Experimental overview of TMD PDFs from SIDIS and Drell-Yan data

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The Nucleon Structure

the three collinear PDFs

\[ f_1(x) \quad g_1(x) \quad h_1(x) \]

- number \[ q(x) \]
- helicity \[ \Delta q(x) \]
- transversity \[ \Delta_T q(x) \]

- a chirally-odd distribution, hence not observable in DIS
- theoretically well known
- first experimental evidence in 2005
The Nucleon Structure

taking into account the quark intrinsic transverse momentum $k_T$,
at leading order 8 Transverse Momentum Dependent PDFs are needed
for a full description of the nucleon structure

<table>
<thead>
<tr>
<th>nucleon polarisation</th>
<th>U</th>
<th>L</th>
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<tr>
<td>U</td>
<td>$f_1$</td>
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<td>$f_{1T}$</td>
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<td>number density</td>
<td>$q$</td>
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<td>Sivers</td>
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<td>L</td>
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<td>helicity</td>
<td>$\Delta q$</td>
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<td>T</td>
<td>$h_1$</td>
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<td>Boer Mulders</td>
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<td>transversity</td>
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<td>$h_{1T}$</td>
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most of the information came from SIDIS
taking into account the quark intrinsic transverse momentum $k_T$, at leading order 8 Transverse Momentum Dependent PDFs are needed for a full description of the nucleon structure.
The most famous new PDFs

$h_1$ transversity function
unpolarized quarks in a transversely polarized nucleon
correlation between the transverse spins

- chiral-odd
- survives to integration over transverse momenta
- tensor charge

$f_{1T}$ Sivers function
unpolarized quarks in a transversely polarized nucleon
correlation between the parton transverse momentum and the nucleon spin

- T-odd

$h_{1T}$ Boer-Mulders function:
transversely polarized quarks in an unpolarized nucleon
correlation between the transverse momentum and the transverse spin of the partons

- T-odd

measurable in SIDIS

IWHSS19, Aveiro, 24 June 2019
F. Bradamante
\[
\frac{d\sigma}{dx \, dy \, d\psi \, dz \, d\phi_h \, dP_{h\perp}^2} = \\
\frac{\alpha^2}{xyQ^2} \frac{y^2}{\epsilon \left(1 + \frac{\gamma^2}{2x}\right)} \left\{ F_{UU,T} + \epsilon F_{UU,L} + \sqrt{2\epsilon(1+\epsilon)} \cos\phi_h F_{UU}^{\cos\phi_h} \right. \\
+ \epsilon \cos(2\phi_h) F_{UU}^{\cos2\phi_h} + \lambda_c \sqrt{2\epsilon(1-\epsilon)} \sin\phi_h F_{UL}^{\sin\phi_h} \right. \\
+ S_{\parallel} \left[ \sqrt{2\epsilon(1+\epsilon)} \sin\phi_h F_{UL}^{\sin\phi_h} + \epsilon \sin(2\phi_h) F_{UL}^{\sin2\phi_h} \right] + S_{\parallel} \lambda_c \left[ \sqrt{1-\epsilon^2} F_{LL} + \sqrt{2\epsilon(1-\epsilon)} \cos\phi_h F_{LL}^{\cos\phi_h} \right] \\
+ |S_{\perp}| \sin(\phi_h - \phi_S) \left( F_{UT,T}^{\sin(\phi_h-\phi_S)} + \epsilon F_{UT,L}^{\sin(\phi_h-\phi_S)} \right) \\
+ \epsilon \sin(\phi_h + \phi_S) F_{UT}^{\sin(\phi_h+\phi_S)} + \epsilon \sin(3\phi_h - \phi_S) F_{UT}^{\sin(3\phi_h-\phi_S)} \\
+ \sqrt{2\epsilon(1+\epsilon)} \sin\phi_S F_{UT}^{\sin\phi_S} + \sqrt{2\epsilon(1+\epsilon)} \sin(2\phi_h - \phi_S) F_{UT}^{\sin(2\phi_h-\phi_S)} \right. \\
+ |S_{\perp}| \lambda_c \left[ \sqrt{1-\epsilon^2} \cos(\phi_h - \phi_S) F_{LT}^{\cos(\phi_h-\phi_S)} + \sqrt{2\epsilon(1-\epsilon)} \cos\phi_S F_{LT}^{\cos\phi_S} \\
+ \sqrt{2\epsilon(1-\epsilon)} \cos(2\phi_h - \phi_S) F_{LT}^{\cos(2\phi_h-\phi_S)} \right]. \]
\]
Semi-Inclusive Deep Inelastic Scattering

\[
\frac{d\sigma}{dx dy d\psi d\phi_h dP_h^2} = \frac{\alpha^2}{xy Q^2} \frac{y^2}{2(1-\varepsilon)} \left(1 + \frac{\gamma^2}{2x}\right) \left\{ F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\varepsilon(1+\varepsilon)} \cos\phi_h F_{UU}^{\cos\phi_h} \right. \\
+ \varepsilon \cos(2\phi_h) F_{UU}^{\cos 2\phi_h} + \lambda_e \sqrt{2\varepsilon(1-\varepsilon)} \sin\phi_h F_{LU}^{\sin \phi_h} \right. \\
+ S_\parallel \left. \left[ \sqrt{2\varepsilon(1+\varepsilon)} \sin\phi_h F_{UL}^{\sin \phi_h} + \varepsilon \sin(2\phi_h) F_{UL}^{\sin 2\phi_h} \right] \right. \\
+ S_\parallel \lambda_e \left. \left[ \sqrt{1-\varepsilon^2} F_{LL} + \sqrt{2\varepsilon(1-\varepsilon)} \cos\phi_h F_{LL}^{\cos\phi_h} \right] \right. \\
+ \sin(\phi_h - \phi_S) \left( F_{UT,T}^{\sin(\phi_h - \phi_S)} + \varepsilon F_{UT,L}^{\sin(\phi_h - \phi_S)} \right) \\
+ \varepsilon \sin(\phi_h + \phi_S) F_{UT}^{\sin(\phi_h + \phi_S)} + \varepsilon \sin(3\phi_h - \phi_S) F_{UT}^{\sin(3\phi_h - \phi_S)} \\
+ \sqrt{2\varepsilon(1+\varepsilon)} \sin\phi_S F_{UT}^{\sin \phi_S} + \sqrt{2\varepsilon(1+\varepsilon)} \sin(2\phi_h - \phi_S) F_{UT}^{\sin(2\phi_h - \phi_S)} \\
+ |S_\perp| \lambda_e \left. \left[ \sqrt{1-\varepsilon^2} \cos(\phi_h - \phi_S) F_{LT}^{\cos(\phi_h - \phi_S)} + \sqrt{2\varepsilon(1-\varepsilon)} \cos\phi_S F_{LT}^{\cos \phi_S} \right. \right. \\
+ \sqrt{2\varepsilon(1-\varepsilon)} \cos(2\phi_h - \phi_S) F_{LT}^{\cos(2\phi_h - \phi_S)} \left. \right] \}, g_{1T} \otimes D_1
\]
MAJOR RESULT:
in the past 15 years 2 of these new PDF’s have been measured and shown to be different from zero by COMPASS and HERMES.
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by COMPASS and HERMES

the transversity PDF
Collins asymmetry \( \sim h_1 \otimes H_{1}^{\perp} \)
amplitude of the sine modulation in \( \phi_h + \phi_s - \pi \)

the Sivers PDF
Sivers asymmetry \( \sim f_{1T}^{\perp} \otimes D_1 \)
amplitude of the sine modulation in \( \phi_h - \phi_s \)

A STEP TOWARDS
THE 3-D STRUCTURE OF THE NUCLEON
Collins asymmetry $\sim h_1 \otimes H_1^\perp$

since 2005 evidence for non-zero Collins asymmetry on proton
Collins asymmetry \( \sim h_1 \otimes H_1^\perp \)

since 2005 evidence for non-zero Collins asymmetry on proton
accessing transversity in SIDIS

recent experimental developments
**Λ / ¯Λ polarisation**

transversity induced Lambda polarisation

measured using the “reflected” direction of the nucleon spin i.e. the transverse polarisation of the struck quark if transversity is different from zero

\[
P_\Lambda = \frac{\sum_q e_q^2 h_q^1 H_{1\Lambda/q}}{\sum_q e_q^2 f_q^1 D_{1\Lambda/q}}
\]

- completely unknown

2010 proton data preliminary

π⁻⁻p invariant mass

\[Q^2 > 1 \text{ (GeV/c)}^2\]

~300k Λ

~150k ¯Λ
transversity induced Lambda polarisation

measured using the “reflected” direction of the nucleon spin i.e. the transverse polarisation of the struck quark if transversity is different from zero

\[ P_\Lambda = \frac{\sum_q e_q^2 h^q_1 H^\Lambda/q_1}{\sum_q e_q^2 f^q_1 D^\Lambda/q_1} \]

with different assumptions, this measurement can give information either on \( h^S_1 \) or on \( H^\Lambda/q_1 / D^\Lambda/q_1 \)

statistically limited still the only existing measurement
\( \Lambda / \bar{\Lambda} \) polarisation in \( e^+e^- \)

\[
D_{1,q}^{\perp h}(z, k_T, Q^2)
\]

\[ P_p \]

\[ P_{\bar{\pi}^-} \]

\[ P_\Lambda \]

\[ \theta \]

\[ q \]

\[ \bar{q} \]

\[ e^- \]

\[ e^+ \]

\[ z \]

\[ k_T \]

\[ Q^2 \]

\[ P_{\Lambda} \]

\[ P_{\bar{\Lambda}} \]

\[ P_{\pi^-} \]

\[ \theta \]

\[ e^- \]

\[ e^+ \]

\[ q \]

\[ \bar{q} \]

\[ \Lambda \]

\[ \bar{\Lambda} \]

\[ z_\Lambda \]

\[ p_t(\Lambda)(\text{GeV}/c) \]

\[ p_t(\bar{\Lambda})(\text{GeV}/c) \]

\[ 0.2 < z_\Lambda < 0.3 \]

\[ 0.3 < z_\Lambda < 0.4 \]

\[ 0.4 < z_\Lambda < 0.5 \]

\[ 0.5 < z_\Lambda < 0.9 \]

\[ 0.2 < z_{\bar{\Lambda}} < 0.3 \]

\[ 0.3 < z_{\bar{\Lambda}} < 0.4 \]

\[ 0.4 < z_{\bar{\Lambda}} < 0.5 \]

\[ 0.5 < z_{\bar{\Lambda}} < 0.9 \]

R. Seidl, DIS2019

Belle preliminary

PRL122 2019

IWHSS19, Aveiro, 24 June 2019

F. Bradamante
Collins difference asymmetries
Collins difference asymmetries

namely
the asymmetries in the difference of opposite charge hadrons distributions

• they have been proposed a long time ago
  L.L. Frankfurt et al., PLB 230 141 (1989) 141
  E. Christova and E. Leader, NPB 607 (2001) 369

• they are in the COMPASS Proposal (1996), for SIDIS off longitudinally and transversely polarised protons and deuterons

• they have been measured in SIDIS off longitudinally polarised deuterons
• they were never measured in SIDIS off transversely polarised nucleons

first extraction from the COMPASS measurement of the Collins asymmetries for $h^+$ and $h^+$ in SIDIS off transversely polarised protons and deuterons

V. Barone et al., PRD99 (2019)
Collins difference asymmetries

cross-sections for hadrons (pions) of opposite charge ($\pm$) transversely polarised nucleons

$$\sigma_t^\pm (\Phi_C) = \sigma_{0,t}^\pm + f \, P_T \, D_{NN} \, \sigma_{C,t}^\pm \sin \Phi_C + \cdots \quad t = p, d$$

- Collins asymmetries
  $$A_{C,t}^\pm = \frac{\sigma_{C,t}^\pm}{\sigma_{0,t}^\pm}$$

- difference asymmetries (two slightly different definitions)
  $$A_{D,t} = \frac{\sigma_{C,t}^+ - \sigma_{C,t}^-}{\sigma_{0,t}^+ + \sigma_{0,t}^-} \quad A_{D,t}' = \frac{\sigma_{C,t}^+ - \sigma_{C,t}^-}{\sigma_{0,t}^+ - \sigma_{0,t}^-}$$

if the acceptances for $h^+$ and $h^+$ are the same, they can be obtained from the measured Collins asymmetries:

$$A_{D,t} = \frac{\sigma_{0,t}^+}{\sigma_{0,t}^+ + \sigma_{0,t}^-} \, A_{C,t}^+ - \frac{\sigma_{0,t}^-}{\sigma_{0,t}^+ + \sigma_{0,t}^-} \, A_{C,t}^- \quad \sigma_{0,t}^\pm \sim N_t^\pm \sim 1/\text{var}(A_{C,t}^\pm)$$

$$= \frac{\text{var}(A_{C,t}^-)}{\text{var}(A_{C,t}^+) + \text{var}(A_{C,t}^+)} \, A_{C,t}^+ - \frac{\text{var}(A_{C,t}^+)}{\text{var}(A_{C,t}^+) + \text{var}(A_{C,t}^-)} \, A_{C,t}^-$$
Collins difference asymmetries

in terms of PDFs

\[
\frac{A_{D,d}}{A_{D,p}} = 3 \frac{\sigma_{0,p}^+ + \sigma_{0,d}^-}{\sigma_{0,d}^+ + \sigma_{0,d}^-} \frac{h_{1}^{uv} + h_{1}^{dv}}{4h_{1}^{uv} - h_{1}^{dv}}
\]

\[
\frac{A'_{D,d}}{A'_{D,p}} = \frac{4f_{1}^{uv} - f_{1}^{dv}}{f_{1}^{uv} + f_{1}^{dv}} \frac{h_{1}^{uv} + h_{1}^{dv}}{4h_{1}^{uv} - h_{1}^{dv}}
\]

from standard PDFs and FFs parametrisations

\[\Rightarrow\] they allow to extract \( xh_{1}^{dv} / xh_{1}^{dv} \) without knowing \( H_{1} \)

- from \( A_{D} \)
- from \( A'_{D} \)
- from \( xh_{1}^{dv} \) and \( xh_{1}^{uv} \)

A. Martin, F.B., V. Barone
PRD91 2015

\[
\frac{xh_{1}^{dv}}{xh_{1}^{uv}}
\]
Collins difference asymmetries

In terms of PDFs

\[
\frac{A_{D,d}}{A_{D,p}} = \frac{3 \sigma_{0,p}^+ + \sigma_{0,p}^-}{\sigma_{0,d}^+ + \sigma_{0,d}^-} \frac{h_1^{uv} + h_1^{dv}}{4h_1^{uv} - h_1^{dv}}
\]

\[
\frac{A_{D,d}'}{A_{D,p}'} = \frac{4f_1^{uv} - f_1^{dv}}{f_1^{uv} + f_1^{dv}} \frac{h_1^{uv} + h_1^{dv}}{4h_1^{uv} - h_1^{dv}}
\]

From standard PDFs and FFs parametrisations

→ they allow to extract \(xh_1^{dv}/xh_1^{dv}\) without knowing \(H_1\)

- From \(A_D\)
- From \(A_D'\)
- From \(xh_1^{dv}\) and \(xh_1^{uv}\)

A. Martin, F.B., V. Barone
PRD91 2015

Ratios \(h_1^{dv}/h_1^{uv}\) essentially identical with ratios obtained from standard transversity extractions using SIDIS and \(e^+e^-\) data

Nice cross-check: everything is consistent
Longitudinal double-spin asymmetries of $e^\pm$ on p and d

$$A^{h^+_1-h^-_1}_x \equiv \frac{(\sigma_{1/2}^{h_1} - \sigma_{1/2}^{h^-_1}) - (\sigma_{3/2}^{h_1} - \sigma_{3/2}^{h^-_1})}{(\sigma_{1/2}^{h_1} - \sigma_{1/2}^{h^-_1}) + (\sigma_{3/2}^{h_1} - \sigma_{3/2}^{h^-_1})}$$

in terms of PDFs

$$A^{h^+_1-h^-_1-\text{LOLT}}_{1,d} = \frac{g^u_1 + g^d_1}{f^u_1 + f^d_1}$$

$$A^{h^+_1-h^-_1-\text{LOLT}}_{1,p} = \frac{4g^u_1 - g^d_1}{4f^u_1 - f^d_1}$$

PRD99 2019

HERMES

COMPASS

PLB660 2008
the Sivers function
Sivers asymmetry \( \sim f_{1T}^T \otimes D_1 \)
as in the Collins case, since 2005 evidence for non-zero asymmetry on proton
Sivers asymmetry \( \sim f_{1T}^\perp \otimes D_1 \)

as in the Collins case, since 2005 evidence for non-zero asymmetry on proton
Sivers asymmetry recent results

PBL 770 2017, multiD analysis proton

~ same $x, Q^2$ range as in the COMPASS Drell-Yan measurement

$IWHSS19$, Aveiro, 24 June 2019

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Sivers asymmetry recent results

PBL 770 2017, multiD analysis proton
~ same $x, Q^2$ range as in the COMPASS Drell-Yan measurement

gluon Sivers related TSAs: high $P_T$ hadron pairs

$J/\Psi$ production

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the $P_T/zM$ weighted Sivers asymmetry

more results in NPB 940 (2019) 34

\[
A_{\text{Siv}}^w(x) = 2 \frac{\sum_q e_q^2 x f_{1T}^{\perp (1) q}(x) \bar{D}_1^q}{\sum_q e_q^2 x f_1^q(x) \bar{D}_1^q}
\]

\[
\bar{D}_1^q = \int_{z_{\text{min}}}^{z_{\text{max}}} dz D_1^q(z)
\]

the trends of the weighted and unweighted asymmetries are similar both for positive and negative hadrons

**positive hadrons:** asymmetry clearly different from zero, in particular at large $x$

assuming u-dominance, $A_{\text{Siv}}^{w+, u}(x) \approx 2 f_{1T}^{\perp (1) u}(x)/f_1^u(x)$

→ first direct measurement of $f_{1T}^{\perp (1) u}(x)$
the $P_T/zM$ weighted Sivers asymmetry

** extraction of $f_{1T}^{(1)}(x)$**

neglecting the sea-quark Sivers distributions, it is

\[
xf_{1T}^{(1)u_v} = \frac{1}{8} \frac{\delta^+ A_{Siv}^{w,+} \tilde{D}_{1,u,+} - \delta^- A_{Siv}^{w,-} \tilde{D}_{1,u,-}}{\tilde{D}_{1,u,+} \tilde{D}_{1,u,-} - \tilde{D}_{1,d,+} \tilde{D}_{1,d,-}}
\]

\[
xf_{1T}^{(1)d_v} = \frac{1}{2} \frac{\delta^- A_{Siv}^{w,-} \tilde{D}_{1,d,+} - \delta^+ A_{Siv}^{w,+} \tilde{D}_{1,d,-}}{\tilde{D}_{1,u,+} \tilde{D}_{1,u,-} - \tilde{D}_{1,d,+} \tilde{D}_{1,d,-}}
\]

\[
\bar{D}_1^{q, \pm} = \int_{z_{min}}^{z_{max}} dz D_1^{q, \pm}(z)
\]

\[
\delta^{\pm} = 9 \sum_q e_q^2 x f_1^q \bar{D}_1^q
\]

$f_1^q, \bar{D}_1^q, \pm$ from parametrisations (CTEQ5D and DSS)

- previous point-by-point extraction
  A.Martin, F.B., V.Barone, PRD95, 2017

using pion Sivers asymmetries from the COMPASS p and d data,

- no assumptions on the Sivers sea quarks,
  Gaussian ansatz

- slightly different trend for $f_{1T}^{(1)d_v}$,
  uncertainties on average larger by a factor $\sim 1.5$

the differences are mainly due to the use of the p data only and to the assumption on the sea-quarks
other non-zero signals in SIDIS
SIDIS off longitudinally polarised p

\[ A_{UL}^{\sin \phi_h} = \frac{F_{UL}^{\sin \phi_h}}{F_{UU}} \]

\[ F_{UL}^{\sin \phi_h} = \frac{2M}{Q} C \left\{ \frac{\hat{h} \cdot p_T}{M_h} \left( x h_L^{q q} H_{1q}^{h} + \frac{M_h}{M} \tilde{G}_{q}^{1h} \right) \right. \\
\left. + \frac{\hat{h} \cdot k_T}{M} \left( x f_{L}^{q q} D_{1q}^{h} - \frac{M_h}{M} \tilde{h}_{1q}^{h} \tilde{H}_{q}^{h} \right) \right\} \]

Q-suppressed, different “twist” contributions

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PLB622 2005
SIDIS off longitudinally polarised p

\[ A_{UL}^{\sin \phi_h} = \frac{F_{UL}^{\sin \phi_h}}{F_{UU}} \]

\[ F_{UL}^{\sin \phi_h} = \frac{2M}{Q} \mathcal{C} \left\{ -\frac{\hat{h} \cdot p_T}{M_h} \left( x h_L^q H_{1q}^{1h} + \frac{M_h}{M} g_{1L}^q \tilde{G}_q^{1h} \right) \right. \]
\[ \left. + \frac{\hat{h} \cdot k_T}{M} \left( x f_{1q} D_{1q}^h - \frac{M_h}{M} h_{1L}^q \tilde{H}_q^h \right) \right\} \]

Q-suppressed, different “twist” contributions

Proton 2007+2011 data

\[ \sin \phi_h, A_{UL} \]

factor \( \sqrt{2 \epsilon (1 + \epsilon)} \)

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Beam helicity asymmetries

$$A_{LU}^{\sin \phi_h} = \frac{F_{LU}^{\sin \phi_h}}{F_{UU}^{\sin \phi_h}}$$

$$F_{LU}^{\sin(\phi)}(x, Q^2, z, P_{h\perp}) = \frac{2M}{Q} C \left[ -\frac{\hat{h} \cdot \tilde{k}_T}{M_h} \left( x e H_1^\perp + \frac{M_h}{M} f_1 \frac{\tilde{G}_1^\perp}{z} \right) 
+ \frac{\hat{h} \cdot \tilde{p}_T}{M} \left( x g_1^\perp D_1 + \frac{M_h}{M} h_1^\perp \frac{\tilde{E}_1}{z} \right) \right]$$

Q-suppressed, different “twist” contributions

$\pi^\pm, K^\pm, p, \bar{p}$ on p and d
Beam helicity asymmetries

\[ A_{LU}^{\sin \phi_h} = F_{LU}^{\sin \phi_h} / F_{UU} \]

\[ F_{LU}^{\sin(\phi)}(x, Q^2, z, P_{h \perp}) = \frac{2M}{Q} C \left[ \hat{h} \cdot \vec{k}_T \left( xeH_1^+ + \frac{M_h}{M} \hat{f}_1 \hat{G}_1^+ \right) \right. \]

\[ \left. + \frac{\hat{h} \cdot \vec{p}_T}{M} \left( xg_1^D + \frac{M_h}{M} \hat{h}_1^+ \hat{E}_1^+ \right) \right] \]

Q-suppressed, different “twist” contributions

\( \pi^\pm, K^\pm, p, \bar{p} \) on p and d

IWHSS19, Aveiro, 24 June 2019

F. Bradamante
Beam helicity asymmetries

$$A_{LU}^{\sin \phi_h} = \frac{F_{LU}^{\sin \phi_h}}{F_{UU}}$$

$$F^{\sin(\phi)}_{LU}(x, Q^2, z, P_{h\perp}) = \frac{2M}{Q} C \left[ -\frac{\hat{h} \cdot \vec{k_T}}{M_h} \left( xeH_{1}^{+} + \frac{M_h}{M} f_{1} \frac{\vec{G}_{1}^{+}}{z} \right) 
+ \frac{\hat{h} \cdot \vec{p_T}}{M} \left( xg_{1}^{+} D_{1} + \frac{M_h}{M} h_{1}^{+} \frac{\vec{E}}{z} \right) \right]$$

Q-suppressed, different “twist” contributions
unpolarised SIDIS
unpolarised SIDIS

Relevance for TMDs:

• the cross-section dependence on $P_{hT}$ comes from:
  • intrinsic $k_T$ of the quarks
  • $p_\perp$ generated in the quark fragmentation
  \[
  \langle P_{hT}^2 \rangle = \langle p_\perp^2 \rangle + z^2 \langle k_T^2 \rangle
  \]

• the azimuthal modulations in the unpolarized cross-sections comes from:
  • intrinsic $k_T$ of the quarks
  • Boer-Mulders PDF

combined analysis should allow to disentangle the different effects

measured on p and/or d at Jlab, HERMES, COMPASS
unpolarised SIDIS – $P_{Th}$ distributions

a lot of phenomenological work ...
also including Drell-Yan data
$e^+e^- - P_{Th}$ distributions
$e^+e^- - P_{Th}$ distributions

NEW PRD99 2019

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$e^+ e^- - P_{Th}$ distributions

NEW PRD99 2019

$P_{Th}$ distributions

$0.10 < z < 0.15$
$0.15 < z < 0.20$
$0.20 < z < 0.25$
$0.25 < z < 0.30$
$0.30 < z < 0.35$
$0.35 < z < 0.40$
$0.40 < z < 0.45$
$0.45 < z < 0.50$
$0.50 < z < 0.55$
$0.55 < z < 0.60$
$0.60 < z < 0.65$
$0.65 < z < 0.70$
$0.70 < z < 0.75$
$0.75 < z < 0.80$
$0.80 < z < 0.85$

$0.85 < T < 0.90$

$0.65 < z < 0.70$

$\langle y_B \rangle = 0.021$

$\langle Q^2 \rangle = 1.23 (GeV/c)^2$
$\langle Q^2 \rangle = 1.92 (GeV/c)^2$
$\langle Q^2 \rangle = 2.94 (GeV/c)^2$
$\langle Q^2 \rangle = 4.07 (GeV/c)^2$

COMPASS

EPJC73 2013
unpolarised SIDIS – $P_{Th}$ distributions

**new:** preliminary results from COMPASS
proton data 2016-2017

precise multiD results expected soon
unpolarised SIDIS – azimuthal asymmetries
unpolarised SIDIS  – azimuthal asymmetries

**unpolarised SIDIS**

- **unpolarised SIDIS**
- **azimuthal asymmetries**

**Graphs and Data**

- **Graphs** showing **2 (cos(ϕ))** and **2 (cos(2ϕ))** for different processes and particles:
  - **π⁺**
  - **π⁻**

- **Parameters**:
  - **x**, **y**, **z**, **P_{nj} [GeV]**
  - **P_{nj} [GeV]**

**Experimental Data**

- **PRD87 2013**
- **HERMES**
- **COMPASS**
- **6LiD NPB886 2014**

**Observations**

- **Not easy to see Boer-Mulders**
unpolarised SIDIS – azimuthal asymmetries

**new**: contribution from exclusive (vector meson) events

Amplitudes of the $\cos \phi$ modulation for exclusive hadron pairs (from data)

\[ r = \frac{N_h^{exc}}{N_h^{exc} + N_h^{SIDIS}} \]

from HEPGEN ($\rho^0$) and Lepto

Preliminary
unpolarised SIDIS – azimuthal asymmetries

**new:** preliminary results from COMPASS 2016-2017 proton data

also, precise multiD results from JLab12 experiments expected soon
DRELL-YAN PROCESS

COMPLEMENTARY APPROACH TO SIDIS
**DRELL-YAN PROCESS**

**COMPLEMENTARY APPROACH TO SIDIS**

COMPASS is measuring for the first time the Drell-Yan process $\pi^- p \rightarrow \mu^+ \mu^- X$ on a transversely polarized proton target $\rightarrow$ Sivers, …

new results for $\bar{d}/\bar{u}$ from SeaQuest

SpinQuest in perspective (end 2019?) @ FNAL for **sea-quark transversity** and **Sivers PDFs**
Drell-Yan cross-section

general expression

\[
\frac{d\sigma}{dq^4 d\Omega} \propto \hat{\delta}_U \left\{ 1 + \cos^2 \theta_{CS} A^1_U + \sin 2\theta_{CS} A^\cos \varphi_{CS} \cos \varphi_{CS} + \sin^2 \theta_{CS} A^{\cos 2\varphi_{CS}}_U \cos 2\varphi_{CS} \\
+ S_T \left[ \left( A^\sin \varphi_S + \cos^2 \theta_{CS} \tilde{A}^{\sin \varphi_S}_T \right) \sin \varphi_S \right. \\
+ \sin 2\theta_{CS} \left( A^\sin(\varphi_{CS}+\varphi_S) T \sin(\varphi_{CS} + \varphi_S) + A^\sin(\varphi_{CS}-\varphi_S) T \sin(\varphi_{CS} - \varphi_S) \right) \right. \\
+ \sin^2 \theta_{CS} \left( A^\sin(2\varphi_{CS}+\varphi_S) T \sin(2\varphi_{CS} + \varphi_S) + A^\sin(2\varphi_{CS}-\varphi_S) T \sin(2\varphi_{CS} - \varphi_S) \right) \right] + \ldots \right\}
\]

\[ \lambda = A^1_U , \mu = A^{\cos \varphi_{CS}}_U , \nu = 2 A^{\cos 2\varphi_{CS}}_U \]
Drell-Yan cross-section

general expression  \( \pi^- p \rightarrow l^+ l^- X \)

\[
\frac{d\sigma}{dq^4 d\Omega} \propto \hat{\delta}_U \left\{ 1 + \cos^2 \theta_{CS} A_U^1 + \sin 2\theta_{CS} A_U^{\cos \varphi_{CS}} \cos \varphi_{CS} + \sin^2 \theta_{CS} A_U^{\cos 2\varphi_{CS}} \cos 2\varphi_{CS} \\
+ S_T \left[ \left( A_T^{\sin \varphi_S} + \cos^2 \theta_{CS} \tilde{A}_T^{\sin \varphi_S} \right) \sin \varphi_S \right. \\
+ \sin 2\theta_{CS} \left( A_T^{\sin(\varphi_{CS} + \varphi_S)} \sin(\varphi_{CS} + \varphi_S) + A_T^{\sin(\varphi_{CS} - \varphi_S)} \sin(\varphi_{CS} - \varphi_S) \right) \\
+ \sin^2 \theta_{CS} \left( A_T^{\sin(2\varphi_{CS} + \varphi_S)} \sin(2\varphi_{CS} + \varphi_S) + A_T^{\sin(2\varphi_{CS} - \varphi_S)} \sin(2\varphi_{CS} - \varphi_S) \right) \right]\} + \cdots
\]

Boer-Mulders of the \( \pi \)  \hspace{1cm}  Boer-Mulders of the \( p \)

\( h_1^+ \otimes h_1^+ \)

Sivers of the \( \pi \)  \hspace{1cm}  Boer-Mulders of the \( p \)

\( f_1 \otimes f_{1T}^\perp \)

Boer-Mulders of the \( \pi \)  \hspace{1cm}  transversity of the \( p \)

\( h_1^+ \otimes h_{1T}^\perp \)

Boer-Mulders of the \( \pi \)  \hspace{1cm}  pretzelosity of the \( p \)

IWHSS19, Aveiro, 24 June 2019  \hspace{1cm}  F. Bradamante
Drell-Yan at COMPASS

190 GeV $\pi^-$ beam, transversely polarised proton (NH3) target

DIS2019
Drell-Yan at COMPASS

190 GeV $\pi^-$ beam, transversely polarised proton (NH3) target

COMPASS 2015 NH3 data
- Combined background
- $J/\psi$ (MC)
- $\psi'$ (MC)
- Open-charm (MC)
- Drell-Yan (MC)
- Total MC + Combined background

DIS2019
Drell-Yan at COMPASS

190 GeV $\pi^-$ beam, transversely polarised proton (NH$_3$) target

Sivers asymmetry

COMPASS Drell-Yan

$4.3 < M_{\mu\mu}/(\text{GeV}/c^2) < 8.5$

● 2015+2018 (~50%) preliminary
Drell-Yan at COMPASS

190 GeV $\pi^-$ beam, transversely polarised proton (NH3) target

Transverse Spin asymmetries

Sivers asymmetry

COMPASS Drell-Yan $4.3 < M_{\mu\mu}/(\text{GeV}/c^2) < 8.5$

- 2015+2018 (~50%) preliminary
Drell-Yan at COMPASS

190 GeV $\pi^-$ beam, transversely polarised proton (NH$_3$) target

$q_T/M$ weighted asymmetries

$$A_T \sin \phi_S \sqrt[3]{M_p M_{\pi}}(x_\pi, x_N) \approx -2 \frac{h_{1,\pi}^{(1)} \bar{u}(x_\pi) h_{1,\rho}^{(2)} u(x_N)}{f_{1,\rho}^u(x_N)}$$

Sivers

$$A_T \sin(2\phi + \phi_S) \sqrt[3]{M_p M_{\pi}}(x_\pi, x_N) \approx -2 \frac{h_{1,\pi}^{(1)} \bar{u}(x_\pi) h_{1,\rho}^{(2)} u(x_N)}{f_{1,\rho}^u(x_N) f_{1,\rho}^u(x_N)}$$

Pretzelosity

$$A_T \sin(2\phi - \phi_S) \sqrt[3]{M_p M_{\pi}}(x_\pi, x_N) \approx -2 \frac{h_{1,\pi}^{(1)} \bar{u}(x_\pi) h_{1,\rho}^{(2)} u(x_N)}{f_{1,\rho}^u(x_N) f_{1,\rho}^u(x_N)}$$

Transversity

COMPASS Drell-Yan

- 2015 + 2018 preliminary
Drell-Yan at COMPASS

190 GeV $\pi^-$ beam, transversely polarised proton (NH$_3$) target

$q_T$-weighted asymmetries

$$ A_T^{\sin \varphi_S M_N}(x_\pi, x_N) \approx -2 \frac{f_{1T}^{(1)u}(x_N)}{f_{1p}^u(x_N)} $$

Sivers

COMPASS Drell-Yan

- 2015 + 2018 preliminary

COMPASS 2015+2018, preliminary

- bins in $x$
- bins combined
- projection from SIDIS
unpolarised Drell-Yan

\[
\frac{d\sigma}{dq^4d\Omega} \propto \hat{\sigma}_U \left\{ 1 + \cos^2 \theta_{CS} A^1_U + \sin 2\theta_{CS} A^{\cos \varphi_{CS}}_U \frac{\lambda}{\mu} \cos \varphi_{CS} + \sin^2 \theta_{CS} A^{\cos 2\varphi_{CS}}_U \frac{\nu}{2} \right\}
\]

- "naive" Drell–Yan model
  - collinear ($k_T = 0$) LO pQCD
    - $\lambda = 1$, $\mu = \nu = 0$
- intrinsic transverse momentum + QCD effects
  - $\lambda \neq 1$, $\mu \neq 0$, $\nu \neq 0$, with $1 - \lambda = 2\nu$ (Lam-Tung relation)
- experimentally
  - $\lambda \neq 1$, $\mu \neq 0$, $\nu \neq 0$

IWHSS19, Aveiro, 24 June 2019
flavor asymmetry of nucleon sea

- \( \frac{\sigma_{pd}(x)}{2\sigma_{pp}(x)} \approx \frac{1}{2} \left( 1 + \frac{\bar{d}(x)}{\bar{u}(x)} \right) \) for \( x_F \gg 0 \)

- Significant deviation of \( \frac{\bar{d}}{\bar{u}} \) from 1
- Asymmetry has a strong dependence on \( x \)
- Can \( x \) dependence be explained?

![Graph showing the ratio of \( \bar{d}/\bar{u} \) as a function of \( x \). The graph includes data points and curves representing FNAL E866/NuSea Drell-Yan and CTEQ4M models.]
flavor asymmetry of nucleon sea

\[ \frac{\sigma_{pd}(x)}{2\sigma_{pp}(x)} \approx \frac{1}{2} \left( 1 + \frac{\bar{d}(x)}{\bar{u}(x)} \right) \]

\( x_F \gg 0 \)

\[ d/\bar{u} \]

\[ 800 \text{ GeV protons} \]

\[ 120 \text{ GeV} \]
TMD PDFs from SIDIS and Drell-Yan

future
TMD PDFs from SIDIS and Drell-Yan

future

SIDIS
• COMPASS: transversely polarised deuteron 2021

projected
gain in precision:
up to 2 for the u-quark
2 to 4 for the d-quark

present
TMD PDFs from SIDIS and Drell-Yan

future

SIDIS
- COMPASS: transversely polarised deuteron 2021
- JLab12: soon later; SoLID ~2026?

One example on Collins asymmetry

\[ Q^2 (\text{GeV/c})^2 \]

- 12 GeV SoLID forward
- 12 GeV SoLID large angle
- 6 GeV Transversity

\[ x_{bj} \]

- \[ <P_T> = 1.1 \text{ (GeV)} \]
- \[ <P_T> = 0.9 \text{ (GeV)} \]
- \[ <P_T> = 0.7 \text{ (GeV)} \]
- \[ <P_T> = 0.5 \text{ (GeV)} \]
- \[ <P_T> = 0.3 \text{ (GeV)} \]
- \[ <P_T> = 0.1 \text{ (GeV)} \]

\[ 2 < Q^2 < 3 \]

\[ 0.40 < z < 0.45 \]

\[ P_T \text{ vs. } x \text{ for one (Q}^2, z \text{) bin} \]

Total > 1400 data points
TMD PDFs from SIDIS and Drell-Yan

future

**SIDIS**
- COMPASS: transversely polarised deuteron 2021
- JLab12: soon later; SoLID ~2026?
- EIC
- ...
TMD PDFs from SIDIS and Drell-Yan

future

**SIDIS**
- COMPASS: transversely polarised deuteron 2021
- JLab12: soon later; SoLID ~2026?
- EIC
- ...

**Drell-Yan**
- SpinQuest ~2019?
- COMPASS++/AMBER ~2024?
- LHC
- ...
TMD PDFs from SIDIS and Drell-Yan

future

SIDIS
- COMPASS: transversely polarised deuteron 2021
- JLab12: soon later; SoLID ~2026?
- EIC
- ...

Drell-Yan
- SpinQuest ~2019?
- COMPASS++/AMBER ~2024?
- LHC
- ...

and soon many new results from already collected data
SIDIS and Drell-Yan cross-sections, SeaQuest, ...