$A_N$ in inclusive lepton-proton collisions

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based on work in collaboration with
M. Anselmino, M. Boglione, S. Melis, F. Murgia, and A. Prokudin
Outline

- Transverse Single Spin Asymmetries (SSA): single- vs. two- scale processes
  \( pp \rightarrow hX \) vs. \( \ell p \rightarrow \ell' h, X \) (SIDIS)

- TMD approach: factorization and universality?

- SSAs in \( \ell p \rightarrow hX \): a bridge or a testing ground of the TMD scheme
  - role of kinematics and dynamics
  - use of TMDs extracted from SIDIS fits

- Recent HERMES results: a comparison

- Predictions for future experiments

- Conclusions
SSAs and theoretical approaches in QCD

single scale process: \( pp \rightarrow hX \) \( A_N = \frac{d\sigma^\uparrow - d\sigma^\downarrow}{d\sigma^\uparrow + d\sigma^\downarrow} \)

- sizeable over a huge energy range (FermiLab...RHIC)
- subleading SSA

- **Twist-3 approach** [Efremov-Teryaev, Qiu-Sterman, Koike-Kanazawa, Kang et al.]
  - collinear factorization established
  - universal \( T_F(x, x) \) quark-gluon correlator, related to the TMD Sivers function
  - \( T_F \) from the Sivers function leads to \( A_N \) opposite in sign w.r.t. data
  - update: \( A_N \) dominated by a twist-3 term in the fragm. [Kanazawa et al. 2014]

- **TMD scheme** (generalization of the parton model with \( k_\perp \)) [Anselmino et al.]
  - factorization (and universality) assumed
  - rich and successful phenomenology

\( A_N \) in inclusive lepton-proton...
two-scale processes (SIDIS, DY, $e^+e^-$): large $Q^2$ and small $P_T$

- leading SSA
- TMD factorization proved
- equivalence with twist-3 approach in one-scale regime
- modified universality: change of sign of T-odd TMDs from SIDIS to DY (to be tested)
- SIDIS extraction of the Sivers and Collins functions (and transversity distribution)
- recent studies with proper scale evolution
\[ \ell p \rightarrow h + X \text{...a bridge} \]

no detection of the final lepton!

<table>
<thead>
<tr>
<th></th>
<th>(\ell p \rightarrow h + X)</th>
<th>(\ell p \rightarrow \ell' h + X)</th>
<th>(pp \rightarrow h + X)</th>
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<tr>
<td>scales</td>
<td>(P_T)</td>
<td>(Q^2, P_T)</td>
<td>(P_T)</td>
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<td>(P_T)</td>
<td>(Q^2)</td>
<td>(P_T)</td>
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<td>TMD fact.</td>
<td>assumed</td>
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<td>assumed</td>
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<td>c.m. frame</td>
<td>(\ell p)</td>
<td>(\gamma^* p)</td>
<td>(pp)</td>
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<td>subprocesses</td>
<td>(\ell q)</td>
<td>(\ell q)</td>
<td>(qq, qg, gg)</td>
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<td>channels</td>
<td>(t)</td>
<td>(t)</td>
<td>(t, u, s)</td>
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Detailed phenomenology [Anselmino, Boglione, UD, Murgia, Melis, Prokudin 10 & 14]

- Analogous/complementary study [She, Mao, Ma 08]
- Twist-3 approach [Kang et al 11]
Kinematics and hard scattering region

partonic subprocess at LO: \( q\ell \rightarrow q\ell \)

\[
d\hat{\sigma}^{q\ell \rightarrow q\ell} \simeq \frac{1}{\hat{t}^2} \quad \hat{t} = (p_q' - p_q)^2 \equiv -Q^2
\]

hard scattering \( \Leftrightarrow \) large \( |\hat{t}| \) (\( \geq 1 \text{ GeV}^2 \))

TMD factorization scheme at large \( P_T \) [assumed as in \( pp \rightarrow h + X \)]:

\[
d\sigma^{p\ell \rightarrow hX} = \sum_q f_{q/p}(x, k_\perp; Q^2) \otimes d\hat{\sigma}^{q\ell \rightarrow q\ell} \otimes D_{h/q}(z, p_\perp; Q^2)
\]

TMD: \( p_q \simeq xp + k_\perp, \quad p_h \simeq zp'_q + p_\perp \)
Kinematical regions

- high statistics at low $P_T$ (around 0.5 GeV)
  ⇒ dominated by quasi-real photon exchange ⇒ OUT of pQCD regime
- consider larger $P_T$ values and proper forward/backward proton hemisphere

large scattering angles: $|t|_{\text{min}} \sim 1 \text{ GeV}^2$

$[\sqrt{s} \sim 5-10 \text{ GeV}]$

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<th>$P_T$</th>
<th>collinear</th>
<th>TMD</th>
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<td></td>
<td>forward</td>
<td>backward</td>
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<td>1 GeV</td>
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<td>2 GeV</td>
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Note: under the assumption of no hard gluon emission
TMD approach to $p \ell \rightarrow h X$:

$$A_N = \frac{d\sigma^\uparrow - d\sigma^\downarrow}{d\sigma^\uparrow + d\sigma^\downarrow} = \frac{d\sigma^\uparrow - d\sigma^\downarrow}{2d\sigma^{\text{unp}}}$$

$$d\sigma^\uparrow - d\sigma^\downarrow = \sum_q \left\{ \Delta^N f_{q/p}^\uparrow \cos \phi_q \otimes d\hat{\sigma} \otimes D_{h/q} \right\} \text{ Sivers effect}$$

$$+ \ h_{1q/p}^q \otimes d\Delta\hat{\sigma} \otimes \Delta^N D_{h/q}^\uparrow \cos \phi_C \quad \text{Collins effect I}$$

$$+ \ h_{1Tq/p}^q \otimes d\Delta\hat{\sigma} \otimes \Delta^N D_{h/q}^\uparrow \cos(\phi_C - 2\phi_q) \right\} \text{Collins effect II}$$

$$d\hat{\sigma} \simeq e_q^2 \frac{\hat{s}^2 + \hat{u}^2}{\hat{t}^2} \quad d\Delta\hat{\sigma} \simeq -e_q^2 \frac{\hat{s}\hat{u}}{\hat{t}^2}$$

$$\phi_C \equiv \phi_h^H + \phi_{q'}^H \ [\phi_h^H \text{ hadron azimuthal angle in } p'_q \text{ helicity frame, Collins effect}]$$

$A_N$ in inclusive lepton-proton ...
Single plane (w.r.t. two planes in SIDIS):
\[
\sin(\phi_h \pm \phi_S) \text{ not measurable} \Rightarrow \text{No separation of effects:}
\]
\[
\Rightarrow \text{hopeless???? Not really:}
\]
- single partonic channel: clear
- \( t \)-channel: \( \hat{t} \) strongly dependent on \( \phi_q \) (Sivers azimuthal dependence)
- backward region (small \( \hat{u} \)):
  - moderately large \( Q^2 \) (ok pQCD)
  - absence of \( u \)-channel (with \( \hat{u} \) almost independent on \( \phi_q \))
    * Sivers effect still active
    * Collins effect strongly suppressed
  - \( p^+p \rightarrow \pi X \): all spin-TMD effects in \( A_N \) strongly suppressed
Unified picture

- use of Sivers and Collins functions (and transversity) from fits to SIDIS and $e^+e^-$:

1. SIDIS 1:
   - FFs from Kretzer 2000;
   - Sivers functs. for up and down quarks [Anselmino et al, 05]
   - first extraction of transversity [Anselmino et al. 07]

2. SIDIS 2:
   - FFs from de Florian-Sassot-Stratmann 07;
   - Sivers functs. with sea quarks [Anselmino et al. 09]
   - updated $h_1$ [Anselmino et al. 09]

   • Some differences in the SIDIS unconstrained large $x$ region for the Sivers and transversity functions (crucial in $A_N$ in $pp$ collisions)
   • well representative of the uncertainties in the available extractions
   • Envelope of the statistical uncertainty bands
**Kinematics vs. HERMES setup**

\[
A_N = \frac{d\sigma^\uparrow - d\sigma^\downarrow}{d\sigma^\uparrow + d\sigma^\downarrow}
\]

\[
A(\phi_S, S_T) = S_T \cdot (\hat{p} \times \hat{P}_T) A_N = S_T \sin \phi_S A_N
\]

**HERMES:**

\[
d\sigma = d\sigma_{UU}[1 + S_T \sin \psi A_{UT}^{\sin \psi}]
\]

\[
\sin \psi = \hat{S}_T \cdot (\hat{P}_T \times \hat{k}) \text{ and } \hat{k} = -\hat{p}
\]

**HERMES configuration:** left and right interchanged but defined looking downstream w.r.t. opposite directions (lepton vs. proton) → only a sign change in \(x_F\): \(x_F > 0\) means backward proton hemisphere.

\[
A_{UT}^{\sin \psi}(x_F, P_T)_{\text{HERMES}} = A_N^{p^\uparrow \ell \rightarrow hX}(-x_F, P_T)
\]

\(A_N\) in inclusive lepton-proton ...
Results

• Fully inclusive case
  – one large scale $P_T \simeq 1$ GeV $\to Q^2 \geq 1$ GeV$^2$ BACKWARD proton hemisphere
  – only one HERMES bin with $\langle P_T \rangle \simeq 1$ GeV

• lepton-tagged or SIDIS category
  – subsample with detection of the final lepton (low rates)
  – $Q^2 > 1$ GeV$^2$ (plus usual SIDIS cuts on $x_B$, $z_h$, $y$, $W^2$)
  – extra cut: $P_T > 1$ GeV [$\ell p$ c.m. frame]
    SIDIS azimuthal asym. $P_T < 1$ GeV [$\gamma^* p$ c.m. frame] to access intrinsic $k_\perp$.
    Note: in $\ell p \to h X$ the final $P_T$ comes also from the hard scattering

*HERMES data: PLB 728 (2014)
Collins effect suppressed: azimuthal phase integration and dynamics

Sivers effect sizeable:
  - backward region but only $t$ channel, and moderate $Q^2 = |\hat{t}| \rightarrow$: Sivers azimuthal phase active in the hard scattering
  - backward hemisphere but valence region ($\sqrt{s} \simeq 7$ GeV and $P_T = 1$ GeV)
  - $\pi^-$: role of up quark Sivers function coupled to non-leading FF

\[ A_N \text{ in inclusive lepton-proton ...} \]
Fully inclusive case: SIDIS 2

- $\pi^+$ similar to SIDIS 1
- $\pi^-$ dominated by negative down quark Sivers function (w.r.t. SIDIS 1)
• Collins effect only partially suppressed (Collins phase picks to $-1$)
• Sivers effect sizeable (cancelation in $\pi^-$ due to the large role of up quark)
Collins effect: larger w.r.t. SIDIS 1 (transversity unsuppressed at large $x$)
Sivers effect: no cancelation in $\pi^-$ (same large $x$ behaviour of up and down quarks)
**Predictions: JLab 12**

\[
p^+ \rightarrow \pi^+ X \quad \text{SIDIS 1, JLab 12}
\]

\[
p^- \rightarrow \pi^- X \quad \text{SIDIS 1, JLab 12}
\]
Predictions at large energies

- Look for a behaviour similar to $A_N$ in $p^\uparrow p \rightarrow \pi X$
- To facilitate the comparison: $p^\uparrow$ along $+Z_{cm}$, i.e. forward region $\equiv x_F > 0$
- Use of SIDIS 1 (better agreement with STAR data *Boglione-UD-Murgia 08*)

Notice: here $Q^2 > 1 \text{ GeV}^2$ also in the forward region
Comments

- **Collins effect**
  - suppressed in the backward region: azimuthal phase integration
  - small in the forward region even if the Collins phase is active

- **Sivers effect**
  - suppressed in the backward region: one channel but large $Q^2$ are not sensitive to the Sivers phase
  - sizeable and increasing in the forward region
  - similar behaviour as for $A_N$ in $pp \rightarrow \pi^0 X$
  - very similar results for $p^\uparrow \ell \rightarrow \text{jet} \ X$

- **Twist-3 (a comparison)**
  - $A_N^{p\ell\rightarrow \text{jet} \ X}$ with $T_F$ from Sivers function: similar results [Kang et al 11]
  - impact of the new large piece in the fragmentation to $p \ell \rightarrow \pi^0 \ X$?
Conclusions

• Test of TMD factorisation in single large-scale inclusive processes

• strong analogy with $p^\uparrow p \rightarrow h X$, where $A_N$ are large and still puzzling

• from $\ell p \rightarrow \ell' h X$ (SIDIS), to $\ell p \rightarrow h X$ at large $P_T$ (i.e. large $Q^2$)

• use of a unified TMD approach (same Sivers and Collins functions)

• new HERMES data and theoretical estimates agree in shape and sign (inclusive and lepton tagged events)

• size a bit overestimated ($\ell p \rightarrow \pi^+ X$): other mechanism at work?

• predictions for a EIC, same behaviour as in $pp \rightarrow \pi X$: crucial to assess the validity of the TMD approach
Thank you

and don’t forget:

TRANSVERSITY 2014 Workshop
9-13 June, Cagliari (Italy)

- 3D-structure of the nucleon: TMDs, GPDs, OAM
- Data from COMPASS, HERMES, JLab, RHIC, BaBar, Belle
Back-up slides
Statistical error band

\[ \chi^2 = \sum_{i=1}^{N} \left( \frac{y_i - F(x_i; a)}{\sigma_i} \right)^2 \]

- \( N \) measurements \( y_i \) at known points \( x_i \), with variance \( \sigma_i^2 \).
- \( F(x_i; a) \) depends non-linearly on \( M \) unknown parameters \( a_i \).
- Best fit: \( \chi^2_{\text{min}} \rightarrow a_0 \)

Error band: all sets of parameters such that \( \chi^2(a_j) \leq \chi^2_{\text{min}} + \Delta \chi^2 \)
- \( \Delta \chi^2 = 1 \leftrightarrow 1-\sigma \): small errors, uncorrelated parameters, linearity, \( \chi^2 \) parabolic
- \( \Delta \chi^2 \): fixed according to the coverage probability

\[ P = \int_0^{\Delta \chi^2} \frac{1}{2\Gamma(M/2)} \left( \frac{\chi^2}{2} \right)^{(M/2)-1} \exp \left( -\frac{\chi^2}{2} \right) \, d\chi^2 \]

\( P \) = probability that true set of parameters falls inside the \( M \)-hypervolume

\[ [P = 0.68 \leftrightarrow 1-\sigma, \ P = 0.95 \leftrightarrow 2-\sigma] \]