q$

\[
\chi^2_{\text{exp}}(J_u, J_d) = \sum_{\text{kin bins}} \left[ A_{\text{UT},i} \sin(\phi - \phi_S) \cos(\phi) \right]_{\text{exp}} - \left[ A_{\text{UT},i} \sin(\phi - \phi_S) \cos(\phi) \right]_{\text{VGG}(J_u, J_d)}^2 \right] \delta A_{\text{stat},i}^2 + \delta A_{\text{syst},i}^2 + \delta A_{\text{accept},i}^2
\]

✧ **Calculate** $A_{\text{UT}} \sin(\phi - \phi_S) \cos(\phi)$
   within VGG-based model

✧ **$J_u, J_d$ kept free in fit**

✧ **Via** $\chi^2$ minimization
   determine $\sigma$ area for $(J_u, J_d)$

More details in:
Z. Ye et al.,
hep-ex/0606061

✧ **First constraint on** $J_u$ vs $J_d$, ALBEIT model-dependent

\[J_u + J_d / 2.9 \; \text{VGG} = 0.42 \pm 0.21 \; \text{(exp_{tot})} \pm 0.06 \; (b_{\text{VGG}}^{\gamma,s} \in [1, \infty])\]

\[\text{Lattice QCDSF } J^\text{val}_{\gamma} (\mu^2 = 4\text{GeV}^2) \; \text{stat. uncertainty only} \; [\text{PRL92}(2004),042002]\]

\[e^+ p \rightarrow e^+ \gamma X \; (M_X < 1.7\text{ GeV}) \]

\[A_{\text{UT}}^{\sin(\phi - \phi_S) \cos(\phi)} = -0.149 \pm 0.058(\text{stat}) \pm 0.033(\text{syst})\]

\[<t> = 0.12\; \text{GeV}^2, \; <x> = 0.095, \; <Q^2> = 2.5\; \text{GeV}^2\]

GPD Model: LO/Regge/D-term=0
Code: VGG [Vanderhaeghen et al., priv. comm.]

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Exclusive Processes at HERMES
More complex interpretation in terms of \( GPDs \): include meson amplitude

Quantum numbers of final meson state filter different contrib. of \( GPDs \)

Vector mesons (\( \rho^0 \)): \( \mathcal{H}, \mathcal{E} \) (flavor singlet)

\( f \)-meson family (\( f_0, f_2 \)): \( \mathcal{H}, \mathcal{E} \) (flavor non-singlet)

Pseudoscalar mesons (\( \pi^+ \)): \( \tilde{\mathcal{H}}, \tilde{\mathcal{E}} \)

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Exclusive Processes at HERMES
Sensitivity to $\mathcal{H}$ and $\mathcal{E}$ in flavour singlet state
TTSA: $A_{UT}(\phi - \phi_S) \propto \frac{N_{\uparrow}^{{\text{excl}}}(\phi-\phi_S)-N_{\downarrow}^{{\text{excl}}}(\phi-\phi_S)}{N_{\uparrow}^{{\text{excl}}}(\phi-\phi_S)+N_{\downarrow}^{{\text{excl}}}(\phi-\phi_S)}$

$A_{UT}^{\sin(\phi-\phi_S)} \sim \frac{\mathcal{E}}{\mathcal{H}} \sim \frac{\mathcal{E}_q+\mathcal{E}_g}{\mathcal{H}_q+\mathcal{H}_g}$
Hard Exclusive $\rho^o_L$ Production

TTSA: $A_{UT}(\phi - \phi_S) \propto \frac{N^\uparrow_{excl}(\phi-\phi_S)-N^\downarrow_{excl}(\phi-\phi_S)}{N^\uparrow_{excl}(\phi-\phi_S)+N^\downarrow_{excl}(\phi-\phi_S)}$

$A_{UT}^{\sin(\phi-\phi_S)} \sim \frac{E}{H} \sim \frac{E_q+E_g}{H_q+H_g}$

Analysis strategy:

✧ $P_T \cdot A_{UT}^{beam} = S_T \cdot A_{UT}^{\gamma^*} + S_L \cdot A_{UL}^{\gamma^*}$

$P_T \cdot A_{UT}^{beam} \sim S_T \cdot A_{UT}^{\gamma^*}$ at HERMES!

✧ $\rho^o_L / \rho^o_T$ separation via angular distribution

⇒ from HERMES data

✧ Because $sCH$ is approximately conserved:

$\rho^o_L / \rho^o_T$ can be mapped into $\gamma^*_L / \gamma^*_T$ separation

✧ Asymmetry extracted with Unbinned Maximum Likelihood fit
Potential sensitivity of $E$ to $2J^u + x J^d$

all 2002-05 available data used!

Combined statistical analysis in progress, to make statement concerning $J$

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Sensitivity to $\mathcal{H}$ and $\mathcal{E}$ in flavour non-singlet state

Complementary to Vector Meson sensitivity
($\mathcal{H}$ and $\mathcal{E}$ in flavour singlet state)
Hard Exclusive Production of $\pi^+\pi^-$

\[ \gamma^*_L p \rightarrow p\pi^+\pi^- \quad \gamma^*_L d \rightarrow d\pi^+\pi^- \]
Hard Exclusive Production of $\pi^+\pi^-$

\[ \gamma_L^* p \rightarrow p\pi^+\pi^- \quad \text{and} \quad \gamma_L^* d \rightarrow d\pi^+\pi^- \]

Which channels may contribute?

- **2-gluon exchange** ($C=+1$)
- **$\rho$ family** ($C=-1, I=1$)
  - $l=1,3,\ldots$
  - $\pi^+\pi^-$

Example:

- $\rho^0$: $I(J^{PC}) = 1(1--)$
Hard Exclusive Production of $\pi^+\pi^-$

$$\gamma_L^* p \rightarrow p\pi^+\pi^- \quad \gamma_L^* d \rightarrow d\pi^+\pi^-$$

Which channels may contribute?

- (a) $\rho$ family
  - C = -1, I = 1
  - $l = 1, 3, \ldots$
  - 2-gluon exchange (C = +1)

- (b) $\rho$ family
  - C = -1, I = 1
  - $l = 1, 3, \ldots$
  - Singlet quark exchange (C = +1)

- (c) $f$ family
  - C = +1, I = 0
  - $l = 0, 2, \ldots$
  - Non-singlet quark exchange (C = -1)

- (d) $f$ family
  - C = +1, I = 0
  - $l = 0, 2, \ldots$
  - Non-singlet quark exchange (C = -1)

Example:
- $\rho^0$: $I(J^{PC}) = 1(1--)$

Example:
- Non-resonant $S$-wave & $f_0^-$:
  - $I(J^{PC}) = 0(0^{++})$
- $f_2^-$: $I(J^{PC}) = 0(2^{++})$
How to highlight the elusive $f$-meson family channel?
How to highlight the elusive $f$-meson family channel?

$$\frac{d\sigma^{\pi^+\pi^-}}{d\cos \theta} \propto \sum_{J,J',\lambda,\lambda'} \rho_{\lambda',\lambda}^{J,J'} Y_J(\theta,\phi) Y_{J'}^*(\theta,\phi)$$

Spin Density Matrix:
How to highlight the elusive $f$-meson family channel?

\[
\frac{d\sigma^{\pi^+\pi^-}}{d\cos\theta} \propto \sum_{JJ'\lambda\lambda'} \rho_{\lambda\lambda'}^{JJ'} Y_{J\lambda}(\theta, \phi) Y_{J'\lambda'}^*(\theta, \phi)
\]

Legendre Moments:

\[
\langle P_l(cos\theta) \rangle_{\pi^+\pi^-} = \frac{\int_{-1}^{1} d\cos\theta \ P_l(cos\theta) \ \frac{d\sigma^{\pi^+\pi^-}}{d\cos\theta}}{\int_{-1}^{1} d\cos\theta \ \frac{d\sigma^{\pi^+\pi^-}}{d\cos\theta}}
\]

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Exclusive Processes at HERMES
How to highlight the elusive $f$-meson family channel?

\[
\frac{d\sigma^{\pi^+\pi^-}}{d \cos \theta} \propto \sum_{JJ'\lambda\lambda'} \rho^{JJ'}_{\lambda\lambda'} Y_{J\lambda}(\theta, \phi) Y_{J'\lambda'}^*(\theta, \phi)
\]

Legendre Moments:

\[
\langle P_l(\cos \theta) \rangle^{\pi^+\pi^-} = \frac{\int_{-1}^{1} d\cos \theta P_l(\cos \theta) \frac{d\sigma^{\pi^+\pi^-}}{d \cos \theta}}{\int_{-1}^{1} d\cos \theta \frac{d\sigma^{\pi^+\pi^-}}{d \cos \theta}}
\]

\[
\langle P_1(\cos \theta) \rangle = \frac{1}{\sqrt{15}} \left[ 4\sqrt{3}\rho_{11}^{21} + 4\rho_{00}^{21} + 2\sqrt{5}\rho_{00}^{10} \right]
\]

- highlighting elusive $f$-meson family channel through its interference with dominating $\rho^0$-meson
- Sensitivity to the interference by measuring $\langle P_1(\cos \theta) \rangle$
Increasing interference vs increasing $x$

between non-resonant $S$-wave and $\rho^0$

$\Rightarrow$ increased contribution of non-singlet $q\bar{q}$ exchange

Described by flavor non-singlet combinations of $\mathcal{H}_q$ & $\mathcal{E}_q$

♦ Potential sensitivity to $J_u, J_d$
\( x \)-dependence of \( \langle P_1(\cos \theta) \rangle \)

- Predicted at \( m_{\pi\pi} = 0.50 \text{ GeV} \) for \( H_2 \)
- \( H_2 \) at \( \langle m_{\pi\pi} \rangle = 0.48 \text{ GeV} \)
- \( D_2 \) at \( \langle m_{\pi\pi} \rangle = 0.48 \text{ GeV} \)

Increasing interference vs increasing \( x \) between non-resonant \( S \)-wave and \( \rho^0 \)
\( \Rightarrow \) increased contribution of non-singlet \( q\bar{q} \) exchange

- B.Lehmann-Dronke, P.V.Pobylitsa, M.V.Polyakov, A.Schäfer, K.Goeke:

\( \Rightarrow \) gluon GPD neglected

\( \Rightarrow \) Reasonable agreement of theory with data
Conclusions & Outlook

✧ Several hard exclusive production channels measured
⇒ interpreted in the GPD framework
Conclusions & Outlook

✦ Several hard exclusive production channels measured interpreted in the GPD framework

  – exclusive photons (DVCS)

✦ Constraints on GPDs model obtained
✦ First model-dependent constraint on $J_u$ & $J_d$
Conclusions & Outlook

✦ Several hard exclusive production channels measured
  \[ \Rightarrow \text{interpreted in the GPD framework} \]
  – exclusive photons (DVCS)

✦ Constraints on GPDs model obtained

✦ First model-dependent constraint on $J_u$ & $J_d$

  – exclusive $\rho^O_L$:

  ✦ $A_{UT} \sin(\phi - \phi_S)$ extracted: \[ \Rightarrow \text{sensitive to } J \]
Conclusions & Outlook

✦ Several hard exclusive production channels measured
   \[ \rightarrow \text{interpreted in the GPD framework} \]
   – exclusive photons (DVCS)

✦ Constraints on GPDs model obtained

✦ First model-dependent constraint on \( J_u \) & \( J_d \)

   – exclusive \( \rho^0_L \):
     \[ A_{UT}^{\sin(\phi-\phi_S)} \text{extracted:} \rightarrow \text{sensitive to } J \]

   – exclusive \( \pi^+\pi^- \):

✦ Legendre moments measured: \( \rightarrow \text{agreement with GPDs predictions} \)

✦ \( \langle P_1 \rangle \text{ increase vs } x: \rightarrow \text{relative increase with } x \text{ of non-singlet } H_q \) & \( E_q \)
Conclusions & Outlook

Near future:

✦ Improved resolution/statistics expected with new RECOIL detector

✦ Expected total $47 \cdot 10^6$ unpol. DIS on H, $\sim 1 \text{fb}^{-1}$ (as in the proposal)
**DVCS: sensitivity to $\tilde{H}$ via LTSA**

**LTSA:** $A_{UL}(\phi) \propto \text{Im}[\tilde{H}] \cdot \sin(\phi) = A_{UL}^{\sin}(\phi) \cdot \sin(\phi)$ at Lead.Twist

Both targets consistent within uncertainties

Only proton GPD predictions exist:
- $\sin \phi$ in agreement with VGG model
- VGG failure in reproduce $\sin 2\phi$

But: only Twist-3 $WW$-term included

Twist-3 $qGq$-term needed? ($\pi^0$ contamination negligible)

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Exclusive Processes at HERMES
V. Guzey and M. Strikman:
GPD-based
Pseudoscalar Mesons

Sensitivity to $\tilde{\mathcal{H}}$ and $\tilde{\mathcal{E}}$
Hard Exclusive $\pi^+$ Cross-section

$e^+ p \rightarrow e^+ \pi^+ n$

Extraction of the exclusive sample

- Detection: $e^+, \pi^+$
- Recoil neutron reconstructed via Missing Mass
- Use of $\pi^-$ to subtract the non-exclusive bg
- $\pi^+$ enhancement
Hard Exclusive $\pi^+$ Cross-section

$e^+ p \rightarrow e^+ \pi^+ n$

Extraction of the exclusive sample

Exclusive peak clearly centered at the neutron mass

$\pi^+ / \pi^- = 1.77$

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Exclusive Processes at HERMES
MC Tuning for Exclusive $\pi^+$ Cross-section

Cross-section: $\sim (\tilde{H} + \tilde{E})^2$

- $X$-section extracted after proper tuning of exclusive MC in the HERMES acceptance
- Vanderhaeghen, Guichon & Guidal (1999)

VGG_MC well reproduces data kin.distributions in the HERMES detector

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Exclusive Processes at HERMES
Hard Exclusive $\pi^+$ Cross-section

Cross-section: $\sim (\tilde{H} + \tilde{E})^2$

- X-section extracted after proper tuning of exclusive MC in the HERMES acceptance

- Vanderhaeghen, Guichon & Guidal (1999)

\[ \Gamma(x, Q^2) = \frac{N_{\pi^+}^{excl}}{L \Delta x \Delta Q^2 \Gamma(x, Q^2) \kappa(x, Q^2)} \]

GPDMs framework in terms of: $\tilde{H}$ & $\tilde{E}$
Hard Exclusive $\pi^+$ Cross-section

Cross-section: $\sim (\bar{H} + \bar{E})^2$

$\gamma^* p \rightarrow \pi^+ n$

uncorrected for radiative effects

$\sigma_{\text{tot}}$ (nb)

$0.02 < x < 0.18$

$0.18 < x < 0.26$

$0.26 < x < 0.80$

$\sigma_L$: VGG: LO

$\sigma_L$: VGG: LO + power corrections

$Q^2$ (GeV$^2$)

$\checkmark$ VGG (1999): $Q^2$ dependence qualitatively in agreement with the data

$\checkmark$ Leading order calculations underestimate the data

$\checkmark$ Power correction calculations overestimate the data

$\checkmark$ No $\sigma_L/\sigma_T$ separation

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Exclusive Processes at HERMES
Acceptance correction found to be model dependent

Comparison with two different models made and included in the systematics
**Exclusive π⁺: Reduced X-section**

Reduced X-section $\sigma_{\text{red}}$ defined as

$$\sigma_{\text{tot}} = \frac{1}{16\pi} \frac{x^2}{1-x} \frac{1}{Q^4} \frac{1}{\sqrt{1 + \frac{4x^2m^2_R}{Q^2}}} \cdot \sigma_{\text{red}}$$

Fit of the form: $1/Q^p$:

- $p = 1.9 \pm 0.5$
- $p = 1.7 \pm 0.6$
- $p = 1.5 \pm 1.0$

agreement with theoretical expectation $1/Q^2$ at fixed $x$ and $t$
Analysis of exclusive $\pi^0$ on unpolarized proton target on going

- no pion-pole contribution in $\tilde{E}$
- predicted sensitivity to $\tilde{E}$

- Mankiewicz et. al. (1999) -
Hard Exclusive $\rho_L^0$ Production

Transverse Target Spin Asymmetry: $\sim \vec{E} \cdot \vec{H}$

$$A_{UT}(\phi - \phi_S) \propto \frac{N_{\text{excl}}^{\uparrow}(\phi - \phi_S) - N_{\text{excl}}^{\downarrow}(\phi - \phi_S)}{N_{\text{excl}}^{\uparrow}(\phi - \phi_S) + N_{\text{excl}}^{\downarrow}(\phi - \phi_S)}$$

- Frankfurt, Polybitsa, Polyakov & Strikman (1999) -

\textit{GPDs framework}

✦ Sizable asymmetry predicted!