COMPASS studies of TMDs; recent results and future perspectives

Andrea Bressan
University of Trieste and INFN
Muon beam: SIDIS setup

- high energy beam
- large angular acceptance
- broad kinematical range

two stages spectrometer

Large Angle Spectrometer (SM1)
- threshold: π ~ 2 GeV/c
- K ~ 10 GeV/c

Small Angle Spectrometer (SM2)

COMPASS
COMPASS target area

Hadron Spectroscopy

Polarised SIDIS

Polarised Drell-Yan

DVCS (GPDs) + unp. SIDIS

COMPASS-I
1997-2011

COMPASS-II
2012-2020
Operations on the target area
Targets

- Microwave cavity
- Dilution refrigerator
- New Magnet

Images: 27.09.2012
Two stage spectrometer
Hadron beam: Drell-Yan setup
Muon beam – DVCS setup
Spectrometer elements
Spectrometer: momentum determination

Target → Magnet1 → RICH → Magnet2
the polarized target system (>2005)

\[ ^3\text{He} - ^4\text{He} \text{ dilution refrigerator (T\text{\~n}50mK)} \]

- Solenoid: 2.5T
- Dipole magnet: 0.6T

\[ ^3\text{He} - ^4\text{He} \text{ dilution refrigerator (T\text{\~n}50mK)} \]

\[ \mu \]

\[ \text{\text{NH}_3} \]

\[ \text{\text{Al}} \]

\[ \text{\text{W}} \]
Vertex determination
Kinematic distributions

DIS cuts: $Q^2 > 1 \text{ (GeV/c)}^2$
$0.1 < y < 0.9$
$W > 5 \text{ GeV/c}^2$
DIS cuts: \( Q^2 > 1 \text{ (GeV/c)}^2 \)
\( 0.1 < y < 0.9 \)
\( W > 5 \text{ GeV/c}^2 \)

hadron selection: \( P_T^h > 0.1 \text{ GeV/c}, \)
\( z > 0.2 \)
## COMPASS data taking

<table>
<thead>
<tr>
<th>Experiment Type</th>
<th>Target</th>
<th>Year(s)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Muon beam</td>
<td>Deuteron ((^6)LiD) PT</td>
<td>2002</td>
<td>80% L/20% T target polarisation</td>
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<tr>
<td></td>
<td></td>
<td>2003</td>
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<tr>
<td></td>
<td></td>
<td>2004</td>
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<tr>
<td></td>
<td></td>
<td>2006</td>
<td>L target polarisation</td>
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<tr>
<td>Proton ((NH_3)) PT</td>
<td>2007</td>
<td>50% L /50% T target polarisation</td>
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<tr>
<td>Hadron</td>
<td>LH target</td>
<td>2008</td>
<td></td>
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<td></td>
<td></td>
<td>2009</td>
<td></td>
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<tr>
<td>Muon beam</td>
<td>Proton ((NH_3)) PT</td>
<td>2010</td>
<td>T target polarisation</td>
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<tr>
<td></td>
<td></td>
<td>2011</td>
<td>L target polarisation</td>
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<tr>
<td>Hadron</td>
<td>Ni target</td>
<td>2012</td>
<td>Primakoff</td>
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<tr>
<td>Muon beam</td>
<td>LH2 target</td>
<td>2012</td>
<td>Pilot DVCS &amp; unpol. SIDIS</td>
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<tr>
<td>Hadron</td>
<td>Proton (NH3) DT PT</td>
<td>2014</td>
<td>Pilot DY run</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2015</td>
<td>DY run</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2018</td>
<td>DY run</td>
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<tr>
<td>Muon beam</td>
<td>LH2 target</td>
<td>2016</td>
<td>DVCS &amp; unpol. SIDIS</td>
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<tr>
<td></td>
<td></td>
<td>2017</td>
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Measurements with the target longitudinally polarized:

<table>
<thead>
<tr>
<th>Year</th>
<th>Obs.</th>
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<tbody>
<tr>
<td>2006</td>
<td>$A_{LL}^{2h} (Q^2 &lt; 0)$, $\Delta g/g$</td>
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<tr>
<td>2007</td>
<td>$g_1^d (x)$, $g_{1T}^d$, $\Gamma_1^d, \Delta \Sigma$</td>
</tr>
<tr>
<td>2008</td>
<td>$A_{1,d}^{h^+ - h^-}$, $\Delta u_v + \Delta d_v$</td>
</tr>
<tr>
<td>2009</td>
<td>$A_{1,d}^{A_{1,d}^\pi^\pm, A_{1,d}^\pi^\pm}$, $\Delta u_v + \Delta d_v, \Delta \bar{u} + \Delta \bar{d}, \Delta s (= \Delta \bar{s})$</td>
</tr>
<tr>
<td>2010</td>
<td>$g_1^p (x)$, $</td>
</tr>
<tr>
<td>2010</td>
<td>$A_{1,d}^{A_{1,d}^\pi^\pm, A_{1,d}^\pi^\pm}$, $A_{1,p}, A_{1,p}^{A_{1,d}^\pi^\pm}$, $\Delta u, \Delta d, \Delta \bar{u}, \Delta \bar{d}, \Delta s, \Delta \bar{s}$</td>
</tr>
<tr>
<td>2010</td>
<td>$\sin \phi, \sin 2\phi, \sin 3\phi, \cos \phi$ asyms, $h_L, f_L^{1T}, h_1, f_1^{1T}, h_{1L}^{1T}, h_1^{1L}, f_1^{1T}$, $g_L, g_1 T$</td>
</tr>
<tr>
<td>2013</td>
<td>$A_{LL}^{2h}$, $\Delta g / g$</td>
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<tr>
<td>2013</td>
<td>$A_D^\gamma N$, $\Delta g / g$ in LO and NLO</td>
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<tr>
<td>2015</td>
<td>$g_1^p (x)$, $\Gamma_1^{NS}, \Delta \Sigma, \Delta u + \Delta \bar{u}$</td>
</tr>
<tr>
<td>2015</td>
<td>$A_{LL}^p$, NLO QCD fits for $\Delta g / g$</td>
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Measurements with the target transversely polarized:

<table>
<thead>
<tr>
<th>Year</th>
<th>Obs</th>
<th>Notes</th>
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<tbody>
<tr>
<td>2005</td>
<td>$A^h_{Siv,d}, A^h_{Col,d}$</td>
<td>First $^6$LiD data</td>
</tr>
<tr>
<td>2006</td>
<td>$A^h_{Siv,d}, A^h_{Col,d}$</td>
<td>Full $^6$LiD statistics</td>
</tr>
<tr>
<td>2009</td>
<td>$A^\pi^\pm, K^\pm, K_S^0_{Siv,d}, A^\pi^\pm, K^\pm, K_S^0_{Col,d}$</td>
<td>Full $^6$LiD statistics</td>
</tr>
<tr>
<td>2010</td>
<td>$A^h_{Siv,p}, A^h_{Col,p}$</td>
<td>2007 NH$_3$ data</td>
</tr>
<tr>
<td>2012</td>
<td>$A^{\sin \phi_{RS}}<em>{UT,d}, A^{\sin \phi</em>{RS}}_{UT,p}$</td>
<td>Full $^6$LiD</td>
</tr>
<tr>
<td>2012</td>
<td>$A^h_{Siv,p}, A^h_{Col,p}$</td>
<td>Full NH$_3$ statistics</td>
</tr>
<tr>
<td>2012</td>
<td>$A^{\sin (\phi_p - \phi_S)}<em>{UT,d}, A^{\sin (\phi_p - \phi_S)}</em>{UT,p}$</td>
<td>Exclusive $\rho^0$</td>
</tr>
<tr>
<td>2013</td>
<td>$A^{(\phi_p, \phi_S)}<em>{UT,d}, A^{(\phi_p, \phi_S)}</em>{UT,p}$</td>
<td>Exclusive $\rho^0$, all asyms.</td>
</tr>
<tr>
<td>2014</td>
<td>$A^{\sin \phi_{RS}}<em>{UT,d}, A^{\sin \phi</em>{RS}}_{UT,p}$</td>
<td>Full $^6$LiD and NH$_3$</td>
</tr>
<tr>
<td>2014</td>
<td>$A^\pi^\pm, K^\pm, K_S^0_{Siv,d}, A^\pi^\pm, K^\pm, K_S^0_{Col,d}$</td>
<td>Full NH$_3$ statistics</td>
</tr>
<tr>
<td>2015</td>
<td>Interplay $A^{\sin \phi_{RS}}<em>{UT,p}$ vs $A^h</em>{Col,p}$</td>
<td>Full NH$_3$ statistics</td>
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Measurements with unpolarised targets:

<table>
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<th>Year</th>
<th>Obs</th>
<th>Notes</th>
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<tbody>
<tr>
<td>2013</td>
<td>$dn^h / (dN^\mu dz , dp_T^2)$</td>
<td>Unpolarized multiplicities on d, 2004</td>
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<tr>
<td>2014</td>
<td>$A_{UU,d}^{\cos \phi_h}$, $A_{UU,d}^{\cos 2 \phi_h}$, $A_{LU,d}^{\sin \phi_h}$</td>
<td>2004, part</td>
</tr>
<tr>
<td>2016</td>
<td>$dn^\pi / (dN^\mu dz)$</td>
<td>Unpolarized multiplicities on d, 2006</td>
</tr>
<tr>
<td>2016</td>
<td>$dn^h / (dN^\mu dz , dp_T^2)$</td>
<td>Unpolarized multiplicities on d, 2006</td>
</tr>
<tr>
<td>2016</td>
<td>$dn^K / (dN^\mu dz)$</td>
<td>Unpolarized multiplicities on d, 2006</td>
</tr>
</tbody>
</table>
Importance of unpolarized SIDIS

- The cross section dependence from $P_{hT}$ results from:
  - intrinsic $k_\perp$ of the quarks
  - $p_\perp$ generated in the quark fragmentation

- The azimuthal modulations in the unpolarised cross sections comes from:
  - Intrinsic $k_\perp$ of the quarks
  - The Boer-Mulders PDF

- Difficult measurements were one has to correct for the apparatus acceptance

- COMPASS and HERMES have
  - results on $^6LiD$ ($\sim d$) and preliminary on $p$ from COMPASS
  - $d$ and $p$ from HERMESS

$\Rightarrow$ COMPASS-II, measurements on LH$_2$ in parallel with DVCS
Positive vs Negative charged hadrons ($^6\text{LiD}$)

\[ F_{UU}^h(x, z, P_{hT}^2; Q^2) = x \sum_q e_q^2 \int d^2 \vec{k}_\perp d^2 \vec{p}_\perp \delta(\vec{p}_\perp + z\vec{k}_\perp - \vec{P}_{hT}) f_1^q(x, k^2; Q^2) D_{1}^{q\to h}(z, p^2_\perp; Q^2) \]

\[
\langle Q^2 \rangle = 9.78 \text{ (eV }/c)^2 \text{ and } \langle x \rangle = 0.149
\]
Positive vs Negative charged hadrons ($p$)
Positive charged hadrons ($\pi$)

COMPASS preliminary

- Positive hadrons
  - $0.2 < z < 0.3$
  - $0.3 < z < 0.4$
  - $0.4 < z < 0.6$

- $0.032 < x < 0.055$
  - $7.0 < Q^2/(\text{GeV/c})^2 < 16.0$
- $0.055 < x < 0.100$
  - $7.0 < Q^2/(\text{GeV/c})^2 < 16.0$
- $0.100 < x < 0.210$
  - $7.0 < Q^2/(\text{GeV/c})^2 < 16.0$

- $0.020 < x < 0.032$
  - $3.0 < Q^2/(\text{GeV/c})^2 < 7.0$
- $0.032 < x < 0.055$
  - $3.0 < Q^2/(\text{GeV/c})^2 < 7.0$
- $0.055 < x < 0.100$
  - $3.0 < Q^2/(\text{GeV/c})^2 < 7.0$
Negative charged hadrons ($p$)

COMPASS preliminary

negative hadrons
- $0.2 < z < 0.3$
- $0.3 < z < 0.4$
- $0.4 < z < 0.6$

$0.032 < x < 0.055$
$0.055 < x < 0.100$
$0.100 < x < 0.210$

$7.0 < Q^2/(GeV/c)^2 < 16.0$
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$P_{hT}^2 (GeV/c)^2$

$M_h$

$10^{-3}$
$10^{-2}$
$10^{-1}$
$10^0$
$10^1$
$10^2$
$10^3$
$10^4$
$10^5$

$0.020 < x < 0.032$
$0.032 < x < 0.055$
$0.055 < x < 0.100$

$3.0 < Q^2/(GeV/c)^2 < 7.0$
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The matching problem ($q_T/Q > 1$ region)

COMPASS 17 $h^+$

data/theory (NLO) vs. $q_T$ (GeV)

PDF: JAM18 FF: JAM18

$q_T > Q$

$< z >= 0.24$
$< z >= 0.34$
$< z >= 0.48$
$< z >= 0.68$
When looking at the content of the structure functions/modulations in terms of TMD PDFs for the $\cos \phi_h$ and $\cos 2\phi_h$ we can write:

\[
F_{UUU}^{\cos \phi_h} = -\frac{2M}{Q} C \left[ \frac{\hat{h} \cdot \vec{k}_\perp}{M} f_1 D_1 - \frac{p_\perp \vec{k}_\perp}{M} \vec{P}_{hT} - z(\hat{h} \cdot \vec{k}_\perp) \frac{h_1^\perp H_1^\perp}{zM_h M} \right] + \text{twists} > 3
\]

\[
F_{UUU}^{\cos 2\phi_h} = C \left[ (\hat{h} \cdot \vec{k}_\perp)(\hat{h} \cdot \vec{p}_\perp) - \vec{p}_\perp \cdot \vec{k}_\perp \frac{h_1^\perp H_1^\perp}{M M_h} \right] + \text{twists} > 3
\]

In the $\cos 2\phi_h$ Cahn effects enters only at twist4

\[
F_{\text{Cahn}}^{\cos 2\phi_h} \approx \frac{2}{Q^2} C \left[ \left\{ 2(\hat{h} \cdot \vec{k}_\perp)^2 - k_\perp^2 \right\} f_1 D_1 \right]
\]
Azimuthal modulations on $p$
Contribution of diffractive VMs

- Determined from $z_1 + z_2 > 0.95$
- Selecting $\rho^0$ and $\phi$
- Smaller, but not negligible, effect for $\cos 2\phi_h$

The diffractive $\rho^0$ production and decay.
Transversity PDF

\[ h_1^q(x) = q^{\uparrow\uparrow}(x) - q^{\uparrow\downarrow}(x) \]

\[ q = u_v, d_v, q_{\text{sea}} \]

quark with spin parallel to the nucleon spin in a transversely polarised nucleon

- probe the relativistic nature of quark dynamics
- no contribution from the gluons \( \rightarrow \) simple \( Q^2 \) evolution
- Positivity: Soffer bound………………\( 2|h_1^q| \leq f_1^q + g_1^q \)
  \( \text{Soffer, PRL 74 (1995)} \)
- first moments: tensor charge………..\( \delta q(Q^2) = \int_0^1 dx [h_1^q(x) - h_1^{\bar{q}}(x)] \)
- is chiral-odd: decouples from inclusive DIS

\( \text{Bakker, Leader, Trueman, PRD 70 (04)} \)
Transversity

**is chiral-odd:**

observable effects are given only by the product of \( h_1^q(x) \) and another chiral-odd function

can be measured in SIDIS on a transversely polarised target via “quark polarimetry”

\[
\ell N^\uparrow \to \ell' h X \\
\ell N^\uparrow \to \ell' h h X \\
\ell N^\uparrow \to \ell' \Lambda X
\]

“Collins” asymmetry

“Collins” Fragmentation Function

“two-hadron” asymmetry

“Interference” Fragmentation Function

\( \Lambda \) polarisation

Fragmentation Function of \( q^\uparrow \to \Lambda \)
$A^p_{\text{Coll}}$ on proton and $^3P_0$ model for FF

- The curves are fits of the Monte Carlo data, scaled by $\lambda\sim\langle h_1^u/f_1^u \rangle \sim 0.055$

- Agreement with the measured Collins asymmetry is quite satisfactory

2h asymmetries on p and $^3P_0$ model for FF

$$A_{UT}^{\sin(\phi_R+\phi_S-\pi)} = \frac{\sum_q e_q^2 h_1^q(x) H_{q\to h_1 h_2}(z, \mathcal{M}_{h_1 h_2}^2)}{\sum_q e_q^2 q(x) D_a^{h_1 h_2}(z, \mathcal{M}_{h_1 h_2}^2)}$$

$$a_p^{u\uparrow\to h^+ h^- X} = \langle \sin(\phi_R + \phi_S - \pi) \rangle$$ and $$\vec{R} = \frac{z_2 \vec{P}_{h_1} - z_1 \vec{P}_{h_2}}{z_1 + z_2}$$ and as before $\lambda \sim \langle h_1^u/f_1^u \rangle \sim 0.055$
\( P_{\Lambda(\bar{\Lambda})}(x, z) = \frac{\sum_q e_q^2 h_1^q(x) H_1^{\Lambda(\bar{\Lambda})}(z)}{\sum_q e_q^2 f_1^q(x) D_1^{\Lambda(\bar{\Lambda})}(z)} \)

\[
\frac{dN}{d\cos \theta^*} \propto A(1 + \alpha P_{\Lambda(\bar{\Lambda})} \cos \theta^*)
\]
Sivers Asymmetry

Sivers: correlates nucleon spin & quark transverse momentum $k_T/T$-ODD

at LO:

$$A_{Siv} = \frac{\sum_q e_q^2 f_{1Tq}^T \otimes D_q^h}{\sum_q e_q^2 q \otimes D_q^h}$$

$\mu p^\uparrow \rightarrow \mu X h^\pm$

The Sivers PDF

<table>
<thead>
<tr>
<th>Year</th>
<th>Event/Research</th>
</tr>
</thead>
<tbody>
<tr>
<td>1992</td>
<td>Sivers proposes $f_{1T}^T$</td>
</tr>
<tr>
<td>1993</td>
<td>J. Collins proofs $f_{1T}^T = 0$ for T invariance</td>
</tr>
<tr>
<td>2002</td>
<td>S. Brodsky, Hwang and Schmidt demonstrate that $f_{1Tq}^T$ may be $\neq 0$ due to FSI</td>
</tr>
<tr>
<td>2002</td>
<td>J. Collins shows that $(f_{1T}^T)<em>{DY} = -(f</em>{1T}^T)_{SIDIS}$</td>
</tr>
<tr>
<td>2004</td>
<td>HERMES on p: $A_{Siv}^{\pi^+} \neq 0$ and $A_{Siv}^{\pi^-} = 0$</td>
</tr>
<tr>
<td>2004</td>
<td>COMPASS on d: $A_{Siv}^{\pi^+} = 0$ and $A_{Siv}^{\pi^-} = 0$</td>
</tr>
<tr>
<td>2008</td>
<td>COMPASS on p: $A_{Siv}^{\pi^+} \neq 0$ and $A_{Siv}^{\pi^-} = 0$</td>
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</table>
Sivers Asymmetry

\[ A_{Siv}(x, z) = \frac{F_{UT}^{Sin\Phi_{Siv}}(x, z)}{F_{UU}(x, z)} = \frac{\sum_q e_q^2 x f_{1T}^{1q}(x, k_T^2) \otimes D_{1q}^h(z, p_T^2)}{\sum_q e_q^2 x f_{1}^q(x, k_T^2) \otimes D_{1q}^h(z, p_T^2)} \]

• To evaluate it we need to solve the convolutions (i.e. make hypothesis on the transverse momenta dependences of the TMDs)

• Gaussian ansatz: \( f_{1T}^{1q}(x) \frac{e^{-k_T^2/\langle k_T^2 \rangle_S}}{\pi \langle k_T^2 \rangle_S} \quad D_{1q}^h(z) \frac{e^{-p_T^2/\langle p_T^2 \rangle}}{\pi \langle p_T^2 \rangle} \)

• Leading to: \( A_{Siv,G}(x, z) = \frac{\sqrt{\pi M}}{\sqrt{z^2 \langle k_T^2 \rangle + \langle p_T^2 \rangle}} \frac{\sum_q e_q^2 x f_{1T}^{1(1)q}(x) z D_{1q}^h(z)}{\sum_q e_q^2 x f_{1q}^q(x) D_{1q}^h(z)} \) with \( f_{1T}^{1(1)q}(x) = \)

\[ \int d^2 k_T \frac{k_T^2}{2M^2} f_{1T}^{1q}(x, k_T^2) \]
Sivers asymmetry on p

charged pions (and kaons), HERMES and COMPASS

\[ A_{Siv}^p \]

<table>
<thead>
<tr>
<th>( p_T^h ) (GeV/c)</th>
<th>( x )</th>
<th>( z )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>0.5</td>
<td>1.0</td>
</tr>
<tr>
<td>1.0</td>
<td>1.0</td>
<td>1.5</td>
</tr>
</tbody>
</table>

COMPASS positive pions \( x<0.032 \) preliminary
COMPASS positive pions \( x>0.032 \) preliminary
HERMES \( \pi^+ \) PRL 103 (2009)
HERMES \( \pi^- \) PRL 103 (2009)
Drell-Yan measurements at COMPASS

I. \( 1 < M_{\mu\mu}(\text{GeV}/c^2) < 2 \), “Low mass”
   - Large background contamination

II. \( 2 < M_{\mu\mu}(\text{GeV}/c^2) < 2.5 \), “Intermediate mass”
   - High DY cross section.
   - Still low DY-signal/background ratio

III. \( 2.5 < M_{\mu\mu}(\text{GeV}/c^2) < 4.3 \), “Charmonia mass”
   - Strong \( J/\psi \) signal: \( J/\psi \) physics.
   - Good signal/background.

IV. \( 4.3 < M_{\mu\mu}(\text{GeV}/c^2) < 8.5 \), “High mass” background <4%
   - Valence quark region \( \rightarrow \) Largest asymmetries!
   - Low DY cross-section

\[ \langle x_\pi \rangle = 0.5 \]
\[ \langle x_N \rangle = 0.17 \]

\[ \langle M_{\mu\mu} \rangle = 5.3 \text{ GeV}/c^2 \]
Transverse Spin Asymmetry in Drell-Yan

190 GeV/c $\pi^-$ beam, transversely polarized NH$_3$ target

$$\frac{d\sigma}{dq^4d\Omega} \propto 1 + \ldots + S_T \left[ A_T^{\sin\phi_S} \sin\phi_S + \ldots \right]$$

Sivers DY TSA

$$A_T^{\sin\phi_S} \propto f_{1T,\pi} \otimes f_{1T,p}^{-q}$$

COMPASS 2015 (PRL 119, 112002 (2017)) + 2018 (~50%)
The weighted Sivers asymmetry

- If we weight the spin dependent part of the cross-section
  \[ F_{UT}^{\sin \Phi_{Siw}}(x, z) = \sum_q e_q^2 \int d^2 \vec{P}_T P_T F_q(x, z, P_T^2) \]

- with \( w = P_T/zM \), i.e.
  \[ F_{UT}^{\sin \Phi_{Siw},w}(x, z) = \sum_q e_q^2 \int d^2 \vec{P}_T \frac{P_T^2}{zM} F_q(x, z, P_T^2) = 2 \sum_q e_q^2 x f_{1T}^\perp(x) D_{1q}^h(z) \]

and
  \[ F_q(x, z, P_T^2) = \int d^2 k_T \int d^2 \vec{p}_T \delta^2(\vec{P}_T - z\vec{k}_T - \vec{p}_T) \frac{\vec{p}_T \cdot \vec{k}_T}{M P_T^2} x f_{1T}^\perp(x, k_T^2) D_{1q}(z, p_T^2) \]

- we have no longer a convolution but a product of two integrals and we can write
  \[ A_{Siw}^w(x, z) = \frac{F_{UT}^{\sin \Phi_{Siw},w}(x, z)}{F_{UU}(x, z)} = 2 \frac{\sum_q e_q^2 x f_{1T}^\perp(x) D_{1q}^h(z)}{\sum_q e_q^2 x f_1^q(x) D_{1q}^h(z)} \]

with
  \[ f_{1T}^\perp(x) = \int d^2 k_T \frac{k_T^2}{2M^2} f_{1T}^\perp(x, k_T^2) \]
The weighted Sivers asymmetry

\[ A_{Siv}^w(x) = 2 \frac{\sum_q e_q^2 x f_{1T}^{\perp q}(x) \int D_{1q}^h(z)dz}{\sum_q e_q^2 x f_1^{q}(x) \int D_{1q}^h(z)dz} \]

\[ w = p_T/zM \]

standard cuts
\[ z > 0.2 \]

\[ \sim 2 \frac{f_{1T}^{\perp(1)u}(x)}{f_1^{u}(x)} \]

both \( f_{1T}^{\perp(1)u} \) and \( f_{1T}^{\perp(1)d} \) contribute
The weighted Sivers asymmetry

\[ A_{Siv}^w(x) = 2 \frac{\sum_q e_q^2 x f_{1T}^{(1)}(x) \int D_{1q}^h(z) dz}{\sum_q e_q^2 x f_1^q(x) \int D_{1q}^h(z) dz} \]

\[ w = \frac{P_T}{z M} \]

The ratio between weighted and unweighted Sivers asymmetries follows the average of \( 4 \langle x \rangle / \pi M \langle zP_T \rangle \) of the unpolarised sample.
\( q_T \) weighted asymmetries: 2015+2018

- The \( q_T \)-weighted asymmetries extracted in the HM range from the combined 2015-2018 Drell Yan data samples. For 2018, only 50% of the data have been used.
- Additional uncertainties of about 5% from the polarization and 8% from dilution factor calculation have to be added to the systematic errors.
Weighted asymmetries: from SIDIS to DY

1st $k_{T}^{2}$-moment of the Sivers function from SIDIS data at $Q_{SIDIS}^{2}(x)$

Assuming:
- $u$-dominance
  \[ A_{T} = \sin(\phi_{S}) \frac{q_{T}}{M_{NN}} \frac{f_{1T}^{(1)u}}{f_{1u}} \]
- Same $Q^{2}$ for SIDIS and DY
- Sine change $f_{1T}^{(1)u} \bigg|_{DY} = f_{1T}^{(1)u} \bigg|_{DIS}$

![Graph showing the 1st $k_{T}^{2}$-moment of the Sivers function from SIDIS data at $Q_{SIDIS}^{2}(x)$](image1)

![Graph showing the $A_{T}$ and $\sin(\phi_{S}) \frac{q_{T}}{M_{NN}} \frac{f_{1T}^{(1)u}}{f_{1u}}$](image2)
Sivers Asymmetry for Gluon from SIDIS

\[ A_{PGF}^{Siv,d} = -0.14 \pm 0.15 \text{(stat.)} \pm 0.10 \text{(syst.)} \]
\[ \langle x_g \rangle = 0.13 \]

\[ A_{PGF}^{Siv,p} = -0.26 \pm 0.09 \text{(stat.)} \pm 0.06 \text{(syst.)} \]
\[ \langle x_g \rangle = 0.15 \]

WHAT WILL COME NEXT
• Benchmark: $h_1$ extraction from Collins asymmetries

Transversity extracted as in PRD 91(2015) 014034
COMPASS proposed to CERN to run a full year with the transversely polarized deuteron target and this proposal has been approved.
New deuteron data

- 1 full year (same as 2010). We also gain from \( \frac{f_p P_{pT}}{f_D P_{DT}} = \frac{0.155 \times 0.8}{0.40 \times 0.5} = 0.6 \)

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**projected**

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**present**

Transversity extracted as in PRD 91(2015) 014034
• Expected gain in precision on u- and d-quark transversity
Proposal for Measurements at the M2 beam line of the CERN SPS

Phase-1: 2022-2024

COMPASS++*/AMBER†
Thank you