Effects of $e^\pm$ Polarization on the Final States at HERA

Ringberg Workshop

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Outline

- HERA II
- Polarization Dependent Inclusive Cross Section
  \textit{CC, NC}
- Deeply Virtual Compton Scattering
  \textit{cross section, asymmetries}
- Asymmetries in Particle Production
- Beam Spin Transfer to $\Lambda$-Baryons
- Conclusion
First Polarized e @H1+ZEUS in 2003

319 GeV
The HERA II Beam Options

**e-beam**
- $e^+$ and $e^-$  \(\rightarrow\) *beam charge dependencies*
- longitudinally parallel/anti-parallel polarizations with expected values up to 50-60% with a precision of $\delta P/P \sim 1\%$  \(\rightarrow\) *beam spin dependencies*

\(\Rightarrow\) *enhanced physics potential!*

**high luminosity**
- up to 1fb$^{-1}$ until 2006,
  - i.e. about 200pb$^{-1}$ per sample $e^+ (\lambda=\pm 1)$, $e^- (\lambda=\pm 1)$
  - expected and wanted

but *p-beam unpolarized still!*

\(\Rightarrow\) *no access to polarized proton and photon PDFs (requires double spin asymmetries)*
The Classic’s...
“Classic” Goal (I): Search for Right-Handed Currents in CC DIS

Forbidden in Standard Model: $\sigma_{CC} \to 0$ for $e^\pm_R$

→ textbook measurement!
**Simulation of $\sigma_{CC}^{\pm}(\lambda)$**

$$\sigma_{CC}^{\pm} = \frac{2\pi a^2}{xQ^4} \kappa_w^2 \left( Q^2 \right)^{1 \pm \lambda} \frac{1}{2} \left( Y_+ W_2^\pm + Y_- x W_3^\pm \right)$$

with $Y_+ = 2 - 2y + y^2 / (1 + R)$

$$Y_- = 1 - (1 - y)^2$$

$$\kappa_w = \frac{Q^2}{Q^2 + M_w^2} \frac{1}{4 \sin^2 \theta_w} = 1 \quad \text{for} \quad Q^2 \gg M_w^2$$

50pb$^{-1}$ per $\lambda = \pm 0.6$

$\Rightarrow$ modest luminosity but high polarization needed

$\Rightarrow$ new physics beyond SM if any deviation from straight line
“Classic” Goal (II): Parity Violation in NC

interference of electromagnetic and weak neutral currents \( \rightarrow \) vector (v) and axial-vector (a) contributions

\[
\frac{d\sigma_{\text{int}}^{\pm}(\lambda)}{dQ^2 d\nu} = \frac{2\pi\alpha^2}{xQ^4} \kappa_Z(Q^2) \left\{ Y_+ (R = 0) G_2(-v_e \pm \lambda a_e) + Y_- xG_3(\mp a_e + \lambda v_e) \right\}
\]

- depending both on beam polarization \( \lambda \) and beam charge \( \pm \)
- new structure functions \( G_2 \) and \( xG_3 \) containing quark couplings to the Z boson

\[
G_2(x) = 2x\sum_q v_q e_q (q(x) + \bar{q}(x))
\]

\[
xG_3(x) = -2x\sum_q a_q e_q (q(x) - \bar{q}(x))
\]

\[
v_f = T_{3f} - 2e_f \sin^2 \theta_w
\]

\[
a_f = T_{3f}
\]
Asymmetries in NC DIS

- **varying beam polarization** [ed: SLAC 1978]
  - one *parity-violation asymmetry* per beam charge

\[
A^{\mp}(\lambda_1', \lambda_2) = \frac{d\sigma^{\mp}(\lambda_1) - d\sigma^{\mp}(\lambda_2)}{d\sigma^{\mp}(\lambda_1) + d\sigma^{\mp}(\lambda_2)} = -\kappa Z \frac{\lambda_1 - \lambda_2}{2} \left( \mp a_e \frac{G_2}{F_2} + v_e \frac{xG_3}{F_2} \frac{1-(1-y)^2}{1+(1-y)^2} \right)
\]

- **varying of both \( \lambda \) and beam charge** [\( \mu C \): BCDMS 1981]
  - ‘*beam conjugation’ asymmetry*

\[
B(\lambda_1', \lambda_2) = \frac{d\sigma^+(\lambda_1) - d\sigma^-(\lambda_2)}{d\sigma^+(\lambda_1) + d\sigma^-(\lambda_2)} = -\kappa Z \left( a_e^+ \frac{\lambda_1 - \lambda_2}{2} v_e \right) \frac{xG_3}{F_2} \frac{1-(1-y)^2}{1+(1-y)^2}
\]

- Measurements require high polarization values and high Q2 values

\[
\kappa_Z = \frac{1}{4 \cos^2 \theta_w \sin^2 \theta_w M_Z^2 + Q^2} \approx 1.7 \cdot 10^{-4} Q^2 / \text{GeV}^2
\]
**Simulation of $G_2(x, Q^2)$ at high $Q^2$**

for $\lambda_2 = -\lambda_1$ and $v_e = 0$:

$$A^\mp(\lambda) = \mp \kappa_2 \lambda a_e \frac{G_2(x \rightarrow 1)}{F_2} \sim \pm \kappa_2 \lambda \frac{1 + d_v / u_v}{4 + d_v / u_v}$$

using approximation:

$$F_2 = \frac{1}{9} x (4 (u + \bar{u}) + (d + \bar{d})) \rightarrow \text{Singlet} + \text{Non-Singlet}$$

$$G_2 = \frac{2}{9} x (u + \bar{u}) + (d + \bar{d})) \rightarrow \text{Singlet}$$

$\rightarrow$ extraction of $G_2(x, Q^2)$ using knowledge of $F_2(x, Q^2)$

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*Uta Stößlein – Effects of $e^\pm$ Polarization on the Final States at HERA*
employ beam polarization and charge to test $M_W$ or $\sin^2\theta_W$ via

- parity-violation asymmetry $A^{\pm}(\lambda)$
- cross section ratio $R^{\pm}(\lambda)$

$$R^{\pm} (\lambda) = \frac{\sigma^{\pm}_{NC} (\lambda)}{\sigma^{\pm}_{CC} (\lambda)}$$

$\Rightarrow$ stat. error of $M_W$ from $R^-$ 

*best* and only 25% worse if $\lambda=0$ instead of -1 ($\delta\lambda=1\%$) although

$$\frac{\sigma_{CC} (\lambda=1)}{\sigma_{CC} (\lambda=0)} \sim 2$$
The “New” Classic’s...
Deeply Virtual Compton Scattering

**DVCS**
- QCD process → sensitive to underlying dynamics

\[ \frac{d^4\sigma}{dx dQ^2 dt d\phi} \propto |\tau_{DVCS}|^2 + |\tau_{BH}|^2 + |\tau_{DVCS}^* \tau_{BH}| + |\tau_{DVCS} \tau_{BH}^*| \]

**Bethe-Heitler**
- QED process → background and interference

Deeply Virtual Compton Scattering (DVCS) is a QCD process sensitive to the underlying dynamics, while the Bethe-Heitler process is a QED process representing background and interference.
**DVCS : Models**

**GPD based models**

- GPD incorporate both a *partonic and distributional amplitude behavior*
  - access to dynamical relation between different partons (particle correlations, orbital angular momentum)
  - three-dimensional distribution of nucleon substructure
- **QCD picture** (hard scattering factorization: LO, beyond LO, beyond twist-2)

**Color Dipole based models**

- simple unified picture of diffractive processes
  - match soft and hard regimes
  - implementation of e.g. saturation effects
- **broad phenomenology**

> \[ x_1 p \]
> \[ x_2 p \]

'handbag'

dominant at low x

\[ b \] impact parameter

dipole size R
Nucleon Holography

GPD provide transverse location of partons in the nucleon

Form factor

Parton density

GPD at \( \eta=0 \)

\[ b \sim 1/(-t)^{1/2} \]

see also talks by A. Freund and C. Weiss at HERA 3 WS02
**DVCS : Experimental Signatures**

[hep-ex/0305028]
DVCS: Cross Section vs $W$

$\rightarrow$ $W$ dependence matches $W^{0.7}$ behavior of hard VM production
**DVCS : Cross Section vs $Q^2$**

- **Graphs**:
  - **ZEUS**:
    - Fit $Q^{-2n}$
    - $e^+p$: $n = 1.54 \pm 0.07\text{(stat.)} \pm 0.06\text{(syst.)}$
  - **H1**:
    - $26\text{pb}^{-1}$
    - $95\text{pb}^{-1}$

- **Comments**:
  - $Q^2$ dependence well described by GPD or color dipole based models (integrated over exp. t range)
  - HERAII : factor 10 more statistics expected

- **Equation**:
  - $<W> = 82\text{ GeV}$
Angular Dependencies of ep → eγp Cross Section

angle between the lepton and hadron scattering planes
\( \phi = \phi_N - \phi_l \)

**BH**

\[
|T_{BH}|^2 = \frac{e^6}{x_B y^2 (1 + e^2)^2 \Delta^2 P_1(\phi) P_2(\phi)} \left\{ c_{0}^{BH} + \sum_{n=1}^{2} c_{n}^{BH} \cos(n\phi) + s_{1}^{BH} \sin(\phi) \right\},
\]

**DVCS**

\[
|T_{DVCS}|^2 = \frac{e^6}{y^2 Q^2} \left\{ c_{0}^{DVCS} + \sum_{n=1}^{2} \left[ c_{n}^{DVCS} \cos(n\phi) + s_{n}^{DVCS} \sin(n\phi) \right] \right\},
\]

**Interference**

\[
I = \frac{\pm e^6}{x_B y^3 \Delta^2 P_1(\phi) P_2(\phi)} \left\{ c_{0}^{I} + \sum_{n=1}^{3} \left[ c_{n}^{I} \cos(n\phi) + s_{n}^{I} \sin(n\phi) \right] \right\},
\]

⇒ Complex and rich angular structure of the cross section!
⇒ But, which angular dependencies are the relevant ones?
Contributions for an Unpolarized $p$

employ angular structure to access more observables, in particular in dependence on beam spin ($\lambda$) and charge ($\pm$)

- DVCS amplitude with gluon transversity (twist-2, but $\alpha_s$ power supp.)
  - squared DVCS term: $\cos\phi$ and $\sin\phi$ dependencies
  - interference term: $\cos\phi$ and $\sin\phi$ dependencies

- BH term: beam polarization dependence only in case of longitudinally or transversely (L,T) polarized target!
Beam Charge and Azimuthal Asymmetry

varying beam charge \[\text{[HERMES 2002]}\]

\( \Rightarrow \) beam charge asymmetry \((CA)\)

\[
CA = \frac{2 \int_0^{2\pi} d\phi \cos(\phi)(d\sigma^+ - d\sigma^-)}{\int_0^{2\pi} d\phi (d\sigma^+ + d\sigma^-)} \propto c_1^{3,\text{unpol}} - \frac{1}{3} c_3^{3,\text{unpol}} - \frac{2(3 - 2y)}{2 - y} K \left( c_0^{3,\text{unpol}} - \frac{1}{3} c_2^{3,\text{unpol}} \right)
\]

or counting events scattered ‘up’ and ‘below’ lepton scattering plane to get \(\cos\phi\) weight \(\Rightarrow 2\) bins in \(\phi\)

\[
\Delta \sigma^{\text{unpol}} = d\sigma^{-,\text{tot}} - d\sigma^{+,\text{tot}}
\]

\[
CA = \frac{\int_{-\pi/2}^{\pi/2} \Delta d\sigma^{\text{tot}} - \int_{-3\pi/2}^{-\pi/2} d\phi \Delta d\sigma^{\text{tot}}}{\int_0^{2\pi} d\phi d\sigma^{\text{tot}}}
\]

varying azimuthal angle (beam spin and charge fixed)

\( \Rightarrow \) azimuthal angle ‘asymmetry’ \((AAA)\)

\[
AAA = \frac{\int_{-\pi/2}^{\pi/2} d\phi (d\sigma - d\sigma^{BH}) - \int_{-3\pi/2}^{-\pi/2} d\phi (d\sigma - d\sigma^{BH})}{\int_0^{2\pi} d\phi d\sigma}
\]

... requires very good \(\phi\) resolution and control of twist-3 contamination

\[
AAA \sim \text{Re} \left( \tau_{BH} \cdot \tau_{\text{DVCS}} \right)
\]
Beam Spin Asymmetry

varying beam polarization [HERMES, CLAS 2001]

⇒ one beam spin asymmetry (SSA) per beam charge

\[
SSA = \frac{2 \int_0^{2\pi} d\phi \sin(\phi)(d\sigma^\uparrow - d\sigma^\downarrow)}{\int_0^{2\pi} d\phi (d\sigma^\uparrow + d\sigma^\downarrow)} - \frac{2(3 - 2y)}{3(2 - y)} \frac{K}{1 - y} \frac{\mathcal{I}}{s_{1,\text{unp}}} - \frac{(1 - y)(2 - y)\Delta^2}{yQ^2} x_{B S_{1,\text{unp}}} D V C S
\]

or counting events scattered ‘up’ and ‘below’ rotated-by-90° lepton scattering plane (left and right) to get \( \sin \phi \) weight ⇒ 2 bins in \( \phi \)

\[
\Delta \sigma = d\sigma^\uparrow - d\sigma^\downarrow
\]

\[
SSA = \frac{\int_0^{\pi} d\phi \Delta \sigma - \int_\pi^{2\pi} d\phi \Delta \sigma}{\int_0^{2\pi} d\phi d\sigma^{tot}}
\]

\[
SSA \sim \text{Im} (\tau_{BH} \cdot \tau_{DVCS})
\]

⇒ combination of SSA and CA or AAA gives access to full twist-2 \( \tau_{BH} \cdot \tau_{DVCS} \) amplitude

⇒ BH contributions absent in CA and SSA measurements
unveiling GPDs from determination of Fourier coefficients obtained from asymmetry measurements

\[ \left\{ \begin{array}{c} e_{1,\text{ump}}^T \\ s_{1,\text{ump}}^T \end{array} \right\} = 8K \left\{ \begin{array}{c} -(2 - 2y + y^2) \\ \lambda_y(2 - y) \end{array} \right\} \left\{ \begin{array}{c} \Re \\ \Im \end{array} \right\} \]

access both parts of CFF $\mathcal{H}$

$K^2 \sim \Delta^2/Q^2 \sim 1/10$

high $y$ needed $\Rightarrow$ high $\gamma^*$ pol.

Compton Form Factors are convolutions of coefficient functions and GPDs: $H, \tilde{H}, E, \tilde{E}$

$\Rightarrow$ appear in linear combinations in interference term

$\Rightarrow$ but in quadratic combinations in unpol. cross section

$H$ (unpol. non-spin-flip) like $q, \bar{q}, g$

$\tilde{H}$ (pol. non-spin-flip) like $\Delta q, \Delta \bar{q}, \Delta g$

$E$ (unpol. spin-flip) no inclusive equivalent!

$\tilde{E}$ (pol. spin-flip) no inclusive equivalent!

complete separation of GPD would require in addition data taken with polarized (T,L) target
CA Simulation for HERA

integrated over $t$, $-t<0.5\text{GeV}^2$, and over $\phi$
SSA Simulation for HERA ($e^+p$)

integrated over $t$, $-t<0.5\text{GeV}^2$, and over $\phi$

[A.Freund, hep-ph/0306012]
Some Measurement Remarks

\( \phi \) and \( t \) are difficult to measure since scattered proton is \textit{not} observed

\[
\phi = \phi_{e'} - \phi_{p'} \approx \phi_{e'} - \phi_{\gamma}
\]

\[
t = (p - p')^2 \approx -|\vec{p}_{Te} + \vec{p}_{T\gamma}|^2
\]

→ determination of \( \phi \) and \( t \) via scattered \( e' \) and \( \gamma \):

DVCS: backward \( e' \) and central \( \gamma \) and veto on p-diss background (→ forward instrumentation)

- \( \Delta t \) dominated by \( E \) and \( \theta \) resolution of \( \gamma \)
- \( \Delta \phi \) dominated by \( E \) resolution of \( e' \)
H1 VFPS and DVCS

- better suppression of p-diss background
- some bins in $t$
- $\Delta_{syst}(b\text{-slope}) \pm 2\text{GeV}^{-2}$ [H1-PRC01/00]
- more bins in $\phi$...?

DVCS events for 1fb$^{-1}$

- $5 < Q^2 < 7 \text{ GeV}^2$
- $7 < Q^2 < 10$
- $10 < Q^2 < 15$
- $15 < Q^2 < 25$
- $25 < Q^2 < 50$
- $Q^2 > 100 \text{ GeV}^2$
- $50 < Q^2 < 100$

$L.\text{Favart, Trento03}$
Simulations for HERA: Some Remarks

- CA and SSA asymmetries predicted to be sizeable, calculations in LO, NLO, and twist-3 available, see also [V.Belitsky et al., hep-ph/0112108]
  - changing of $t$ cut-off to $1\text{GeV}^2$ alters results on 10% level
- AAA predicted to have similar size as CA
- twist-3 effects estimated to be negligible for CA and for SSA

- NLO corrections are large, up to 100% for CA and up to 50% for SSA (large NLO gluon contribution in real part of DVCS amplitude)
  - NLO corrections important for precision extraction of GPDs

- in general: cross section and asymmetry data can be well modeled, but too many parameters not constrained yet!
  - asymmetry measurements feasible!
electroproduction of muon pairs allows clear study of GPDs via **single beam spin**, single hadron spin, **beam charge**, azimuthal and double spin asymmetries employing angular dependencies of recoiled $p$ and of lepton pair

\( \Rightarrow \) **mapping in both scaling variables** \( \eta \) and \( \xi \) \( \Rightarrow \) constrain angular momentum sum rule:

\[
\int_{-1}^{1} d\xi \xi \left( H_{q,g}(\xi, \eta, \Delta^2) + E_{q,g}(\xi, \eta, \Delta^2) \right) = 2J_{q,g}
\]

**but cross section very small \( \Rightarrow \) high luminosity!**
Another view on the angular momentum sum rule

\[ J^q = \lim_{\Delta \to 0} \sum_{i=u,d,s} \frac{1}{2} \int_{-1}^{1} dx \, x \left\{ H^i(x, \xi, \Delta^2, Q^2) + E^i(x, \xi, \Delta^2, Q^2) \right\} \]

\[ = \frac{1}{2} \left\{ (1 + \kappa_p + \kappa_n/2) \, P_{uval} + (1 + \kappa_p + 2\kappa_n) \, P_{dval} + (1 + \kappa_{sea}) \, P_{sea} \right\} \]

with proton and neutron magnetic moments

\[ \kappa_p = 1.793 \text{ and } \kappa_n = -1.913 \]

and \( \kappa_{sea} \) is the orbital angular momentum carried by the quarks

momentum fraction \( P^i \) carried by the quarks can be deduced from DIS data alone
select different GPDs (and quark flavors) via
detection of different final states

vector mesons: \( H, E \), e.g. \( p^0 \rightarrow 2J_u + J_d \) [X.Ji, hep-lat/0211016]
pseudoscalar mesons: \( H, E \)

transitions within the baryon octet: transition GPDs, e.g. \( H_{p \rightarrow \Lambda}^{su} \)

but additional complication due to presence of
distribution amplitude of the particle, e.g. the pion wave function
\( \rightarrow \) for unpol. e beam and transv. pol. target large asymmetries
have been predicted, see e.g. [K.Goeke et al, hep-ph/0106012]
\( \rightarrow \) HERMES, CLAS, COMPASS

\( \rightarrow \) special: exclusive strangeness production \( \gamma_L p \rightarrow K^+ \Lambda \)
where an azimuthal spin asymmetry can be measured on an
unpolarized target by measuring the polarization of the recoiling
hyperon through its angular distribution
\( \rightarrow \) not studied yet for HERA
Single Spin Asymmetry in π electroproduction

CLAS: first observation of a positive SSA in SiDIS π⁺ production

\[ A_{\text{LU}}^{\sin \phi} = \frac{2}{P \pm N \pm} \sum_{i=1}^{N \pm} \sin \phi_i \]

but expected to be zero in LO
⇒ related to either NLO or higher twist effect

NLO: [A.Afanasev, C.E.Carlson, hep-ph/0308163]
final state gluon exchange deliver contribution to anti-symmetric part of hadronic tensor
⇒ lepton beam spin asymmetry is generated due to interference between absorption of longitudinal and transverse virtual photons
\[ A_{\text{LU}} \sim r_T / \sqrt{Q^2} \]
with transverse component of the final quark momentum \( r_T \)

twist-3: [A.V.Efremov et al., hep-ph/0208124]
SSA arises from chirally odd twist-3 proton distribution function \( e^a(x) \)
in combination with chirally-odd and T-odd twist-2 Collins FF

⇒ very interesting to test it also at HERA
 Beam Spin Transfer to Λ-Baryon

\[ \ell(\lambda) p(\mu) \rightarrow \ell \Lambda(h) X \]

four independent observables:

the unpolarized cross-section

\[ d\sigma^\Lambda = \frac{2\pi\alpha^2}{sx} \frac{1 + (1 - y)^2}{y^2} \sum_q e_q^2 q(x) D_{\Lambda/q} \]

the double spin asymmetry

\[ A_\parallel = \frac{d\sigma^\Lambda_{++} - d\sigma^\Lambda_{--}}{2 d\sigma^\Lambda} = \frac{y(2 - y)}{1 + (1 - y)^2} \frac{\sum_q e_q^2 \Delta q(x) D_{\Lambda/q}(z)}{\sum_q e_q^2 q(x) D_{\Lambda/q}(z)} \]

the spin transfer from \( \ell \) to \( \Lambda \) (with an unpolarized nucleon)

\[ P_{+0} = \frac{d\sigma^\Lambda_{+0} - d\sigma^\Lambda_{0-}}{d\sigma^\Lambda} = \frac{y(2 - y)}{1 + (1 - y)^2} \frac{\sum_q e_q^2 q(x) \Delta D_{\Lambda/q}(z)}{\sum_q e_q^2 q(x) D_{\Lambda/q}(z)} \]

and the spin transfer from \( N \) to \( \Lambda \) (with an unpolarized lepton)

\[ P_{0+} = \frac{d\sigma^\Lambda_{0+} - d\sigma^\Lambda_{+0}}{d\sigma^\Lambda} = \frac{\sum_q e_q^2 \Delta q(x) \Delta D_{\Lambda/q}(z)}{\sum_q e_q^2 q(x) D_{\Lambda/q}(z)} \]

in current fragmentation region pol. FF \( \Delta D_{\Lambda/q}(z) \) sensitive to distribution of polarized quarks in unpolarized nucleon
**Longitudinal Λ Polarization**

parity violating weak deacy of $\Lambda \rightarrow p\pi$

$\Rightarrow$ distribution of decay angle $\theta^*$ depends on

Λ pol. $P : I(\theta^*) \sim 1 - \alpha P \cos \theta^* \ (\alpha=0.64)$

exp.: $P^\Lambda = P_{\text{beam}} D(y) S^\Lambda \Rightarrow$ requires high beam pol. and high $y$

$\Rightarrow$ Λ could contain polarized quark!

$\Rightarrow$ using relation pol FF pol PDF

Gribov-Lipatov ‘reciprocity’ relation [1971]

$$S^\Lambda_q = \frac{\Delta D^\Lambda_q}{D^\Lambda_q} = \frac{\Delta q^\Lambda}{q^\Lambda}$$

$\Rightarrow$ study Λ spin structure and test SU(3)$_f$:

[e.g. B.Ma et al., hep-ph/0208122]

$$\Delta u^\Lambda = \Delta d^\Lambda = \frac{1}{6} \Delta u_p + \frac{2}{3} \Delta d_p + \frac{1}{6} \Delta s_p$$

$$\Delta s^\Lambda = \frac{2}{3} \Delta u_p - \frac{1}{3} \Delta d_p + \frac{2}{3} \Delta s_p$$

$\Rightarrow$ more data needed!

$\Rightarrow$ measurements seems to be feasible

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Conclusion

HERA II with high luminosity and with longitudinally polarized electrons and positrons opens new horizons to study electroweak theory and parton dynamics

and

may deliver even surprises we could not imagine today...

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