Measurement of Semi-Inclusive Double-Spin Asymmetries and Spin-Structure Function g2 at HERMES

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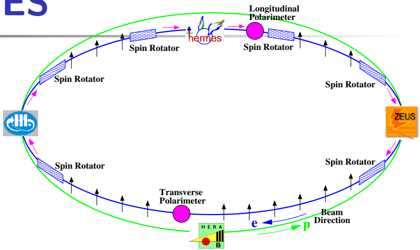
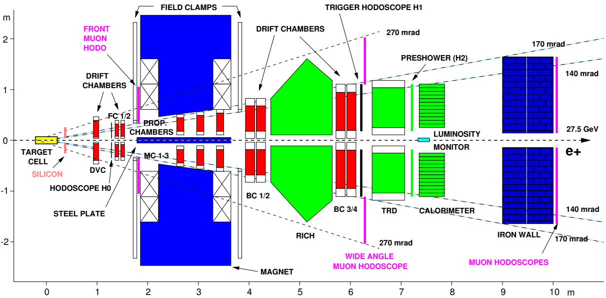
Outline

- Experiment HERMES
- Inclusive DIS: Measurement of $g_2(x)$
- Semi-Inclusive Longitudinal Double-Spin Asymmetries
  - 2D binned asymmetries $A_1(x, p_{h\perp})$ and $A_1(x, z)$
  - Hadron charge difference asymmetry
  - Valence Quark Distributions
- Summary

Experiment HERMES

27.5 GeV polarized e^+/e^- beam of HERA





Internal gas Target: polarized - $H^{\uparrow}$

Angular acceptance: $40 < \theta < 220$ mrad

RICH: π / K / p

- e/h rejection: TRD, Preshower, Calorimeter, RICH
- magnetic spectrometer: $\Delta p/p < 2.5\%$ and $\Delta\theta < 0.6$ mrad

Polarized Inclusive DIS

$$e(k,s) + p(P,S) \longrightarrow e'(k') + X(P_X)$$

$$Q^2 = -q^2 = -(k-k')^2, \quad x_B = \frac{Q^2}{2P\cdot q}, \quad y = \frac{P\cdot q}{P\cdot k}, \quad W^2 = (P+q)^2$$

$$\frac{d^2\sigma(s,S)}{dx\,dQ^2} = \frac{2\pi\alpha^2 y^2}{Q^6} L_{\mu\nu}(s) W^{\mu\nu}(S)$$

$W^{\mu\nu}$ parameterized in terms of Structure Functions $F_{1,2}$ and $g_{1,2}$

QPM:

$$F_1(x) = \frac{1}{2}\sum_q e_q^2 f_1^q(x) \qquad F_2(x) = x\sum_q e_q^2 f_1^q(x)$$

$$g_1(x) = \frac{1}{2}\sum_q e_q^2 g_1^q(x) \qquad g_2(x) = 0$$

OPE:

$$g_2(x,Q^2) = g_2^{WW}(x,Q^2) + \bar{g}_2(x,Q^2), \quad g_2^{WW}(x,Q^2) = -g_1(x,Q^2) + \int_x^1 g_1(y,Q^2)\frac{dy}{y}\ .$$

$\bar{g}_2(x,Q^2)$ — twist-3 part of $g_2(x,Q^2)$; $d_2(Q^2) = 3\int_0^1 x^2\,\bar{g}_2(x,Q^2)\,dx$ — lattice

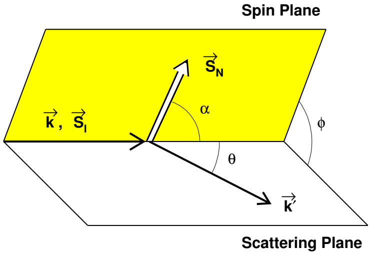
The Burkhardt-Cottingham sum rule: $\int_0^1 g_2(x,Q^2)\,dx = 0$

$$A_1 = \frac{\sigma^T_{1/2} - \sigma^T_{3/2}}{\sigma^T_{1/2} + \sigma^T_{3/2}} = \frac{g_1 - \gamma^2 g_2}{F_1}, \qquad A_2 = \frac{2\sigma^{TL}_{1/2}}{\sigma^T_{1/2} + \sigma^T_{3/2}} = \gamma\frac{g_1 + g_2}{F_1}$$

Polarized Inclusive DIS

$$\frac{d^3\sigma}{dx\,dy\,d\phi} \propto \frac{y}{2}F_1(x,Q^2) + \frac{1-y-\gamma^2y^2/4}{2xy}F_2(x,Q^2)$$
$$-P_B\cdot P_T\cos\alpha\left[\left(1-\frac{y}{2}-\frac{\gamma^2y^2}{4}\right)g_1(x,Q^2)-\frac{\gamma^2y}{2}g_2(x,Q^2)\right]$$
$$+P_B\cdot P_T\sin\alpha\cos\phi\,\gamma\sqrt{1-y-\frac{\gamma^2y^2}{4}}\left(\frac{y}{2}g_1(x,Q^2)+g_2(x,Q^2)\right)$$

$$\gamma = \frac{2Mx}{\sqrt{Q^2}}$$



Measurements of A_2^p, g_2^p:

- SMC (D.Adams et al., Phys.Rev. D56, 5330 (1997))
- E143 (K.Abe et al., Phys.Rev. D58, 112003 (1998))
- E155 (P.L.Anthony et al., Phys.Lett. B553, 18 (2003))
- JLAB (resonanse region)

HERMES has measured $A_1^{p,d}$, $g_1^{p,d}$ (A.Airapetian et al., Phys.Rev. D75, 012007 (2007))

Experimental Data

- 2002 - 2005 : data taking with transversely polarized hydrogen target.
- 2002 - essentially unpolarized beam.
- Flip of the target polarisation direction every 90 sec in 0.5 sec;
- Electron beam polarization reversed every few months.

The following kinematic requirements were imposed on the data:
$0.004 < x < 0.90$, $0.18 < Q^2 < 20$ GeV^2, $W > 1.8$ GeV, $0.1 < y < 0.91$
10 million events were accepted.

The target polarization $\langle P_T \rangle = 0.708 \pm 0.064$
The beam polarization $\langle P_B \rangle = 0.338 \pm 0.013$
(HERA Run 1 $\langle P_B \rangle \geq 50\%$)
$P_B > 0$: $\langle |P_B \cdot P_T| \rangle = 0.266 \pm 0.024$
$P_B < 0$: $\langle |P_B \cdot P_T| \rangle = 0.222 \pm 0.024$

$A_\perp$ Measurement

Four independent cross-sections, $\sigma^{\leftarrow\Uparrow}$, $\sigma^{\leftarrow\Downarrow}$, $\sigma^{\rightarrow\Uparrow}$, $\sigma^{\rightarrow\Uparrow}$.
One may construct two independent definitions of asymmetrty $A_\perp$:

$$
\begin{aligned}
\mathbf{A}_\perp(\phi, \mathbf{x}, \mathbf{Q}^2) &= +\frac{\sigma^{\leftarrow\Uparrow}(\phi, \mathbf{x}, \mathbf{Q}^2) - \sigma^{\leftarrow\Downarrow}(\phi, \mathbf{x}, \mathbf{Q}^2)}{\sigma^{\leftarrow\Uparrow}(\phi, \mathbf{x}, \mathbf{Q}^2) + \sigma^{\leftarrow\Downarrow}(\phi, \mathbf{x}, \mathbf{Q}^2)} \\
&= -\frac{\sigma^{\rightarrow\Uparrow}(\phi, \mathbf{x}, \mathbf{Q}^2) - \sigma^{\rightarrow\Downarrow}(\phi, \mathbf{x}, \mathbf{Q}^2)}{\sigma^{\rightarrow\Uparrow}(\phi, \mathbf{x}, \mathbf{Q}^2) + \sigma^{\rightarrow\Downarrow}(\phi, \mathbf{x}, \mathbf{Q}^2)} \\
&= \mathbf{A}_\mathbf{T}(\mathbf{x}, \mathbf{Q}^2) \cdot \cos\phi
\end{aligned}
$$

$$
\mathbf{A}_\mathbf{T}(\mathbf{x}, \mathbf{Q}^2) = \frac{-\gamma\sqrt{1 - \mathbf{y} - \frac{\gamma^2\mathbf{y}^2}{4}}\left(\frac{\mathbf{y}}{2}\mathbf{g}_1(\mathbf{x}, \mathbf{Q}^2) + \mathbf{g}_2(\mathbf{x}, \mathbf{Q}^2)\right)}{\frac{\mathbf{y}}{2}\mathbf{F}_1(\mathbf{x}, \mathbf{Q}^2) + \frac{1}{2\mathbf{xy}}(1 - \mathbf{y} - \gamma^2\mathbf{y}^2/4)\mathbf{F}_2(\mathbf{x}, \mathbf{Q}^2)}
$$

Extraction of A_T provides an access to g_2.

$A_\perp$ Measurement

Azimuthal angle ϕ is defined by vectors $\vec{k}$, $\vec{k}'$, and $\vec{S}_N$:

$$\phi = \frac{(\vec{k} \times \vec{S}_N) \cdot \vec{k}'}{|(\vec{k} \times \vec{S}_N) \cdot \vec{k}'|} \arccos \frac{(\vec{k} \times \vec{k}') \cdot (\vec{k} \times \vec{S}_N)}{|\vec{k} \times \vec{k}'||\vec{k} \times \vec{S}_N|}$$

Asymmetries for two beam polarization directions:

$$\mathbf{A}_\perp^{\rightarrow}(\phi_\mathbf{i}, \mathbf{x_j}) = \frac{-1}{\langle|\mathbf{P_B P_T}|\rangle^{\rightarrow}} \frac{\frac{\mathbf{n}^{\rightarrow\Uparrow}(\phi_\mathbf{i}, \mathbf{x_j})}{\mathbf{N}^{\rightarrow\Uparrow}} - \frac{\mathbf{n}^{\rightarrow\Downarrow}(\phi_\mathbf{i}, \mathbf{x_j})}{\mathbf{N}^{\rightarrow\Downarrow}}}{\frac{\mathbf{n}^{\rightarrow\Uparrow}(\phi_\mathbf{i}, \mathbf{x_j})}{\mathbf{N}^{\rightarrow\Uparrow}} + \frac{\mathbf{n}^{\rightarrow\Downarrow}(\phi_\mathbf{i}, \mathbf{x_j})}{\mathbf{N}^{\rightarrow\Downarrow}}}$$

$$\mathbf{A}_\perp^{\leftarrow}(\phi_\mathbf{i}, \mathbf{x_j}) = \frac{1}{\langle|\mathbf{P_B P_T}|\rangle^{\leftarrow}} \frac{\frac{\mathbf{n}^{\leftarrow\Uparrow}(\phi_\mathbf{i}, \mathbf{x_j})}{\mathbf{N}^{\leftarrow\Uparrow}} - \frac{\mathbf{n}^{\leftarrow\Downarrow}(\phi_\mathbf{i}, \mathbf{x_j})}{\mathbf{N}^{\leftarrow\Downarrow}}}{\frac{\mathbf{n}^{\leftarrow\Uparrow}(\phi_\mathbf{i}, \mathbf{x_j})}{\mathbf{N}^{\leftarrow\Uparrow}} + \frac{\mathbf{n}^{\leftarrow\Downarrow}(\phi_\mathbf{i}, \mathbf{x_j})}{\mathbf{N}^{\leftarrow\Downarrow}}}$$

$A_\perp^{\rightarrow}$ and $A_\perp^{\leftarrow}$ measure the same physical quantity - can be averaged.

Unfolding of the Asymmetry

- Raw asymmetries have to be corrected for:
  - QED radiative effects
  - detector smearing
- Event migration is simulated by Monte Carlo which includes a full detector description and a model for the cross section.
- The approach is independent on the model for the asymmetry in the measured region.

Unfolding procedure as in HERMES g_1 paper (A.Airapetian et al., Phys.Rev. D75, 012007 (2007))

$$\mathbf{A}_{\perp}^{\mathbf{B}}(\mathbf{j}) = -\mathbf{1} + \frac{\mathbf{2}}{\mathbf{N}_{\mathbf{B}}^{\mathbf{unpMC}}(\mathbf{j})} \sum_{\mathbf{i}=\mathbf{1}}^{\mathbf{n_{bins}}} \left[\mathbf{S}^{\rightarrow\Downarrow} + \mathbf{S}^{\rightarrow\Uparrow}\right]^{-\mathbf{1}}(\mathbf{j},\mathbf{i}) \times$$

$$\left[\mathbf{A}_{\perp}^{\mathbf{obs}}(\mathbf{i}) \cdot \mathbf{N}_{\mathbf{obs}}^{\mathbf{unpMC}}(\mathbf{i}) - \mathbf{n}_{\mathbf{bg}}^{\mathbf{MC}}(\mathbf{i}) + \sum_{\mathbf{k}=\mathbf{1}}^{\mathbf{n_{bins}}} \mathbf{S}^{\rightarrow\Uparrow}(\mathbf{i},\mathbf{k}) \cdot \mathbf{N}_{\mathbf{B}}^{\mathbf{unpMC}}(\mathbf{k})\right]$$

Here, $S(i,j)$ is the smearing matrix.
Unfolding procedure produces a correlation between data points.
The covariance matrix should be used for any further analysis of the data.

$A_2(x)$ and $g_2(x)$ Extraction

Asymmetries $A_\perp^B(\phi, x)$ were used to get $A_T(x)$: $A_\perp^B(\phi, x) = A_T(x) \cdot \cos\phi$.

$$A_T \quad \Longrightarrow \quad \begin{aligned} \mathbf{A_2} &= \frac{\mathbf{1}}{\mathbf{1}+\gamma\xi}\left(\frac{\mathbf{A_T}}{\mathbf{d}} + \xi(\mathbf{1}+\gamma^2)\,\frac{\mathbf{g_1}}{\mathbf{F_1}}\right), \\ \mathbf{g_2} &= \frac{\mathbf{F_1}}{\gamma(\mathbf{1}+\gamma\xi)}\left(\frac{\mathbf{A_T}}{\mathbf{d}} - (\gamma-\xi)\,\frac{\mathbf{g_1}}{\mathbf{F_1}}\right) \end{aligned}$$

Here, $F_1(x, Q^2) = \dfrac{1+\gamma^2}{2x(1+R(x, Q^2))} F_2(x, Q^2)$

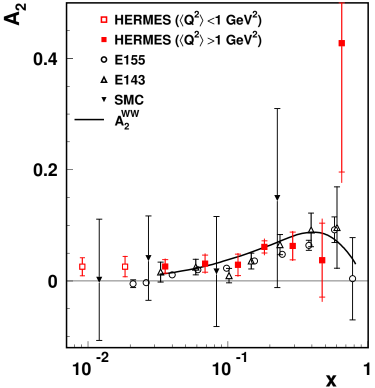
The following parameterizations were used:

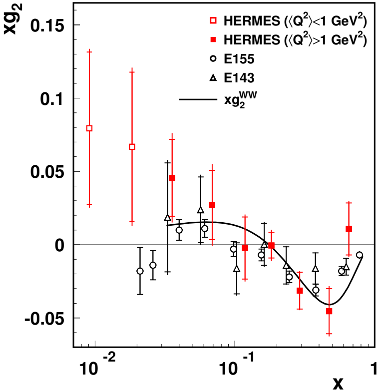
$R(x, Q^2) = \sigma_L/\sigma_T$ – R1998 (E143 Coll. K. Abe et al., Phys.Lett. B452, 194 (1999))
$F_2(x, Q^2)$ – HERMES data (A. Airapetian et al., JHEP **0511**, 126 (2011))
$g_1/F_1(x, Q^2)$ – (E155 Coll. P.L. Anthony et al., Phys.Lett. B493, 19 (2000))

Systematic uncertainties were estimated to be much less then statistical ones.

$A_2(x)$ and $xg_2(x)$ Results

Final results — Eur. Phys. J. C 72 (2012) 1921





$d_2 = 0.0148 \pm 0.0096(stat) \pm 0.0048(syst)$ $d_2 = 0.0032 \pm 0.0017$ (E143 and E155)

Burkhardt–Cottingham integral at $Q^2 = 5$ GeV^2

$\int_{0.023}^{0.9} g_2(x, Q^2)\, dx = 0.006 \pm 0.024 \pm 0.017$ $\int_{0.02}^{0.8} g_2(x, Q^2)\, dx = -0.042 \pm 0.008$ (E143 and E155)

HERMES made first measurement of g_2 using the target with the dilution factor $= 1$

Semi-Inclusive Long. Double-Spin Asymmetries

Inclusive virtual-photon nucleon asymmetry:

$$A_1(x, Q^2) = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} - \sigma_{3/2}} \simeq \frac{\sum_q e_q^2 \Delta q(x, Q^2)}{\sum_q e_q^2 q(x, Q^2)}$$

DIS doesn't allow to study the flavor structure of the nucleon.

Semi-Inclusive virtual-photon nucleon asymmetry:

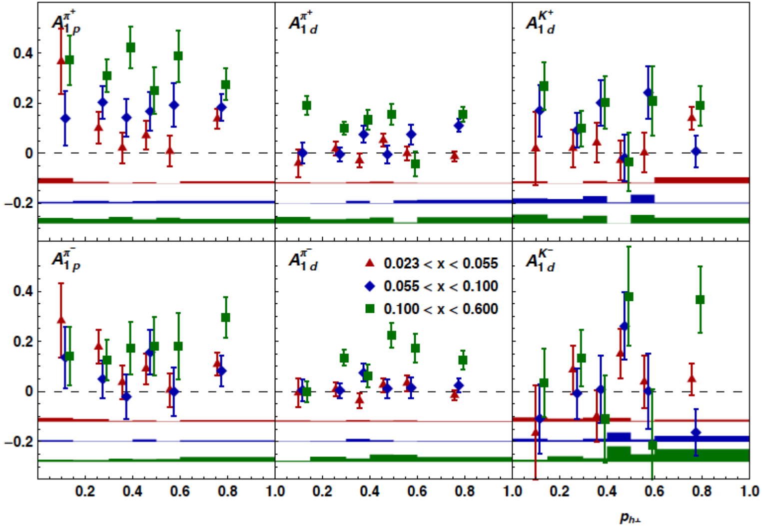
$$A_1(x, z, p_{h\perp}) = \frac{\sigma^h_{1/2} - \sigma^h_{3/2}}{\sigma^h_{1/2} - \sigma^h_{3/2}} \simeq \frac{\sum_q e_q^2 \Delta q(x) D_q^h(z, p_{h,\perp})}{\sum_q e_q^2 q(x) D_q^h(z, p_{h,\perp})}$$

SIDIS provides additional information about the flavor-dependence of the parton distributions and about the fragmentation process. Three additional kinematic variables: z, $p_{h\perp}$ and ϕ.

HERMES studied 3D binned kinematic-dependent asymmetries $A_1(x, z, p_{h\perp})$.
The asymmetries could be useful for many future possible studies:
– e.g., the intrinsic parton $k_\perp$ and the fragmentation related $p_\perp$ combine to produce the $p_{h\perp}$ dependence of the asymmetry. A multidimensional dataset potentially provides a possiblity to disentangle the individual contributions.
– empirical results should be made available with as few model assumptions and model-related kinematic requirements as possible in order to allow for the broadest range of theoretical models and assumptions.

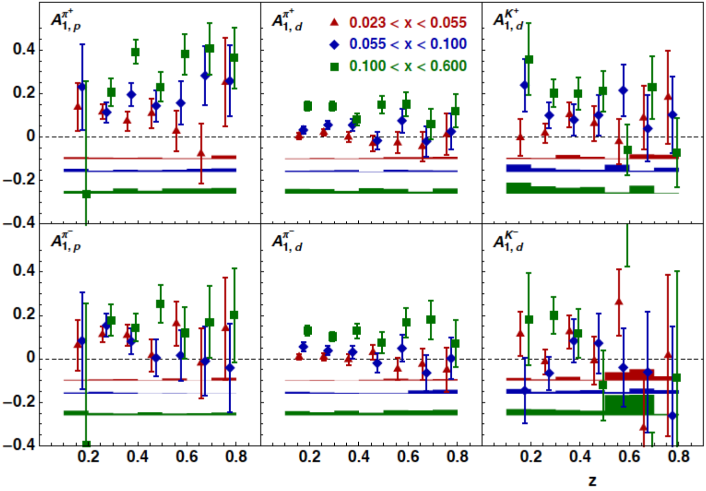
Kinematic dependencies were studied at proton and deuteron targets in the following region:
$Q^2 > 1$ GeV^2, $W^2 > 10$ GeV^2, $y < 0.85$, $0.2 < z < 0.9$

2D binned asymmetry $A_1(x, p_{h\perp})$



No significant $p_{h\perp}$ dependence observed.

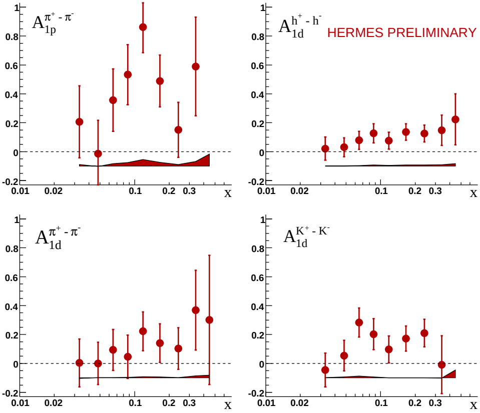
2D binned asymmetry $A_1(x, z)$



No significant z dependence observed.

Hadron charge difference asymmetry

$$A_1^{h^+-h^-} = \frac{(\sigma_{\uparrow\downarrow}^{h^+} - \sigma_{\uparrow\downarrow}^{h^-}) - (\sigma_{\uparrow\uparrow}^{h^+} - \sigma_{\uparrow\uparrow}^{h^-})}{(\sigma_{\uparrow\downarrow}^{h^+} - \sigma_{\uparrow\downarrow}^{h^-}) + (\sigma_{\uparrow\uparrow}^{h^+} - \sigma_{\uparrow\uparrow}^{h^-})}$$



Provides additional spin-structure information

Valence Quark Distributions

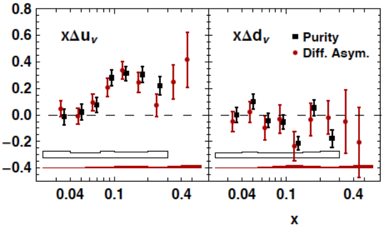
Separation of valence quark distributions:

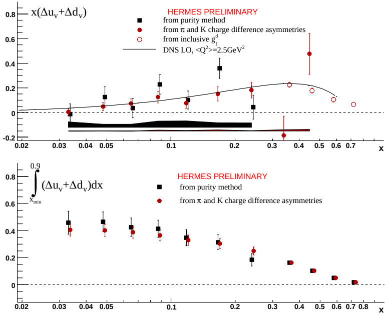
- Leading-order QCD
- Charge conjugation symmetry for FF: $D_q^{h^+} = D_{\bar{q}}^{h-}$
- Isospin symmetry in fragmentation: $D_u^{\pi^+} = D_d^{\pi^-}$

$$A_{1,p}^{\pi^+-\pi^-} = \frac{4\Delta u_V - \Delta d_V}{4u_V - d_V}$$

For isoscalar target and $\Delta s = \Delta\bar{s}$:

$$A_{1,d}^{\pi^+-\pi^-} = A_{1,d}^{K^+-K^-} = \frac{\Delta u_V + \Delta d_V}{u_V + d_V}$$





Summary

- Structure function g_2 and the virtual photon asymmetry A_2 were measured. This is a first measurement using the target with dilution factor $= 1$.
  - For the covered x-range the measured integral of $g_2(x)$ converges to the null result of the Burkhardt-Cottingham sum rule.
  - The x^2 moment, $d_2(x)$, is found to be compatible with zero, in agreement with expectations on its smallness from lattice calculations.
  - The results are overall in good agreement with measurements of SMC, E143 and E155, but they are not statistically precise enough to detect a deviation of g_2 from its Wandzura-Wilczek part, as seen by the SLAC experiments.
- Kinematic Dependence of Semi-Inclusive Longitudinal Double-Spin Asymmetries is studied
  - No significant $p_{h\perp}$ and z dependence of the asymmetry observed
  - Hadron charge difference asymmetry constructed and the valence quark distributions are extracted. The distributions are in a good agreement with those measured by HERMES using the purity method.