Exclusive Reactions at HERMES

Exclusive Reactions as Access to GPDs

DVCS Asymmetries
...with and without Recoil Detection
...on unpolarized, longitudinal and transversely polarized targets

Exclusive Meson Production
spin density matrix elements
natural and unnatural parity exchange

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DVCS

\( \gamma^* \rightarrow \gamma : H, E, \tilde{H}, \tilde{E} \)

- The cleanest channel to access GPDs
  - Experimental access restricted to CFF
- Theoretically accurate at NNLO
- X-section decomposition w.r.t. Beam and target polarisation states:

\[
\begin{align*}
    d\sigma &\sim d\sigma^{BH}_{UU} + e_\ell d\sigma^{I}_{UU} + d\sigma^{DVCS}_{UU} \\
    &+ e_\ell P_\ell d\sigma^{I}_{LU} + P_\ell d\sigma^{DVCS}_{LU} \\
    &+ e_\ell S_L d\sigma^{I}_{UL} + S_L d\sigma^{DVCS}_{UL} \\
    &+ e_\ell S_T d\sigma^{I}_{UT} + S_T d\sigma^{DVCS}_{UT} \\
    &+ P_\ell S_L d\sigma^{BH}_{LL} + e_\ell P_\ell S_L d\sigma^{I}_{LL} + P_\ell S_L d\sigma^{DVCS}_{LL} \\
    &+ P_\ell S_T d\sigma^{BH}_{LT} + e_\ell P_\ell S_T d\sigma^{I}_{LT} + P_\ell S_T d\sigma^{DVCS}_{LT}.
\end{align*}
\]

- Unpolarized target: GPD \( H \)
- Longitudinal target: GPD \( \tilde{H} \)
- Transverse target: GPD \( E \)
Exclusive Hard Processes at DVCS

\( \gamma^* \rightarrow \gamma : H, E, \bar{H}, \bar{E} \)

- The cleanest channel to access GPDs
  - Experimental access restricted to CFF

- Theoretically accurate at NNLO

- X-section decomposition w.r.t. Beam and target polarisation states:

\[
\begin{align*}
\frac{d\sigma}{d\Omega} & \sim \frac{d\sigma}{d\Omega}^{BH} + e_\ell d\sigma^{LU}_{UU} + d\sigma^{DVCS}\left( \text{beam: } p_1, \text{ target: } s_2, s_3 \right) \\
& + e_\ell p_1 d\sigma^{LU}_{UU} + P_\ell d\sigma^{DVCS} \\
& + e_\ell S_L d\sigma^{UL}_{UL} + S_L d\sigma^{DVCS}_{UL} \\
& + e_\ell S_T d\sigma^{UL}_{UT} + S_T d\sigma^{DVCS}_{UT} \\
& + P_\ell S_L d\sigma^{LL}_{UU} + e_\ell p_1 S_L d\sigma^{LL}_{UL} + P_\ell S_L d\sigma^{DVCS}_{LL} \\
& + P_\ell S_T d\sigma^{LT}_{LT} + e_\ell p_1 S_T d\sigma^{LT}_{LT} + P_\ell S_T d\sigma^{DVCS}_{LT}
\end{align*}
\]

- Unpolarized target: GPD \( H \)
- Longitudinal target: GPD \( \bar{H} \)
- Transverse target: GPD \( E \)

**Meson Production**

- Unlike \( \gamma \): L and T states possible (VM)!
  - Factorization only proven in collinear approximation for \( \gamma_L \rightarrow (\rho_L, \omega_L, \phi_L) \)
  - \( \gamma_T \rightarrow \rho_T \) suppressed by \( 1/Q \)
  - \( \gamma_T \) suppressed by \( 1/Q^2 \)
  - \( \gamma_T \rightarrow \rho_T \) transitions calculable

- Sensitive to \( H \) and \( E \) in twist-2
  - \( \bar{H} \) and \( \bar{E} \) in twist-3
DVCS

$\gamma^* \to \gamma : H, E, \tilde{H}, \tilde{E}$

- The cleanest channel to access GPDs
- Theoretically accurate at NNLO
- X-section decomposition w.r.t. Beam and target polarisation states:

\[
\begin{align*}
    d\sigma & \sim d\sigma^{BH}_{UU} + e_\ell d\sigma^{L}_{UU} + d\sigma^{DVCS}_{UU} \\
    & + e_\ell P e d\sigma^{L}_{LU} + P e d\sigma^{DVCS}_{LU} \\
    & + e_\ell S L d\sigma^{L}_{UL} + S L d\sigma^{DVCS}_{UL} \\
    & + e_\ell S T d\sigma^{L}_{UT} + S T d\sigma^{DVCS}_{UT} \\
    & + P e S L d\sigma^{B}_{LL} + e_\ell P e S L d\sigma^{L}_{LL} + P e S L d\sigma^{DVCS}_{LL} \\
    & + P e S T d\sigma^{B}_{LT} + e_\ell P e S T d\sigma^{L}_{LT} + P e S T d\sigma^{DVCS}_{LT}
\end{align*}
\]

- Unpolarized target: GPD $H$
- Longitudinal target: GPD $\tilde{H}$
- Transverse target: GPD $E$

Meson Production

- Unlike $\gamma : L$ and $T$ states possible (VM)!
  - Factorization only proven in collinear approximation for $\gamma_L \to (\rho_L, \omega_L, \phi_L)$
  - $\gamma_T \to \rho_T$ suppressed by $1/Q$
  - $\gamma_T$ suppressed by $1/Q^2$
  - $\gamma_T \to \rho_T$ transitions calculable

- Sensitive to $H$ and $E$ in twist-2
  - $\tilde{H}$ and $\tilde{E}$ in twist-3

- Pseudoscalar mesons ($\pi^+$):
  - Sensitive to $\tilde{H}$ and $\tilde{E}$ in twist-2
  - $H_T$ in twist-3
**DVCS (no recoil)** \( e p \rightarrow e' \gamma X \)

> Missing mass technique

\[
M_X^2 = (p + e - e' - \gamma)^2
\]
Exclusive Hard Processes at HERMES

**DVCS (no recoil)** \( e p \rightarrow e' \gamma X \)

- Missing mass technique
  \[ M_X^2 = (p + e - e' - \gamma)^2 \]

**DVCS (with recoil detection)**

- Kinematic fitting  \( e p \rightarrow e' \gamma p' \)
**DVCS (no recoil)** \( ep \rightarrow e' \gamma X \)

- Missing mass technique
  \[ M_X^2 = (p + e - e' - \gamma)^2 \]

**DVCS (with recoil detection)** \( ep \rightarrow e' \gamma p' \)

- Kinematic fitting
- Resonant excitation: \( X = \Delta^* \)

**VM** \( ep \rightarrow e' VM p' \)

- Small missing energy
- Elastic scattering
  \[ \Delta E = \frac{M_X^2 - M^2}{2M} \approx 0 \]
- Little energy transferred to the target
  \[ t = (q - v)^2 \]
**DVCS (no recoil)**  \( e_p \rightarrow e' \gamma X \)

- Missing mass technique
  \[
  M_X^2 = (p + e - e' - \gamma)^2
  \]

**VM**  \( e_p \rightarrow e' \{VM\} p' \)

- Small missing energy
- Elastic scattering
  \[
  \Delta E = \frac{M_X^2 - M^2}{2M} \approx 0
  \]
- Little energy transferred to the target
  \[
  t = (q - v)^2
  \]

**DVCS (with recoil detection)**

- Kinematic fitting  \( e_p \rightarrow e' \gamma p' \)

**π⁺ (no neutron detection)**  \( e_p \rightarrow e' \pi^+ n \)

\[
N_{excl} = (\pi^+ - \pi^-)_{data} - (\pi^+ - \pi^-)_{MC}
\]

- \( \pi^+ - \pi^- \) yield difference used for background subtraction

- Missing mass technique
  \[
  M_X^2 = (p + e - e' - \pi^+)^2
  \]
GPD H: DVCS on Unpolarized Target

Pre-recoil data

\[
\sigma(\phi, P_l, e_l) = \sigma_{UU}(\phi)[1 + P_l A_{LU}^{DVCS}(\phi) + e_l P_l A_{LU}^{I}(\phi) + e_l A_{C}(\phi)]
\]

\[
A_C(\phi) = \frac{\sigma^{++} + \sigma^{+-}}{(\sigma^{++} + \sigma^{+-}) + (\sigma^{--} + \sigma^{-+})}
\]

\[
A_C^{\cos \phi} \propto \text{Re}[F_1 H]
\]

\[
A_C(\phi) = \sum_{n=0}^{3} A_C^{\cos(n\phi)} \cos(n\phi)
\]

\[
A_{LU}^{I}(\phi) = \sum_{n=0}^{2} A_{LU,I}^{\sin(n\phi)} \sin(n\phi)
\]

**Beam-charge** asymmetry

- Large signal
- Strong t-dependence
- No Q2-dependence
GPD H: DVCS on Unpolarized Target

Pre-recoil data

\[ \sigma(\phi, P_l, e_l) = \sigma_{UU}(\phi)[1 + P_l A_{LU}^{DVCS}(\phi) + e_l P_l A_{LU}^I(\phi) + e_l A_C(\phi)] \]

\[ A_C(\phi) = \frac{(\sigma^{++} + \sigma^{+-}) - (\sigma^{--} + \sigma^{+-})}{(\sigma^{---} + \sigma^{++}) + (\sigma^{--} + \sigma^{+-})} \]

\[ A_{C}^{\cos \phi} \propto \text{Re}[F_1 H] \]

\[ A_C(\phi) = \sum_{n=0}^{3} A_{C}^{\cos(n\phi)} \cos(n\phi) \]

\[ A_{LU}^I(\phi) = \sum_{n=0}^{2} A_{LU,I}^{\sin(n\phi)} \sin(n\phi) \]

Beam-charge asymmetry

➢ Large signal
➢ Strong t-dependence
➢ No Q2-dependence

Charge-difference beam helicity asymmetry

➢ Large signal
➢ No kinematic dependences

Charge-averaged beam helicity asymmetry

➢ Consistent with zero

\[ A_{LU,DVCS}^{\sin \phi} \propto \text{Im}[\mathcal{H}^* - \tilde{\mathcal{H}}^*] \]
GPD H: DVCS with Recoil Detector

Single-charge (+) beam helicity asymmetry

\[
\sigma(\phi, P_l, e_l) = \sigma_{UU}(\phi)[1 + P_l A_{LU}^{DVCS}(\phi) + e_l P_l A_{LU}^{I}(\phi) + e_l A_C(\phi)]
\]

\[
A_{LU}(\phi) \approx \sum_{n=0}^{2} A_{LU}^{\sin(n\phi)} \sin(n\phi)
\]

Magnitude of the leading asymmetry has increased by 0.054 ± 0.016

All sets are strongly correlated but the unresolved samples contain an average contribution of 12 - 14% of associated processes
GPD H: DVCS with Recoil Detector

Single-charge (+) beam helicity asymmetry in associated DVCS

\[ \Delta^+ \rightarrow p\pi^0 \]

Fractional purity:
Associated DVCS/BH 85.7 ± 1.8
Elastic DVCS/BH (ep → eγp) 1.1 ± 0.1
SIDIS 13.2 ± 1.9

\[ \Delta^+ \rightarrow n\pi^+ \]

Fractional purity:
Associated DVCS/BH 75.6 ± 2.6
Elastic DVCS/BH (ep → eγp) 0.1 ± 0.1
SIDIS 24.4 ± 3.4
GPD $\tilde{H}$ : with Longitudinally Polarized Target

Pre-recoil data

$$\sigma(\phi, P_z, P_l, e_l) = \sigma_{UU}(\phi, e_l)[1 + P_z A_{UL}(\phi) + P_l P_z A_{LL}^I(\phi)]$$

No separate access to DVCS and Interference terms possible

$$A_{UL}(\phi) \simeq \sum_{n=0}^{3} A_{UL}^{\sin(n\phi)} \sin(n\phi)$$

$$A_{LL}(\phi) = \sum_{n=0}^{2} A_{LL}^{\cos(n\phi)} \sin(n\phi)$$
GPD $\tilde{H}$: with Longitudinally Polarized Target $e\bar{p} \rightarrow e'\gamma X_{\text{hermes}}$

**Pre-recoil data**

$$\sigma(\phi, P_z, P_l, e_l) = \sigma_{UU}(\phi, e_l)[1 + P_z A_{UL}(\phi) + P_l P_z A_{LL}^I(\phi)]$$

> No separate access to DVCS and Interference terms possible

$$A_{UL}(\phi) \approx \sum_{n=0}^{3} A_{UL}^{\sin(n\phi)} \sin(n\phi)$$

$$A_{LL}(\phi) = \sum_{n=0}^{2} A_{LL}^{\cos(n\phi)} \sin(n\phi)$$

$$A_{UL}^{\sin(\phi)} \propto \left\{ \begin{array}{ll} \text{DVCS} : \text{twist - 3} \\ \text{I} : \text{twist - 2} \end{array} \right.$$  

$$A_{UL}^{\sin(\phi)} \propto F_1 \text{Im}\tilde{H}$$
GPD $\tilde{H}$: with Longitudinally Polarized Target $e\bar{p} \rightarrow e'\gamma X_{\text{hermes}}$

Pre-recoil data

$$\sigma(\phi, P_z, P_l, e_l) = \sigma_{UU}(\phi, e_l)[1 + P_z A_{UL}(\phi) + P_l P_z A^I_{LL}(\phi)]$$

No separate access to DVCS and Interference terms possible

$$A_{UL}(\phi) \approx \sum_{n=0}^{3} A^\sin(n\phi)_{UL} \sin(n\phi)$$

$$A_{LL}(\phi) = \sum_{n=0}^{2} A^\cos(n\phi)_{LL} \sin(n\phi)$$

$$A^\sin\phi_{UL} \propto \begin{cases} 
\text{DVCS} : \text{twist} - 3 \\
1 : \text{twist} - 2 
\end{cases}$$

$$A^\sin\phi_{UL} \propto F_1 \text{Im} \tilde{H}$$

$$A^\sin 2\phi_{UL} \propto \begin{cases} 
1 : \text{quark twist} - 3 \\
or \text{gluon twist} - 2 \\
\text{DVCS} : \text{twist} - 4 
\end{cases}$$

Unexpectedly large value
GPD $\widetilde{H}$ : with Longitudinally Polarized Target

**Pre-recoil data**

$$\sigma(\phi, P_z, P_l, e_l) = \sigma_{UU}(\phi, e_l)[1 + P_z A_{UL}(\phi) + P_l P_z A_{LL}^I(\phi)]$$

- No separate access to DVCS and Interference terms possible

$$A_{UL}(\phi) \simeq \sum_{n=0}^{3} A_{UL}^{\sin(n\phi)} \sin(n\phi)$$

$$A_{LL}(\phi) = \sum_{n=0}^{2} A_{LL}^{\cos(n\phi)} \sin(n\phi)$$

$$A_{UL}^{\sin \phi} \propto \left\{ \begin{array}{ll} \text{DVCS} : \text{twist} - 3 \\
\text{I} : \text{twist} - 2 
\end{array} \right.$$

$$A_{UL}^{\sin 2\phi} \propto \left\{ \begin{array}{ll} 1 : \text{quark twist} - 3 \\
\text{or gluon twist} - 2 \\
\text{DVCS : twist} - 4 
\end{array} \right.$$

$$A_{LL}^{\cos 0\phi} \propto \left\{ \begin{array}{ll} \text{DVCS} : \text{twist} - 2 \\
\text{I} : \text{twist} - 2 
\end{array} \right.$$

$$A_{LL}^{\cos 0\phi} \propto F_1 \text{Re}\widetilde{H}$$

Unexpectedly large value
GPD E: with Transversely Polarized Target

Pre-recoil data

\[
\sigma(\phi, \phi_S, e_l, S_\perp, \lambda) = \sigma_{UU}(\phi) \{1 + e_l A_C(\phi) + \lambda A_{LU}^{DVCS}(\phi) + e_l \lambda A_{LU}^I(\phi)
+ S_\perp A_{UT}^{DVCS}(\phi, \phi_S) + e_l S_\perp A_{UT}^I(\phi, \phi_S)
+ S_\perp \lambda A_{LT}^{BH+DVCS}(\phi, \phi_S) + e_l \lambda S_\perp A_{LT}^I(\phi, \phi_S)\}
\]

\[\propto \text{Im}[F_2 \mathcal{H} - F_1 \mathcal{E}]\]
\[\propto \text{Im}[\mathcal{H} \mathcal{E}^* - \mathcal{E} \mathcal{H}^* + \xi \tilde{\eta} \tilde{\mathcal{H}}^* - \tilde{\eta} \xi \tilde{\mathcal{E}}^*]\]

\[A_{UT, I} = \sin(\phi - \phi_S) \cos(\phi)\] has the highest sensitivity to GPD E and, through Ji formalism, to J\text{u} total orbital angular momentum of quarks

\[A_{UT, I}\] With a good model allows a model-dependent constraint
GPD E: with Transversely Polarized Target

Pre-recoil data

\[
\sigma(\phi, \phi_S, e_l, S_\perp, \lambda) = \sigma_{UU}(\phi)\{1 + e_l A_C(\phi) + \lambda A_{LU}^{DVCS}(\phi) + e_l \lambda A_{LU}^I(\phi) + S_\perp A_{LT}^{DVCS}(\phi, \phi_S) + e_l S_\perp A_{LT}^I(\phi, \phi_S)\}
\]

\[
A_{UT}^{DVCS}(\phi, \phi_S) = \frac{(\sigma^{+\uparrow} - \sigma^{+\downarrow})^\perp (\sigma^{-\uparrow} - \sigma^{-\downarrow})}{(\sigma^{+\uparrow} + \sigma^{+\downarrow}) + (\sigma^{-\uparrow} + \sigma^{-\downarrow})}
\]

\[
\sin(\phi - \phi_S) \cos \phi
\]

\[
\frac{A_{LT}^{BH+DVCS}(\phi, \phi_S)}{(\sigma^{+\uparrow} + \sigma^{+\downarrow} - \sigma^{-\uparrow} - \sigma^{-\downarrow}) + (\sigma^{+\uparrow} + \sigma^{+\downarrow} + \sigma^{-\uparrow} + \sigma^{-\downarrow})^\perp + (\sigma^{-\uparrow} + \sigma^{+\downarrow})^\perp + (\sigma^{-\uparrow} + \sigma^{+\downarrow})^\perp + (\sigma^{-\uparrow} + \sigma^{+\downarrow})^\perp}
\]

\[
A_{LT,I}^{sin(\phi - \phi_S) \sin \phi}
\]

\[
\propto \text{Im}[F_2H - F_1E]
\]

\[
\propto \text{Im}[\mathcal{H}E^* - \mathcal{E}H^* + \xi \bar{\mathcal{H}}\bar{E}^* - \bar{\mathcal{H}}\xi \bar{E}^*]
\]

\[
A_{LT,I}^{sin(\phi - \phi_S) \sin \phi}
\]

\[
\propto \text{Re}[F_2H - F_1E]
\]

\[
\propto \text{Im}[\mathcal{H}E^* - \mathcal{E}H^* + \xi \bar{\mathcal{H}}\bar{E}^* - \bar{\mathcal{H}}\xi \bar{E}^*]
\]

\[
A_{LT,I}^{sin(\phi - \phi_S) \sin \phi}
\]

\[
\propto \text{Re}[F_2H - F_1E]
\]

\[
\propto \text{Im}[\mathcal{H}E^* - \mathcal{E}H^* + \xi \bar{\mathcal{H}}\bar{E}^* - \bar{\mathcal{H}}\xi \bar{E}^*]
\]
Meson Production at
Vector Meson cross-section decompositions

> Fully differential cross-section

\[
\frac{d\sigma}{d\phi_s d\phi d\cos \theta d\varphi} \sim \frac{d\sigma}{d\phi_s d\phi d\cos \theta d\varphi} W(x_B, Q^2, t, \phi_s, \phi, \cos \theta, \varphi)
\]

> Decomposed through production and decay angular distributions \( W \)

\[
W = W_{UU} + P_l W_{LU} + S_L W_{UL} + P_l S_L W_{LL} + S_T W_{UT} + P_l S_T W_{LT}
\]

> Parametrized through SDMEs or helicity amplitudes:

> Describe the helicity transfer from virtual photon to the produced meson

> and the parity of the exchange process:

- Natural parity (vacuum quantum numbers) related to \( H \) and \( E \)
- Unnatural parity related to \( \tilde{H} \) and \( \tilde{E} \)
23 SDMEs in 5 classes:

- **A**: leading class, helicity transfer conforms SCHC
  - $\phi$ SDMEs are 10% larger than $\rho$
- **B**: similar values for L/T interference SDME
- **C**: pronounced differences between $\phi/\rho$
  - Hints of smaller longitudinal quark motion in $\phi$ meson
- **D, E**: mainly compatible with zero

Proton and Deuterium results compatible
SDMEs on Unpolarized Target(s)\( \quad ep \rightarrow e' \rho^0 p' \quad ep \rightarrow e' \omega^0 p' \)

23 SDMEs in 5 classes:

- **A:** different sign of leading twist SDMEs compared to \( \rho \)
  - indication of unnatural parity exchange!

- **D:** Some SDMEs indicate SCHC violation
At large $Q^2$ and $W$ the **unnatural** parity exchange should be suppressed by $M_V/Q$.

The combinations of SDMEs expected to be zero in case of natural parity exchange dominance:

\[
\begin{align*}
    u_1 &= 1 - r_{00}^{04} + 2r_{1-1}^{04} - 2r_{11}^{-1} - 2r_{1-1}^{-1} \\
    u_2 &= r_{11}^{5} + r_{1-1}^{5} \\
    u_3 &= r_{11}^{8} + r_{1-1}^{8}
\end{align*}
\]

(Wolf-Schilling notation)

**Unnatural Parity Exchange Observations ($\rho, \omega, \phi$)**

- $\rho$: non-zero UPE (3σ)
- $\omega$: Dominant UPE signal!
- $\phi$: UPE compatible with zero

Possible access to GPD $\tilde{H}$
Unnatural Parity Exchange Observations ($\rho, \omega, \phi$)
SDMEs on a Transversely Polarized Target

\[ ep^\uparrow \rightarrow e^\prime \rho^0 p' \]

> Suppressed by factor \( \sqrt{-t}/2M_p \)

> Out of 30 SDMEs only one sensitive to GPD \( E \)

\[ A_{UT}^{\sin(\phi-\phi_s)} = \frac{\text{Im}n^{00}_{00}}{u^{00}_{00}} \propto \frac{\text{Im}(\mathcal{E}_V^* \mathcal{H}_V)}{|\mathcal{H}_V|^2} \propto \left| \frac{\mathcal{E}_V}{\mathcal{H}_V} \right| \sin \delta \]

(Diehl notation)

> Model-based constraint on \( J_u \) indicates preference towards positive values

> UPE signature:

\[ s_{\mu\mu'}^{\nu\nu'} > \gamma_{\mu\mu'}^{\nu\nu'} \]

> Access GPD \( \widetilde{H}, \widetilde{E} \)


[Ellinghaus, Nowak, Vinnikov, Ye (2004)]
**π⁺ on a Transversely Polarized Target**


- No $\sigma_L/\sigma_T$ separation

- Small overall asymmetry with possible sign change

\[
A_{UT}^{\sin(\phi-\phi_S)} \propto \frac{\text{Im}(\tilde{H} \ast \tilde{E})}{|\tilde{H}|^2} \propto \left|\frac{\tilde{E}}{\tilde{H}}\right| \sin \delta
\]

- Theoretical expectations – suppression by $\sqrt{-t}$
  - Frankfurt et al. (2001)
  - Belitsky, Muller (2001)
  - Goloskokov, Kroll (2009)
  - Bechler, Muller (2009)

- Evidence of contribution from $\gamma_T^*$

- Unexpectedly large signal for subleading twist

- No turnover towards 0 at $t' \to 0$

- Can be explained by $\sigma_L/\sigma_T$ interference

- In good agreement with model prediction
  - Goloskokov, Kroll (2009)

- Sensitive to $H_T$ GPD

- Evidence of contribution from $\gamma_T^*$
Summary – DVCS

HERMES DVCS

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<thead>
<tr>
<th>Amplitude Value</th>
<th>GPDs</th>
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<tr>
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<td>Re(H)</td>
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<td>Im(H)</td>
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A. Airapetian et al, JHEP 06 (2008) 066
A. Airapetian et al, JHEP 06 (2010) 019
A. Airapetian et al, JHEP 07 (2012) 032
A. Airapetian et al, JHEP 10 (2012) 042
Summary – Mesons

> Single- and double-spin azimuthal asymmetries in meson production provide access to GPDs

> Transverse target asymmetries give model-based predictions/constraints for quark total orbital angular momentum (Ji framework)

> Significant signal of unnatural parity exchange observed in $w$ meson production provides access to spin-flip GPD $\tilde{H}$

> $\pi^+$ production allows access to subleading twist “transverse” GPD $H_T$
GPD $E$ and $J_u$ Constraint

![Graph showing GPD $E$ and $J_u$ Constraint with data points from HERMES, DD, and JLab Dual.](image-url)