Transverse Target-Spin Asymmetries of Exclusive ρ^0 and π^+ Mesons

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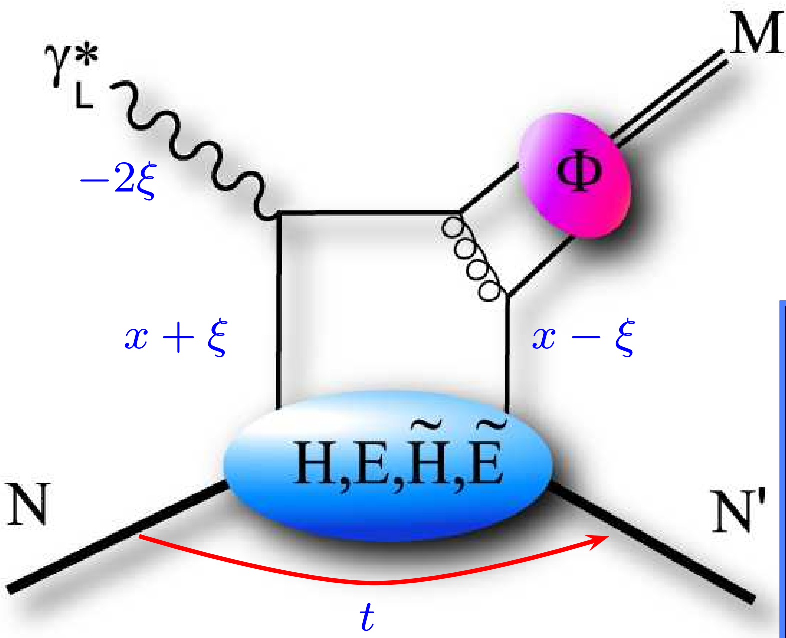
(on behalf of the HERMES collaboration)

Factorization theorem

$$\mathcal{A} \propto F(x, \xi, t; \mu^2) \otimes K(x, \xi, z; \log(Q^2/\mu^2) \otimes \Phi(z; \mu^2)$$

x, ξ	longitudinal momentum fractions
t	squared four-momentum transfer



at leading-twist F:H, E, $\widetilde{H}$, $\widetilde{E}$

- H and $\widetilde{H}$ conserve the nucleon helicity
- E and $\widetilde{E}$ describe the nucleon helicity flip

Quantum numbers of final state selects different GPDs

- vector mesons ($\gamma^*_L \rightarrow \rho_L, \omega_L, \phi_L$): H, E
- pseudoscalar mesons ($\gamma^*_L \rightarrow \pi, \eta$): $\widetilde{H}, \widetilde{E}$

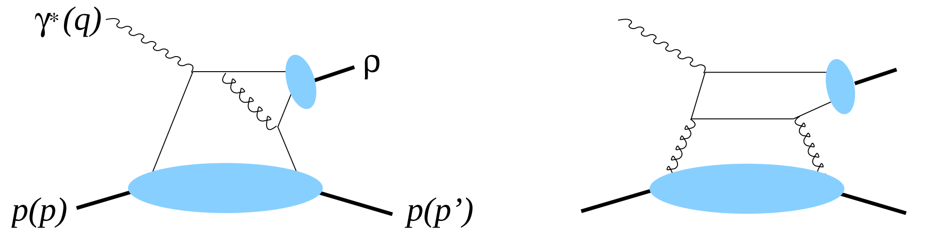
Factorization for longitudinal photons only

- suppression of σ_T

$$\frac{\sigma_T}{\sigma_L} \sim \frac{1}{Q^2}$$

Advantage of exclusive ρ^0 production

- the only process where the gluon contribution enters in LO
- exclusive ρ^0 sensitive to $H_{q,g}$ and $E_{q,g}$ at the same order in α_s



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- Ji's sum rules

$$J_q = \frac{1}{2} \lim_{t \to 0} \int_{-1}^{1} dx\, x\, [H_q + E_q]$$

$$J_g = \frac{1}{2} \lim_{t \to 0} \int_{0}^{1} dx\, x\, [H_g + E_g]$$

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- E_g is completely unknown

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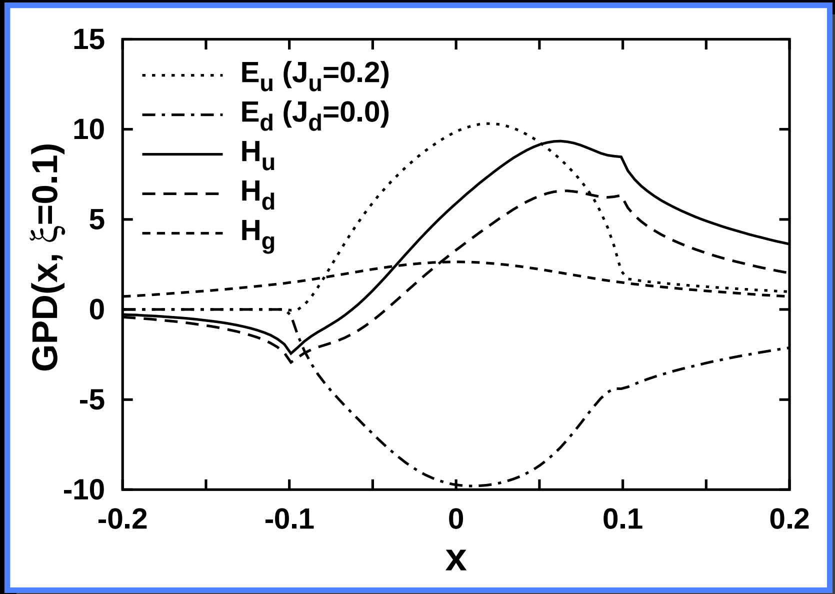
- E_g is completely unknown
  - expectation: E_g is not large

- Diehl (2003) -

$$\int_0^1 dx\, E_g + \sum_q \int_{-1}^{1} dx\, x E_q = 0$$

  - $E_u \approx -E_d$
  - E_s - small
  - $E_g = -2E_s$



-Ellinghaus,Nowak,Vinnikov,Ye (2005)-

-VGG code-

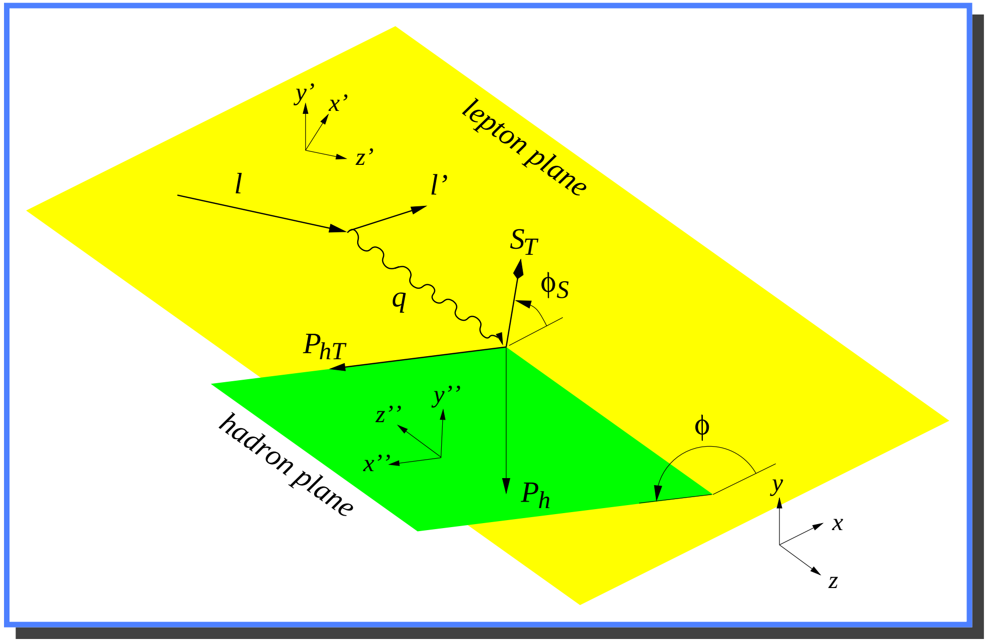
The transverse target polarization

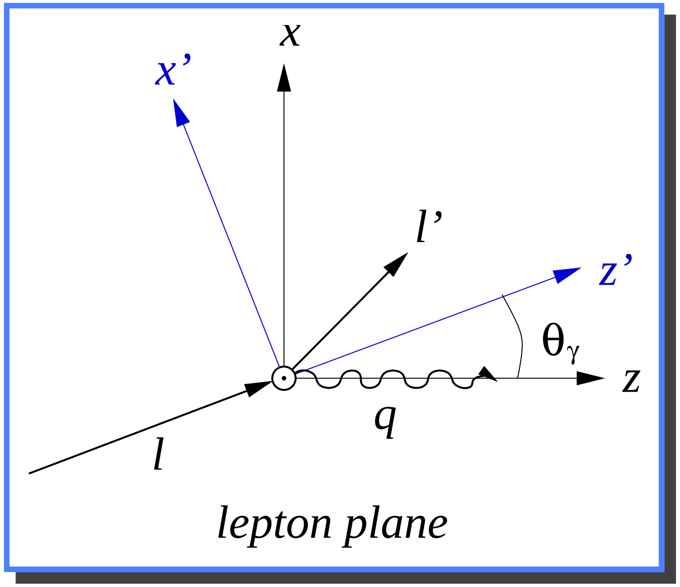
- experimentally:
  - P_T defined with respect to the lepton beam direction
- theoretically:
  - S_T defined with respect to the γ^* direction
- S_T and P_T are related to each other:

$$S_T = \frac{\cos\theta_\gamma}{\sqrt{1-\sin^2\theta_\gamma\,\sin^2\phi_S}} P_T$$

$$S_L = \frac{\sin\theta_\gamma\,\cos\phi_S}{\sqrt{1-\sin^2\theta_\gamma\,\sin^2\phi_S}} P_T$$

- $\theta_\gamma << 1$
  - $P_T \approx S_T$
  - $S_L << S_T$





Polarized Cross Section

$$\left[\frac{\alpha_{\rm em}}{8\pi^3}\,\frac{y^2}{1-\varepsilon}\,\frac{1-x_B}{x_B}\,\frac{1}{Q^2}\right]^{-1}\frac{d^4\sigma}{dx_B\,dQ^2\,d\phi\,d\phi_s} =$$

$$\frac{1}{2}\left(\sigma_{++}^{++}+\sigma_{++}^{--}\right)+\varepsilon\,\sigma_{00}^{++}$$

$$-\varepsilon\cos(2\phi)\,\Re\sigma_{+-}^{++}-\sqrt{\varepsilon(1+\varepsilon)}\cos\phi\,\Re(\sigma_{+0}^{++}+\sigma_{+0}^{--})$$

$$-\frac{P_T}{\sqrt{1-\sin^2\theta_\gamma\,\sin^2\phi_S}}\Bigg[\sin\phi_S\,\cos\theta_\gamma\sqrt{\varepsilon(1+\varepsilon)}\,\Im\sigma_{+0}^{+-}$$

$$+\sin(\phi-\phi_S)\Big(\cos\theta_\gamma\,\Im(\sigma_{++}^{+-}+\varepsilon\,\sigma_{00}^{+-})+\frac{1}{2}\sin\theta_\gamma\sqrt{\varepsilon(1+\varepsilon)}\,\Im(\sigma_{+0}^{++}-\sigma_{+0}^{--})\Big)$$

$$+\sin(\phi+\phi_S)\Big(\cos\theta_\gamma\,\frac{\varepsilon}{2}\,\Im\sigma_{+-}^{+-}+\frac{1}{2}\sin\theta_\gamma\sqrt{\varepsilon(1+\varepsilon)}\,\Im(\sigma_{+0}^{++}-\sigma_{+0}^{--})\Big)$$

$$+\sin(2\phi-\phi_S)\Big(\cos\theta_\gamma\sqrt{\varepsilon(1+\varepsilon)}\,\Im\sigma_{+0}^{-+}+\frac{1}{2}\sin\theta_\gamma\,\varepsilon\,\Im\sigma_{+-}^{++}\Big)$$

$$+\sin(2\phi+\phi_S)\,\frac{1}{2}\sin\theta_\gamma\,\varepsilon\,\Im\sigma_{+-}^{++}+\sin(3\phi-\phi_S)\,\cos\theta_\gamma\,\frac{\varepsilon}{2}\,\Im\sigma_{+-}^{-+}\Bigg]$$

-Diehl, Sapeta (2005)-

X-section decomposition in terms of:

σ_{mn}^{ij} $(\gamma^* p\to\rho^0 p',\,\gamma^* p\to\pi^+ n)$

virtual photon helicity: $m,n=0,\pm1$

proton spin state: $i,j=\pm(\frac{1}{2})$

Leading asymmetry amplitude

- transverse target-spin asymmetry:

$$A^{l}_{UT}(\phi,\phi_s) = \frac{\sigma_{UT}}{\sigma_{UU}} = A_{UT}^{\sin(\phi_s)}\sin(\phi_s) + A_{UT}^{\sin(\phi-\phi_s)}\sin(\phi-\phi_s)$$
$$+ A_{UT}^{\sin(\phi+\phi_s)}\sin(\phi+\phi_s) + A_{UT}^{\sin(2\phi-\phi_s)}\sin(2\phi-\phi_s)$$
$$+ A_{UT}^{\sin(2\phi+\phi_s)}\sin(2\phi+\phi_s) + A_{UT}^{\sin(3\phi-\phi_s)}\sin(3\phi-\phi_s)$$

- in leading twist:

$$\mathcal{A}^{\gamma^*}_{UT}(\phi,\phi_s) = \frac{\sigma_{UT}}{\sigma_{UU}} \Rightarrow A_{UT}^{\gamma^*_L\,\sin(\phi-\phi_s)} = \frac{\sigma_{00}^{+-}}{\sigma_{00}^{++}}$$

- $A_{UT}^{\sin\phi_s}$ and $A_{UT}^{\sin(2\phi-\phi_s)}$ are suppressed by at least $1/Q$
- $A_{UT}^{\sin(\phi+\phi_s)}$, $A_{UT}^{\sin(2\phi+\phi_s)}$ and $A_{UT}^{\sin(3\phi-\phi_s)}$ are suppressed by at least $1/Q^2$
- various azimuthal moments are extracted using Maximum Likelihood
  - 6 fit parameters

Leading asymmetry amplitude

- in leading twist:

$$\mathcal{A}_{UT}^{\gamma^*}(\phi,\phi_s) = \frac{\sigma_{UT}}{\sigma_{UU}} \Rightarrow A_{UT}^{\gamma_L^*\,\sin(\phi-\phi_s)} = \frac{\sigma_{00}^{+-}}{\sigma_{00}^{++}}$$

π^+

$$A_{UT}^{\gamma_L^*}(\phi,\phi_s) \propto -\frac{\xi\ \mathrm{Im}(\widetilde{\mathcal{E}}_\pi^*\widetilde{\mathcal{H}}_\pi)}{|\widetilde{\mathcal{H}}_\pi|^2} \propto -\left|\frac{\xi\widetilde{\mathcal{E}}_\pi}{\widetilde{\mathcal{H}}_\pi}\right|$$

- access to $\widetilde{E}$ and $\widetilde{H}$

ρ^0

$$A_{UT}^{\gamma_L^*}(\phi,\phi_s) \propto \frac{\mathrm{Im}(\mathcal{E}_\rho^*\mathcal{H}_\rho)}{|\mathcal{H}|^2} \propto \left|\frac{\mathcal{E}_\rho}{\mathcal{H}_\rho}\right|$$

- access to E and H

- E and $\widetilde{H}$ are kinematically not suppressed
- linear dependence on GPDs

γ_L^*/γ_T^* separation of the $\gamma^* p$ X-section

$$\Im\left(\sigma_{++}^{+-} + \epsilon\sigma_{00}^{+-}\right)$$

$$d\sigma(\phi,\phi_s) = \sigma_0 + \sigma_1|\vec{S}_\perp|\sin(\phi-\phi_s) + \sigma_2|\vec{S}_\perp|\frac{\epsilon}{2}\sin(\phi+\phi_s)...$$

$$\sigma_T + \epsilon\sigma_L$$

γ_L^*/γ_T^* separation of the $\gamma^* p$ X-section

$$\Im(\sigma_{++}^{+-} + \epsilon\sigma_{00}^{+-})$$

$$d\sigma(\phi,\phi_s) = \sigma_0 + \sigma_1|\vec{S}_\perp|\sin(\phi-\phi_s) + \sigma_2|\vec{S}_\perp|\frac{\epsilon}{2}\sin(\phi+\phi_s)...$$

$$\sigma_T + \epsilon\sigma_L$$

π^+:

- no Rosenbluth separation
- the asymmetry can not be separated into L and T components

γ^*_L/γ^*_T separation of the $\gamma^* p$ X-section

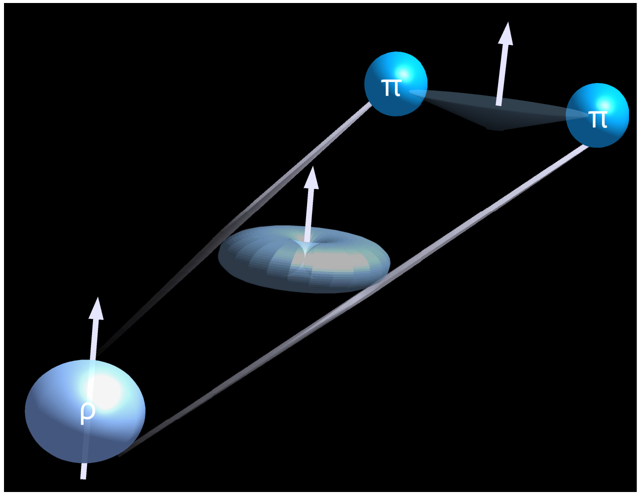
$$\Im(\sigma^{+-}_{++} + \epsilon\sigma^{+-}_{00})$$

$$d\sigma(\phi,\phi_s) = \sigma_0 + \sigma_1|\vec{S}_\perp|\sin(\phi-\phi_s) + \sigma_2|\vec{S}_\perp|\frac{\epsilon}{2}\sin(\phi+\phi_s)...$$

$$\sigma_T + \epsilon\sigma_L$$

ρ^0: γ^* and ρ^0 polarization states are reflected in the ρ^0 production and decay angular distributions W

- γ^* and ρ^0 have the same quantum numbers
  - a correlation of ρ^0 polarization with the polarization of the initial γ^*
  - signature: ρ^0 production angular distribution
- the spin-state of the ρ^0 is reflected in the orbital angular momentum of the decay particles
  - ρ^0 (in the rest frame): $J = L + S = 1$
  - $\pi : S = 0,\ L = 1$
  - signature: decay angular distribution



γ^*_L/γ^*_T separation of the $\gamma^* p$ X-section

$$\Im(\sigma_{++}^{+-} + \epsilon\sigma_{00}^{+-})$$

$$d\sigma(\phi,\phi_s) = \sigma_0 + \sigma_1|\vec{S}_\perp|\sin(\phi-\phi_s) + \sigma_2|\vec{S}_\perp|\frac{\epsilon}{2}\sin(\phi+\phi_s)...$$

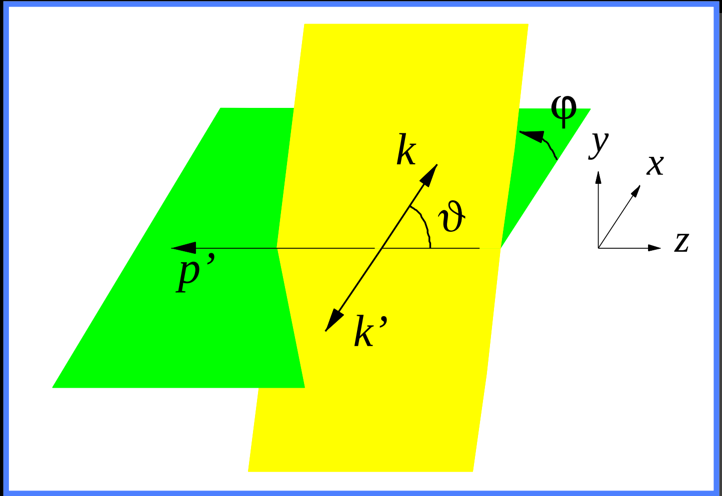
$$\sigma_T + \epsilon\sigma_L$$

ρ^0:

- Diehl, Sapeta (2005) -

σ^{ij}_{mn}: different dependences on $\cos\theta$

$$\frac{d\sigma^{ij}_{mn}(\gamma^* p \to \pi^+\pi^- p)}{d(\cos\vartheta)} = \frac{3\cos^2\vartheta}{2}\sigma^{ij}_{mn}(\gamma^* p \to \rho^0_L p) + \frac{3\sin^2\vartheta}{4}\sigma^{ij}_{mn}(\gamma^* p \to \rho^0_T p)$$



- under the assumption of SCHC a ρ^0_L/ρ^0_T is equivalent γ^*_L/γ^*_T, separation
- the cross section is integrated over φ: the interference terms between ρ^0_L and ρ^0_T are canceled

Asymmetry and ρ^0_L/ρ^0_T separation

The cress section $\sigma(P_T, \cos\theta, \phi, \phi_s)$ can be written in terms of asymmetries:

$$\sigma(P_T, \cos\theta, \phi, \phi_s) \propto$$

$$\Big[\cos^2\theta \;\; \widehat{\sigma}_{UU,\rho_L} \; \Big(1 + A_{UU,\rho_L}(\phi) + P_T A^l_{UT,\rho_L}(\phi, \phi_s)\Big) \; +$$

$$\frac{1}{2}\sin^2\theta \; \widehat{\sigma}_{UU,\rho_T} \Big(1 + A_{UU,\rho_T}(\phi) + P_T A^l_{UT,\rho_T}(\phi, \phi_s)\Big) \Big]$$

Asymmetry and ρ_L^0/ρ_T^0 separation

The cross section $\sigma(P_T, \cos\theta, \phi, \phi_s)$ can be written in terms of asymmetries:

$$\sigma(P_T, \cos\theta, \phi, \phi_s) \propto$$

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$$\frac{1}{2}\sin^2\theta \; \widehat{\sigma}_{UU,\rho_T} \Big(1 + A_{UU,\rho_T}(\phi) + P_T A^l_{UT,\rho_T}(\phi,\phi_s)\Big) \Big]$$

$$\widehat{\sigma}_{UU,\rho_L} = r^{04}_{00}$$

$$\widehat{\sigma}_{UU,\rho_T} = 1 - r^{04}_{00}$$

Asymmetry and ρ^0_L/ρ^0_T separation

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$$\sigma(P_T, \cos\theta, \phi, \phi_s) \propto$$

$$\Big[\cos^2\theta \; r^{04}_{00} \left(1 + A_{UU,\rho_L}(\phi) + P_T A^l_{UT,\rho_L}(\phi,\phi_s)\right) +$$

$$\frac{1}{2}\sin^2\theta \; (1 - r^{04}_{00})\left(1 + A_{UU,\rho_T}(\phi) + P_T A^l_{UT,\rho_T}(\phi,\phi_s)\right) \Big]$$

where $A_{UU}(\phi)$ and $A^l_{UT}(\phi,\phi_s)$ are parameterized as:

$$A_{UU}(\phi) = A^{\cos(\phi)}_{UU}\cos(\phi) + A^{\cos(2\phi)}_{UU}\cos(2\phi)$$

Asymmetry and ρ^0_L / ρ^0_T separation

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$$\sigma(P_T, \cos\theta, \phi, \phi_s) \;\propto$$

$$\Big[\quad \cos^2\theta \;\; r^{04}_{00} \; \Big(1 + A_{UU,\rho_L}(\phi) + P_T \; A^l_{UT,\rho_L}(\phi,\phi_s)\Big) +$$

$$\frac{1}{2}\sin^2\theta \; (1 - r^{04}_{00}) \Big(1 + A_{UU,\rho_T}(\phi) + P_T \; A^l_{UT,\rho_T}(\phi,\phi_s)\Big) \quad \Big]$$

where $A_{UU}(\phi)$ and $A^l_T(\phi,\phi_s)$ are parameterized as:

$$A_{UU}(\phi) = A^{\cos(\phi)}_{UU}\cos(\phi) + A^{\cos(2\phi)}_{UU}\cos(2\phi)$$

$$A^l_{UT}(\phi,\phi_s) = A^{\sin(\phi_s)}_{UT}\sin(\phi_s) + A^{\sin(\phi-\phi_s)}_{UT}\sin(\phi-\phi_s) +$$

$$A^{\sin(\phi+\phi_s)}_{UT}\sin(\phi+\phi_s) + A^{\sin(2\phi-\phi_s)}_{UT}\sin(2\phi-\phi_s) +$$

$$A^{\sin(2\phi+\phi_s)UT}\sin(2\phi+\phi_s) + A^{\sin(3\phi-\phi_s)}_{UT}\sin(3\phi-\phi_s)$$

Asymmetry and ρ_L^0/ρ_T^0 separation

The cross section $\sigma(P_T, \cos\theta, \phi, \phi_s)$ can be written in terms of asymmetries:

$$\sigma(P_T, \cos\theta, \phi, \phi_s) \propto$$

$$\Big[\cos^2\theta \;\; r_{00}^{04} \Big(1 + A_{UU,\rho_L}(\phi) + P_T \; A^l_{UT,\rho_L}(\phi,\phi_s)\Big) +$$

$$\frac{1}{2}\sin^2\theta \; (1 - r_{00}^{04}) \Big(1 + A_{UU,\rho_T}(\phi) + P_T \; A^l_{UT,\rho_T}(\phi,\phi_s)\Big) \Big]$$

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$$A_{UU}(\phi) = A_{UU}^{\cos(\phi)} \cos(\phi) + A_{UU}^{\cos(2\phi)} \cos(2\phi)$$

$$A^l_{UT}(\phi,\phi_s) = A_{UT}^{\sin(\phi_s)} \sin(\phi_s) + A_{UT}^{\sin(\phi-\phi_s)} \sin(\phi-\phi_s) +$$

$$A_{UT}^{\sin(\phi+\phi_s)} \sin(\phi+\phi_s) + A_{UT}^{\sin(2\phi-\phi_s)} \sin(2\phi-\phi_s) +$$

$$A^{\sin(2\phi+\phi_s)UT} \sin(2\phi+\phi_s) + A_{UT}^{\sin(3\phi-\phi_s)} \sin(3\phi-\phi_s)$$

- the number of azimuthal moments double: 12 fit parameters
- azimuthal moments extracted using Maximum Likelihood

Exclusive π^+ production: $ep \rightarrow e'\pi^+(n)$

- no recoil nucleon detection
- select exclusive π^+ reaction through the missing mass technique:

$$M_x^2 = (P_e + P_p - P_{e'} - P_{\pi^+})^2$$

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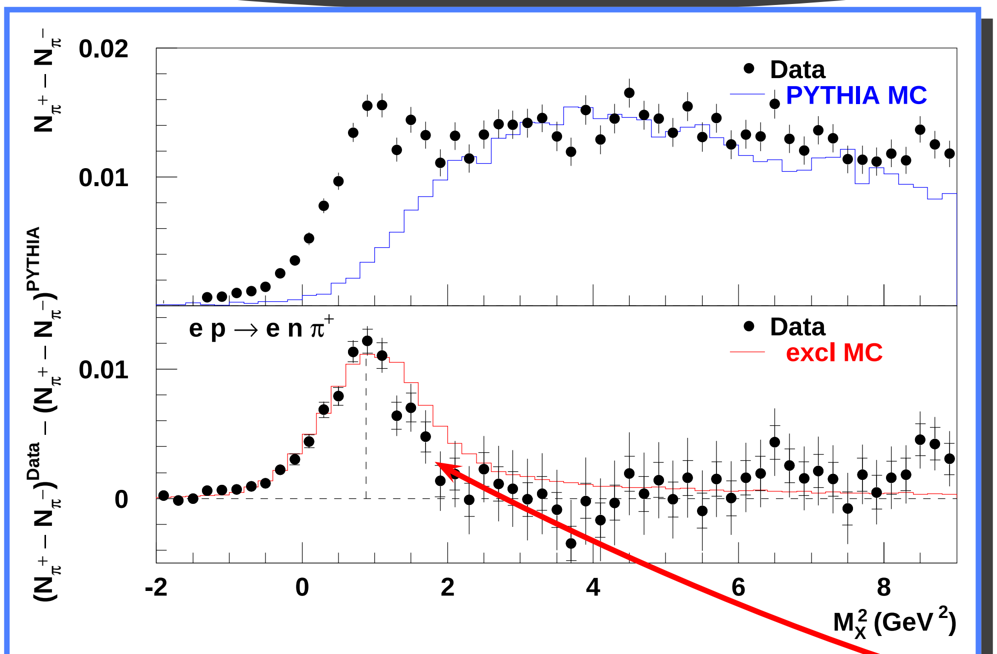
- select exclusive π^+ reaction through the missing mass technique:

$$M_x^2 = (P_e + P_p - P_{e'} - P_{\pi^+})^2$$

$$N^{excl} = (\pi^+ - \pi^-)^{data} - (\pi^+ - \pi^-)^{MC}$$

π^+	exclusive π^+	VM_{π^+}	SIDIS
π^-		VM_{π^-}	SIDIS



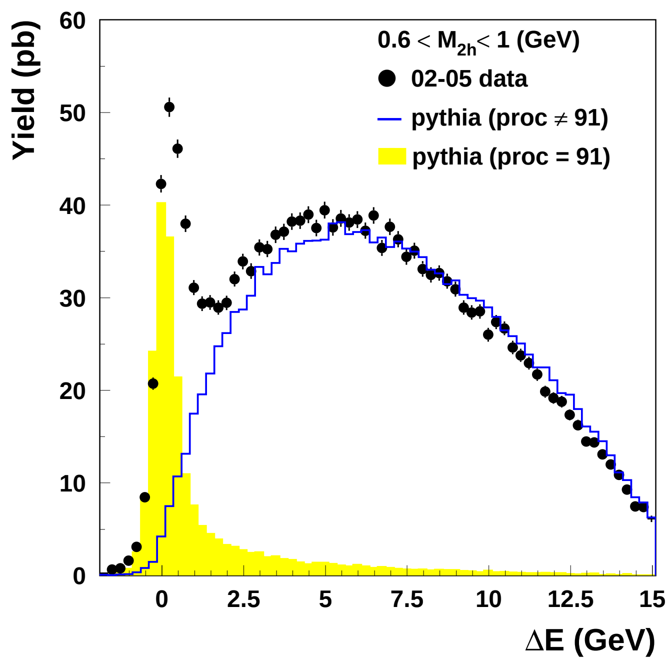
- $\pi^+ - \pi^-$ yield difference was used to subtract the non exclusive background
- exclusive peak centered at the nucleon mass
- exclusive MC based on GPD model

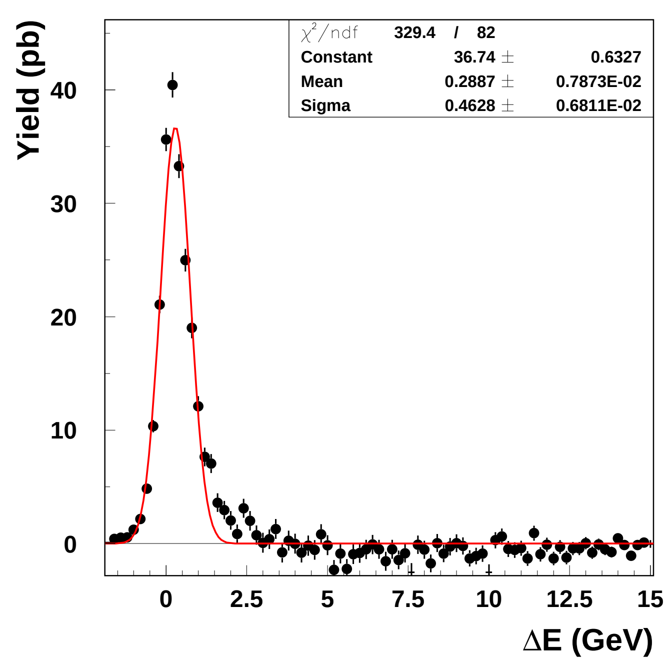
Exclusive ρ^0 production: $ep \rightarrow e'\pi^+\pi^-(p')$

- exclusive events: main contribution at small values of

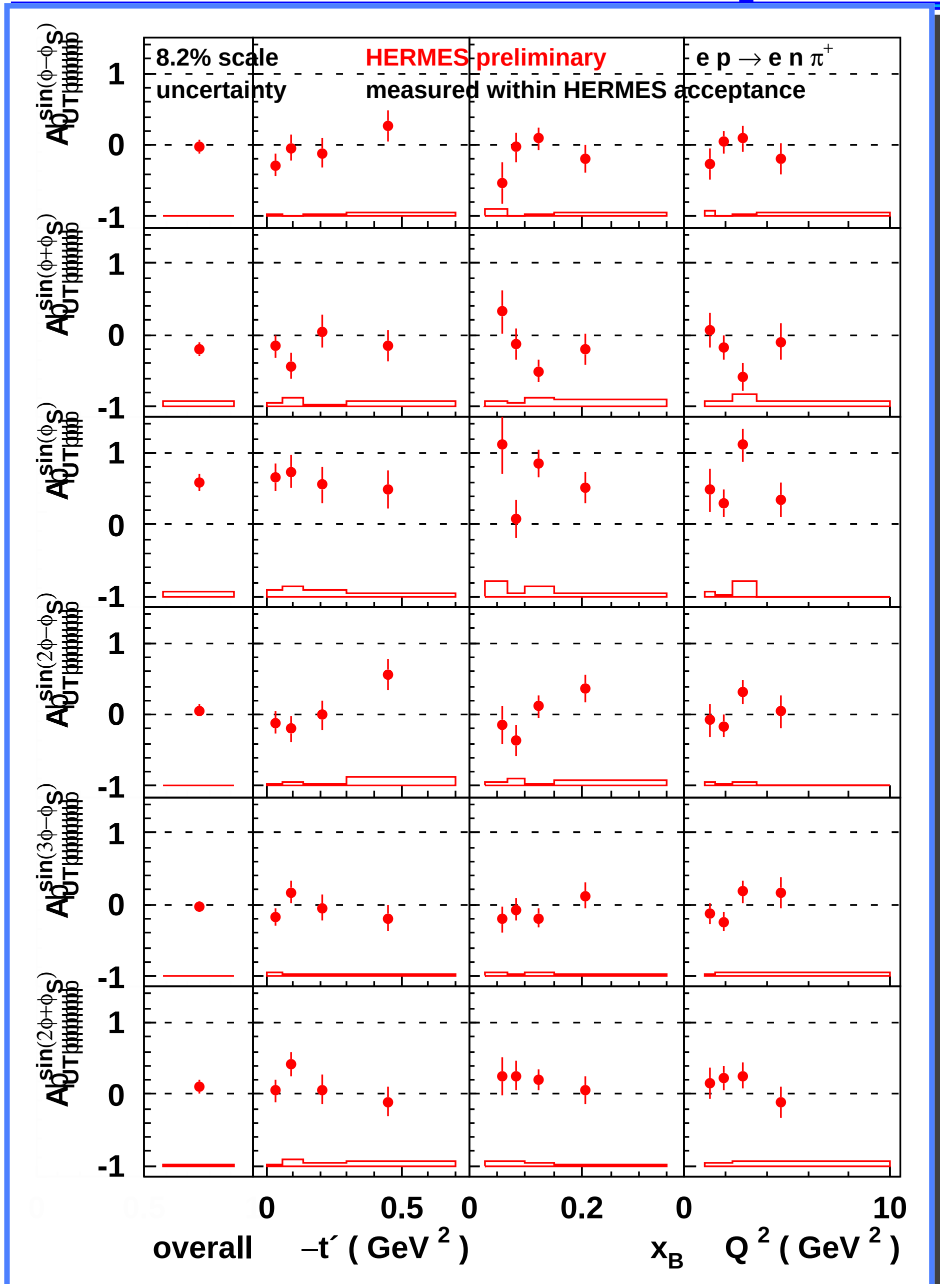
  $\Delta E = E_e + E_p - E_{e'} - E_\rho - E_{p'}$ and $t' = t - t_0$

- non-exclusive events ($\Delta E > 0$) contribute due to the experimental resolution and restricted acceptance
- events produced in non-exclusive processes as an estimate of the background size: 11%
- background corrected ΔE distribution: a clear Gaussian distribution



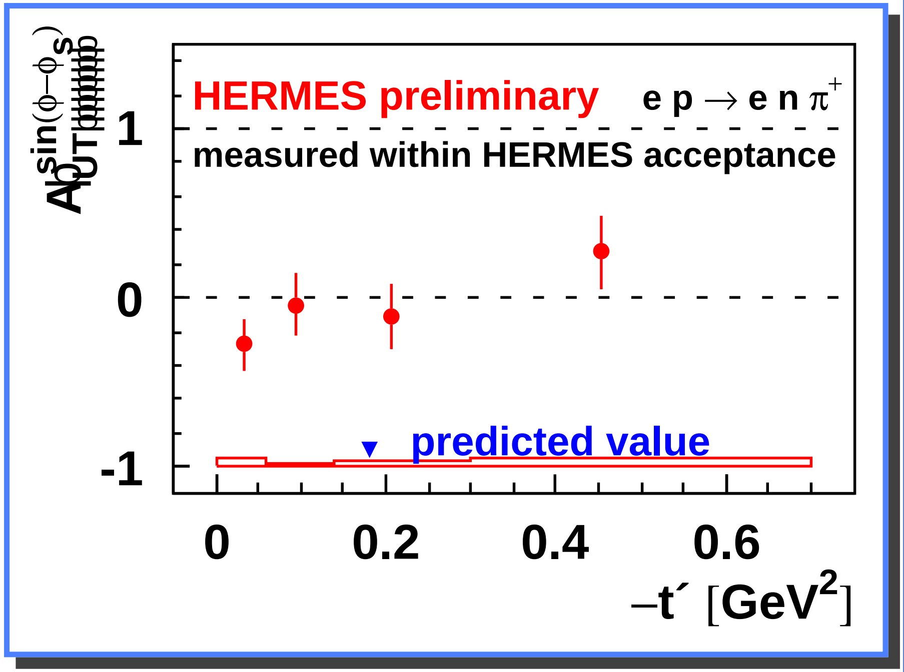


Kinematic dependences of $A_{UT}^{\pi^+}$



- full data set
- average kinematics:
  $\langle -t' \rangle = 0.18$ GeV^2
  $\langle x_B \rangle = 0.13$
  $\langle Q^2 \rangle = 2.38$ GeV^2
- small overall value for leading asymmetry amplitude $A_{UT}^{\sin(\phi-\phi_s)}$
- unexpected large overall value for asymmetry amplitude $A_{UT}^{\sin\phi_s}$

Leading asymmetry amplitude

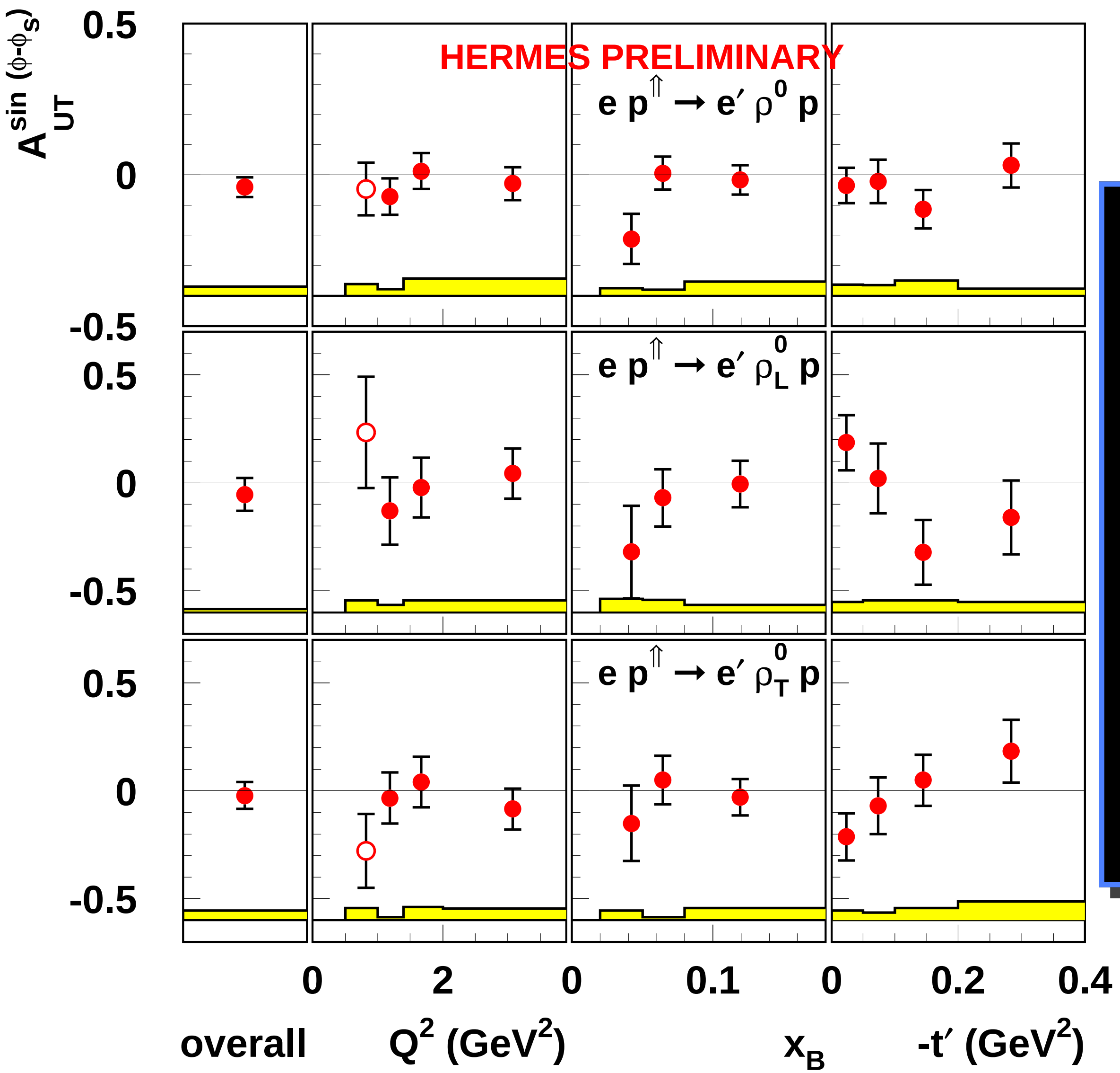


- measurement indicates for
  - a sign change
  - consistency with zero
- cross section result indicates:

  -Airapetian et al. (2008)-
  - σ_T is predicted to be
    - about 6% of σ at very low t
    - $15 - 25\%$ of σ
- smaller asymmetry than predicted
- the leading asymmetry amplitude

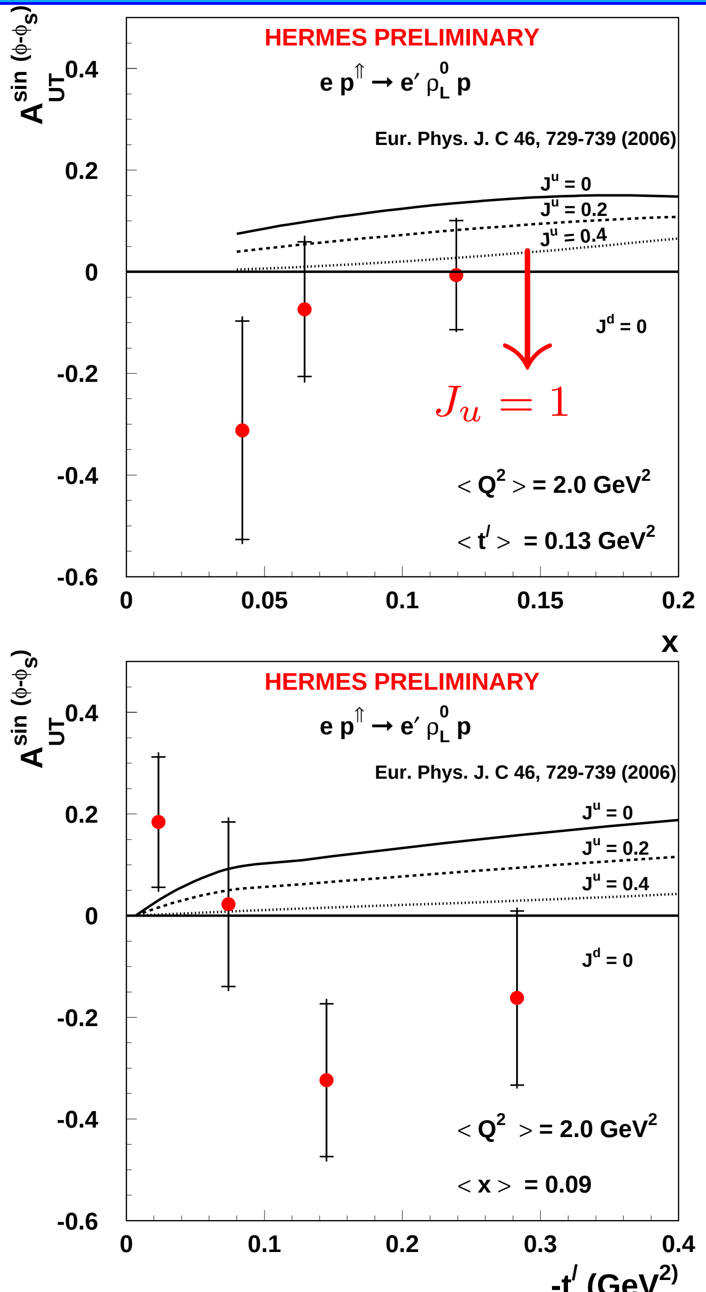
  $A_{UT}^{\sin(\phi-\phi_s)} \propto \mathrm{Im}(\widetilde{\mathcal{E}}_\pi^* \widetilde{\mathcal{H}}_\pi)$
  - $\widetilde{E}$ is supposedly large
  - $\widetilde{H}$ remains small

Kinematic dependences of $A_{UT}^{\rho^0}$



- full data set
- average kinematics:
  $\langle -t' \rangle = 0.13$ GeV^2
  $\langle x_B \rangle = 0.09$
  $\langle Q^2 \rangle = 1.95$ GeV^2
- σ_L and σ_T separation using the ρ^0 spin density matrix elements
- compatible with zero overall value for leading amplitude

Comparison with theory



- Ellinghaus, Nowak, Vinnikov, Ye (2006)-

- strongly simplified asymmetry:

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

  - parameterizations for H_q, $H_{\bar{q}}$, H_g
  - E_q is related to the total angular momenta J_u and J_d
    - predictions for $J_d = 0$
  - $E_{\bar{q}}$ and E_g are neglected
- data favors positive J_u
  - statistics too low to reliably determine the value of J_u and its uncertainty
- within the statistical uncertainty in agreement with theoretical calculations
  - indication of small E_g and $E_{\bar{q}}$?
- NLO corrections

Summary

π^+

- first experimental attempt to extract $A_{UT}^{\pi^+}$
- no separation of γ_L^*/γ_T^* contributions
  - cross section result indicates small σ_T contribution
- the leading asymmetry amplitude is compared to theoretical calculations
  - smaller asymmetry than predicted by theory
  - supposedly $\widetilde{E} >> \widetilde{H}$

ρ^0

- the asymmetry of exclusive ρ^0 mesons is extracted separately for ρ_L^0 and ρ_T^0
  - under the assumption of SCHC, is equivalent to $\gamma_L^*, \gamma_T^*,$ separation
- the leading asymmetry amplitude is compared to model calculation
  - the statistical accuracy of the presently available data prevents a reliable determination of J^u of u-quarks
    - data favors positive J^u
  - agreement of the extracted values of the asymmetry with the model predictions suggests small contributions for the GPDs $E^{\bar{q},g}$