Measurement of $q_T$-weighted TSAs in 2015 COMPASS Drell–Yan data

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Outline

1. TSAs in the Drell–Yan process
2. Measurement
3. The weighted Sivers asym. in SIDIS and DY
4. Conclusion
1. TSAs in the Drell–Yan process

2. Measurement

3. The weighted Sivers asym. in SIDIS and DY

4. Conclusion
TSAs in the Drell–Yan process: The cross-section

- $\pi^-$ beam, NH$_3$ target with T-polarized H nuclei

$$\pi^- (P_\pi) + p(P_N, S) \rightarrow \mu^- (l^-) + \mu^+ (l^+) + X.$$ 


$$\frac{d\sigma_{DY}}{dx_\pi dx_p dq_T^2 d\phi_S d\cos \theta d\phi} = C_0 \left\{ (1 + \cos^2 \theta) F_U^1 + \sin^2 \theta \cos 2\phi F_U^{\cos 2\phi} + |S_T| (1 + \cos^2 \theta) \sin \phi_S F_T^{\sin \phi_S} + \sin^2 \theta \sin (2\phi + \phi_S) F_T^{\sin (2\phi + \phi_S)} + \sin^2 \theta \sin (2\phi - \phi_S) F_T^{\sin (2\phi - \phi_S)} \right\},$$

**Diagram:**

- Target frame.

- Collins–Soper frame.
TSAs in the Drell–Yan process: The cross-section

- $\pi^-$ beam, NH$_3$ target with T-polarized H nuclei

\[
\pi^-(P_\pi) + p(P_N, S) \rightarrow \mu^- (l^-) + \mu^+ (l^+) + X.
\]


\[
\frac{d\sigma_{DY}}{dx \pi dx_p dq_T^2 d\phi_S d\cos \theta d\phi} = C_0 \left\{ (1 + \cos^2 \theta) F^1_U + \sin^2 \theta \cos 2\phi F^{\cos 2\phi}_U \\
+ |S_T| \left[ (1 + \cos^2 \theta) \sin \phi_S F^{\sin \phi_S}_T \\
+ \sin^2 \theta \sin(2\phi + \phi_S) F^{(2\phi + \phi_S)}_T \\
+ \sin^2 \theta \sin(2\phi - \phi_S) F^{(2\phi - \phi_S)}_T \right] \right\},
\]

where $F_X^{[mod]}$ can be interpreted (LO in $1/q$ and $q_T \ll q$) as convolutions of TMD PDFs$^1$

\[
F^1_U = C \left[ f_{1, \pi} f_{1,p} \right], \quad \text{(number densities)}
\]
\[
F^{\cos \phi}_U = C \left[ \frac{2(q_T \cdot k_{\pi T})(q_T \cdot k_{p T}) - q_T^2 (k_{\pi T} \cdot k_{p T})}{q_T^2 M_{\pi} M_{p}} h_{\perp 1, \pi} h_{\perp 1,p} \right], \quad \text{(Boer–Mulders functions)}
\]
\[
F^{\sin \phi_S}_T = -C \left[ \frac{q_T \cdot k_{p T}}{q_T M_{p}} f_{1, \pi} f_{1T,p} \right], \quad \text{(Sivers function and number density)} \quad \text{(Boer–Mulders function and pretzelosity)}
\]
\[
F^{(2\phi + \phi_S)}_T = -C \left[ \frac{2(q_T \cdot k_{p T})(q_T \cdot k_{\pi T}) - q_T^2 (k_{\pi T} \cdot k_{p T})}{2q_T^3 M_{\pi} M_{p}^2} h_{\perp 1, \pi} h_{\perp 1T,p} \right],
\]
\[
F^{(2\phi - \phi_S)}_T = -C \left[ \frac{q_T \cdot k_{\pi T}}{q_T M_{\pi}} h_{\perp 1, \pi} h_{1,p} \right]. \quad \text{(transversity and pretzelosity)}
\]

TSAs in the Drell–Yan process: The convolution

- The convolution of the TMDs runs over intrinsic transverse momenta:

\[
C[w(k_{\pi T}, k_{pT}, q_T)f_{\pi}f_p] = \frac{1}{N_c} \sum_q e_q^2 \int d^2 k_{\pi T} d^2 k_{pT} \delta^{(2)}(q_T - k_{\pi T} - k_{pT}) \times w(k_{\pi T}, k_{pT}, q_T)[f_{\pi}(x_{\pi}, k_{\pi T}^2) f_{p}(x_p, k_{pT}^2) + f_{\pi}(x_{\pi}, k_{\pi T}^2) f_{\bar{p}}(x_p, k_{pT}^2)] .
\]

Drell–Yan reaction.

Transverse momenta in target frame.
TSAs in the Drell–Yan process: The convolution

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C[w(k_{\pi T}, k_{pT}, q_T) f_{\pi} f_p] = \frac{1}{N_c} \sum_q e_q^2 \int d^2 k_{\pi T} d^2 k_{pT} \delta^{(2)}(q_T - k_{\pi T} - k_{pT}) \times w(k_{\pi T}, k_{pT}, q_T) [f_1^\bar{q}(x_\pi, k_{\pi T}^2) f_1^q(x_p, k_{pT}^2) + f_1^q(x_\pi, k_{\pi T}^2) f_1^\bar{q}(x_p, k_{pT}^2)].
\]

- Drell–Yan reaction.

- Integration of \( F_{U}^1 \) over \( d^2 q_T \)

\[
\int d^2 q_T F_{U}^1 = \int d^2 q_T C \left[ f_{1,\pi} f_{1,p} \right] = \int d^2 q_T \frac{1}{N_c} \sum_q e_q^2 \int d^2 k_{\pi T} d^2 k_{pT} \delta^{(2)}(q_T - k_{\pi T} - k_{pT}) \times \left[ f_1^\bar{q}(x_\pi, k_{\pi T}^2) f_1^q(x_p, k_{pT}^2) + f_1^q(x_\pi, k_{\pi T}^2) f_1^\bar{q}(x_p, k_{pT}^2) \right] = \frac{1}{N_c} \sum_q e_q^2 \left[ \int d^2 k_{\pi T} f_{1,\pi}^\bar{q}(x_\pi) \int d^2 k_{pT} f_{1,p}^q(x_p) + (q \leftrightarrow \bar{q}) \right] = \frac{1}{N_c} \sum_q e_q^2 [f_{1,\pi}^\bar{q}(x_\pi) f_{1,p}^q(x_p) + (q \leftrightarrow \bar{q})].
\]
TSAs in the Drell–Yan process: The convolution

- The convolution of the TMDs runs over intrinsic transverse momenta:

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C[w(k_{\pi T}, k_{pT}, q_T)f_{\pi}f_p] = \frac{1}{N_c} \sum_q e_q^2 \int d^2k_{\pi T}d^2k_{pT}\delta^{(2)}(q_T - k_{\pi T} - k_{pT})
\times w(k_{\pi T}, k_{pT}, q_T)[f_{\pi}(x_{\pi}, k_{\pi T}^2)f_p(x_p, k_{pT}^2) + f_{\pi}(x_{\pi}, k_{\pi T}^2)f_{\perp}(x_p, k_{pT}^2)].
\]

- Integration of \(F_T^{\sin \phi_S}\) over \(d^2q_T\):

\[
\int d^2q_T F_T^{\sin \phi_S} = - \int C \left[ \frac{q_T \cdot k_{pT}}{q_T M_p} f_{1, \pi} f_{1T, p} \right]
= - \frac{1}{N_c} \sum_q e_q^2 \int d^2k_{\pi T}d^2k_{pT} \frac{(k_{\pi T} + k_{pT}) \cdot k_{pT}}{|k_{\pi T} + k_{pT}|M_p}
\times [f_{1, \pi}^q(x_{\pi}, k_{\pi T}^2) f_{1T, p}^q(x_p, k_{pT}^2) + (q \leftrightarrow \bar{q})].
\]

Popular solution: Gaussian model for the \(k_T\) dependence.

Drell–Yan reaction.

Transverse momenta in target frame.
TSAs in the Drell–Yan process: The $q_T$-weighting

- Possible alternative: weighting with powers of the transverse momentum
- First developed for SIDIS:
- Recent COMPASS SIDIS measurement:
  - [F. Bradamante (COMPASS), arXiv:1702.0062 [hep-ex], proc. of SPIN 2016]
- Also suggested for Drell–Yan, e.g.:

- Example: integration of $F_T^{\sin \phi_S}$ over $d^2q_T$ with weight $= q_T/M_p$,

$$\int d^2q_T \frac{q_T}{M_p} F_T^{\sin \phi_S} = - \int d^2q_T \frac{q_T}{M_p} C \left[ \frac{q_T \cdot k_{pT}}{q_T M_p} f_{1,\pi} f_{1T,p} \right]$$

$$= - \frac{1}{N_c M_p^2} \sum_q e_q^2 \int d^2 k_{\pi T} d^2 k_{pT} (k_{\pi T} + k_{pT}) \cdot k_{pT}$$

$$\times \left[ f_{1,\pi}^q (x, k_{\pi T}) f_{1T,p}^\perp (x, k_{pT}) + (q \leftrightarrow \bar{q}) \right]$$

$$= - \frac{2}{N_c} \sum_q e_q^2 \left[ f_{1,\pi}^q (x) f_{1T,p}^{\perp(1)q} (x) + (q \leftrightarrow \bar{q}) \right],$$

where $f_{1T}^{\perp(1)q}$ is the 1st $k_T^2$-moment of the Sivers function

$$f_{1T}^{\perp(1)q} (x) = \int d^2 k_T \frac{k_T^2}{2 M^2} f_{1T}^{\perp q} (x, k_T^2).$$
Possible alternative: weighting with powers of the transverse momentum

First developed for SIDIS:

Recent COMPASS SIDIS measurement:
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Also suggested for Drell–Yan, e.g.:

Example: integration of \( F_T^{\sin \phi_S} \) over \( d^2 q_T \) with weight \( q_T/M_p \),

\[
\int d^2 q_T \frac{q_T}{M_p} F_T^{\sin \phi_S} = - \int d^2 q_T \frac{q_T}{M_p} C \left[ \frac{q_T \cdot k_{\perp T}}{q_T M_p} f_{1,\pi} f_{1T,p}^{1,\perp} \right] \\
= - \frac{1}{N_c M_p} \sum_q e_q^2 \int d^2 k_{\perp T} d^2 k_{\perp T} (k_{\perp T} + k_{\perp T}) \cdot k_{\perp T} \\
\times \left[ f_{1,\pi}(x, k_{\perp T}^2) f_{1T,p}^{1,\perp}(x, k_{\perp T}^2) + (q \leftrightarrow \bar{q}) \right] \\
= - \frac{2}{N_c} \sum_q e_q^2 \left[ f_{1,\pi}(x) f_{1T,p}^{1,\perp}(x) + (q \leftrightarrow \bar{q}) \right],
\]

where \( f_{1T}^{1,\perp}(1)q \) is the 1st \( k_{T}^2 \)-moment of the Sivers function

\[
f_{1T}^{1,\perp}(1)q(x) = \int d^2 k_T \frac{k_T^2}{2 M^2} f_{1T}^{1,\perp}(x, k_T^2).
\]
Single T-polarised Drell–Yan spin-dependent azimuthal modulations, integrated with the appropriate $q_T$-weights:

$$
\int d^2 q_T \frac{q_T}{M_p} F_T^{\sin \phi_S} = -\frac{2}{N_c} \sum_q e_Q^2 [f_{1,\pi}^R(x_{\pi}) f_{1T,p}^{\perp(1)}q(x_N) + (q \leftrightarrow \bar{q})] \approx \frac{2e_u^2}{N_c} f_{1,\pi}^R(x_{\pi}) f_{1T,p}^{\perp(1)}u(x_N),
$$

$$
\int d^2 q_T \frac{q_T}{M_\pi} F_T^{\sin(2\phi - \phi_S)} = -\frac{2}{N_c} \sum_q e_Q^2 [h_{1,\pi}^{\perp(1)}q(x_{\pi}) h_{1,p}^{\perp}q(x_N) + (q \leftrightarrow \bar{q})] \approx \frac{2e_u^2}{N_c} h_{1,\pi}^{\perp(1)}u(x_{\pi}) h_{1,p}^{\perp}(x_N),
$$

$$
\int d^2 q_T \frac{q_T^3}{2M_\pi M_p^2} F_T^{\sin(2\phi + \phi_S)} = -\frac{2}{N_c} \sum_q e_Q^2 [h_{1,\pi}^{\perp(1)}q(x_{\pi}) h_{1T,p}^{\perp(2)}q(x_N) + (q \leftrightarrow \bar{q})] \approx \frac{2e_u^2}{N_c} h_{1,\pi}^{\perp(1)}u(x_{\pi}) h_{1T,p}^{\perp(2)}u(x_N).
$$

$q_T$-weighted TSA = direct measurement of TMD PDF $k_T^2$-moments!

$$
A_T^{\sin \Phi_W}(x_{\pi}, x_N) = \frac{\int d^2 q_T W_\Phi F_T^{\sin \Phi}(x_{\pi}, x_N)}{\int d^2 q_T F_T^{1U}(x_{\pi}, x_N)}, \quad \Phi = \phi_S, 2\phi \pm \phi_S.
$$

Example: $q_T$-weighted Sivers asymmetry

$$
A_T^{\sin \phi_S \frac{q_T}{M_p}}(x_{\pi}, x_N) = -2 \sum_q e_Q^2 [f_{1,\pi}^R(x_{\pi}) f_{1T,p}^{\perp(1)}q(x_N) + (q \leftrightarrow \bar{q})] \approx -2 \frac{f_{1T,p}^{\perp(1)}u(x_N)}{f_{1T,p}^{u}(x_N)}.
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$$

$$
\int d^2 q_T \frac{q_T}{M_\pi} F_T \sin(2\phi - \phi_S) = -\frac{2}{N_c} \sum_q e_q^2 [h_{1,\pi}^\perp(1)q(x_N) h_{1,p}^q(x_N) + (q \leftrightarrow \bar{q})] \approx \frac{2e^2_u}{N_c} h_{1,\pi}^\perp(x_\pi)h_{1,p}^u(x_N),
$$

$$
\int d^2 q_T \frac{q_T^3}{2M_\pi M_p^2} F_T \sin(2\phi + \phi_S) = -\frac{2}{N_c} \sum_q e_q^2 [h_{1,\pi}^\perp(1)q(x_N) h_{1T,p}^\perp(2)(x_N) + (q \leftrightarrow \bar{q})] \approx -\frac{2e^2_u}{N_c} h_{1,\pi}^\perp(x_\pi)h_{1T,p}^\perp(2)(x_N).
$$

$q_T$-weighted TSA = direct measurement of TMD PDF $k_T^2$-moments!

$$
A_T^\sin \Phi W_\Phi (x_\pi, x_N) = \frac{\int d^2 q_T W_\Phi F_T^\sin \Phi(x_\pi, x_N)}{\int d^2 q_T F_U^1(x_\pi, x_N)}, \quad \Phi = \phi_S, 2\phi \pm \phi_S.
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$$
1 TSAs in the Drell–Yan process

2 Measurement

3 The weighted Sivers asym. in SIDIS and DY

4 Conclusion
COMPASS Collaboration: 24 institutions from 13 countries (≈ 220 physicists).

Experimental area: CERN Super Proton Synchrotron (SPS) North Area.

Multi-purpose apparatus. Drell–Yan setup:
- Transversely polarised \( p \) (\( \text{NH}_3 \)) target polarisation \( \approx 73\% \), 2 oppositely-pol. cells.
- 190 GeV/c \( \pi^- \) beam, about \( 10^9 \) \( \pi^- \)/spill of 10 s
- Hadron absorber – \( \mu \) filter, ensures reasonable detector occupancies.
- Two-stage spectrometer, about 350 detector planes, \( \mu \) identification.

Location of the site at CERN’s SPS

Image credit: Wikimedia Commons
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Multi-purpose apparatus. Drell–Yan setup:
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- 190 GeV/c \( \pi^- \) beam, about \( 10^9 \pi^- /\text{spill of 10 s} \)
- Hadron absorber – \( \mu \) filter, ensures reasonable detector occupancies.
- Two-stage spectrometer, about 350 detector planes, \( \mu \) identification.
The range $M_{\mu\mu} \in [4.3, 8.5]$ GeV/$c^2$ is selected.

The same event selection as for the standard TSA analysis (previous talk of M. Pešek), except the cut on $q_T$, which we do not use (weighted asymmetry – must be integrated over the whole range of $q_T$).
Measurement: Distribution of $q_T$

Distributions of $q_T$ in the kinematic bins.

Acceptance in $q_T$. 

Distribution of $q_T$. 

Jan Matoušek (Prague & Trieste)  The $q_T$-weighted TSAs in Drell–Yan  12. 9. 2017, DSPIN-17 11 / 21
Measurement: $q_T$-weighted TSAs extraction

- Definition:

$$A_T^\sin \Phi W_\Phi (x_\pi, x_N) = \frac{\int d^2 q_T W_\Phi F_T^\sin \Phi (x_\pi, x_N)}{\int d^2 q_T F_U^1 (x_\pi, x_N)}, \quad \Phi = \phi_S, 2\phi \pm \phi_S.$$  

- Only the spin-dependent part is weighted!  
  $\rightarrow$ we use different methods from the standard TSAs (no UML).

- Polarised target with 2 cells $c = U, D$,

- and periods $p = 1, 2$ with opposite polarisation $\uparrow \downarrow, \downarrow \uparrow$.

- $N_{cp}(\Phi)$ – number of events

- $N_{cp}^W(\Phi)$ – sum of weights of events

- "Modified double ratio method":

$$R_{DM}^W(\Phi) = \frac{N_{U1}^W N_{D2}^W - N_{U2}^W N_{D1}^W}{\sqrt{(N_{U1}^W N_{D2}^W + N_{U2}^W N_{D1}^W)(N_{U1} N_{D2} + N_{U2} N_{D1})}} \approx 2 \tilde{D}_\Phi S_T A_T^\sin \Phi W_\Phi \sin \Phi,$$

- Used also in $P_T/z$-weighted SIDIS analysis  
  [F. Bradamante (COMPASS), arXiv:1702.0062 [hep-ex], proc. of SPIN 2016].

- Acceptance $a(\Phi)$ is canceled.

- $R_{DM}^W(\Phi)$ is fitted in 8 bins of $\Phi$.

- Separately in 9 pairs of periods.

- Statistically-weighted average is taken.

- $\tilde{D}_{\phi_S} = 1,$

- $\tilde{D}_{2\phi \pm \phi_S} = \frac{1 - \langle \cos^2 \theta \rangle}{1 + \langle \cos^2 \theta \rangle},$

- $S_T = \langle f_{dil.} \rangle \langle P_{\text{targ.}} \rangle.$
Measurement: $q_T$-weighted TSAs extraction

- **Definition:**
  \[
  A_T^{\sin \Phi W_{\Phi}}(x_\pi, x_N) = \frac{\int d^2q_T W_{\Phi} F_T^{\sin \Phi}(x_\pi, x_N)}{\int d^2q_T F_T^1_{U}(x_\pi, x_N)}, \quad \Phi = \phi_S, 2\phi \pm \phi_S.
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  \]

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- Acceptance $a(\Phi)$ is canceled.
  $R_{DM}^{W}(\Phi)$ is fitted in 8 bins of $\Phi$.
  Separately in 9 pairs of periods.
  Statistically-weighted average is taken.
  \[
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  \]
  \[
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  \]
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\[ \tilde{D}_{2\phi \pm \phi_{S}} = \frac{1 - \langle \cos^2 \theta \rangle}{1 + \langle \cos^2 \theta \rangle}, \]
\[ \overline{S}_{T} = \langle f_{\text{dil.}} \rangle \langle P_{\text{targ.}} \rangle. \]
The $q_T$-weighted TSAs from the 2015 Drell–Yan run.

The combined systematic uncertainty is about $0.8 \sigma_{\text{stat}}$.

(+ about 5% from the polarisation and dilution factor calculation.)
1. TSAs in the Drell–Yan process

2. Measurement

3. The weighted Sivers asym. in SIDIS and DY

4. Conclusion
The weighted Sivers asym. in SIDIS and DY: Motivation

**T-polarised SIDIS**
- COMPASS, $p^\uparrow$ 2010.
- TSA = $DF_{q,N} \otimes FF_{q\rightarrow h}$.
- $P_T$-weighted TSA = $DF_{q,N} \times FF_{q\rightarrow h}$.
- Sivers $P_T$-weighted asym. measured

[F Bradamante (COMPASS), proc. of SPIN 2016, Urbana, USA]

**T-polarised Drell–Yan**
- COMPASS, $p^\uparrow$ 2015 (1st ever).
- TSA = $DF_{q,N} \otimes DF_{\bar{q},h_{beam}}$.
- $q_T$-weighted $A = DF_{q,N} \times DF_{\bar{q},h_{beam}}$.
- Sivers $q_T$-weighted asym. measured!
The weighted Sivers asym. in SIDIS and DY: Motivation

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- COMPASS, $p^\uparrow$ 2010.
- TSA = $DF_{q,N} \otimes FF_{q\rightarrow h}$.
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**T-polarised Drell–Yan**
- COMPASS, $p^\uparrow$ 2015 (1st ever).
- TSA = $DF_{q,N} \otimes DF_{\bar{q},h_{beam}}$.
- $q_T$-weighted $A = DF_{q,N} \times DF_{\bar{q},h_{beam}}$.
- Sivers $q_T$-weighted asym. measured!

\[ f_{1T}^{\perp q}_{\text{SIDIS}} = -f_{1T}^{\perp q}_{\text{DY}} \]

The weighted Sivers asym. in SIDIS and DY: Strategy

- Fit of the $P_T/z$-weighted Sivers asymmetry in SIDIS,
- Calculation of the corresponding $q_T$-weighted Sivers asymmetry in DY.

- Reaction: $\mu + p^\uparrow \rightarrow \mu' + h^\pm + X$.
- $h^+$ and $h^−$ with $z > 0.2$.
- $u, d, s, \bar{u}, \bar{d}, \bar{s}$ quarks.
- Sivers func. of sea quarks assumed zero.
- So we can write\(^2\)

\[
A_{UT,T,h^\pm}^{\sin(\phi_h-\phi_S)}(x,Q^2) = 2 \frac{4}{9} f_{1T}^{(1)u}(x,Q^2) \tilde{D}_{1,u}^{h^\pm}(Q^2) + \frac{1}{9} f_{1T}^{(1)d}(x,Q^2) \tilde{D}_{1,d}^{h^\pm}(Q^2) \sum_q e_q^2 f_1^q(x,Q^2) \tilde{D}_{1,q}^{h^\pm}(Q^2).
\]

- Sivers 1st $k_T^2$-moment – parametrisation:

\[
xf_{1T}^{(1)q}(x) = a_q x^{b_q} (1 - x)^{c_q}.
\]

Inspiration: weighted Sivers in SIDIS $\rightarrow$ DY  \cite{Efremov:2005ym}

- Fit of the $P_T/z$-weighted Sivers asymmetry in SIDIS,
- Calculation of the corresponding $q_T$-weighted Sivers asymmetry in DY.

Reaction: $\mu + p^\uparrow \rightarrow \mu' + h^\pm + X$.
- $h^+$ and $h^-$ with $z > 0.2$.
- $u, d, s, \bar{u}, \bar{d}, \bar{s}$ quarks.
- Sivers func. of sea quarks assumed zero.
- So we can write
  \[
  A_{UT,T,h^\pm}^{\sin(\phi_h - \phi_S) \frac{P_T}{z M}}(x, Q^2) = 2 \frac{4}{9} f_{1T}^{(1)u}(x, Q^2) \tilde{D}_{1,u}^{h^\pm}(Q^2) + \frac{1}{9} f_{1T}^{(1)d}(x, Q^2) \tilde{D}_{1,d}^{h^\pm}(Q^2) \]
  \[
  \sum_q e_q^2 f_1^q(x, Q^2) \tilde{D}_{1,q}^{h^\pm}(Q^2).
  \]
- Sivers 1st $k_{T}^2$-moment – parametrisation:
  \[
  x f_{1T}^{(1)q}(x) = a_q x^{b_q} (1 - x)^{c_q}.
  \]

\[^2\text{Sign convention opposite to the Trento convention} \text{ } \text{[M. Anselmino \emph{et al.}, Phys.Rev. D70 (2004) 117504]}\]
The weighted Sivers asym. in SIDIS and DY: PDFs and FFs

\[ A_{UT,T,h^\pm}^{\sin(\phi_h-\phi_S)} \frac{p_T}{zM} (x, Q^2) = 2 \frac{4}{9} f_{1T}^{(1)u}(x, Q^2) \tilde{D}_{1,u}^{h^\pm}(Q^2) + \frac{1}{9} f_{1T}^{(1)d}(x, Q^2) \tilde{D}_{1,u}^{h^\pm}(Q^2) \frac{\sum q e_q^2 f_q^q(x, Q^2) \tilde{D}_{1,u}^{h^\pm}(Q^2)}{}, \]

- Collinear evolution of PDFs and FFs, \( Q^2 = Q^2_{SIDIS}(x) \) from fit.
- Same choices and approach as
- PDFs – from CTEQ 5D global fit
  (from LHAPDF library)
- The FFs from DSS 07 LO global fit

\[ \tilde{D}_{1,q}^{h^\pm}(Q^2) = \int_{0.2}^{1} dz D_{1,q}^{h^\pm}(z, Q^2) \]
The weighted Sivers asym. in SIDIS and DY: PDFs and FFs

\[ A^{\sin(\phi_h - \phi_S)}_{UT,T,h^\pm}(x, Q^2) = 2 \frac{4}{9} f^{(1)u}_{1T}(x, Q^2) \tilde{D}^{h^\pm}_{1,u}(Q^2) + \frac{1}{9} f^{(1)d}_{1T}(x, Q^2) \tilde{D}^{h^\pm}_{1,u}(Q^2) }{\sum_q e_q^2 f^q(x, Q^2) \tilde{D}^{h^\pm}_{1,q}(Q^2)}, \]

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The weighted Sivers asym. in SIDIS and DY: PDFs and FFs

\[ A_{UT, T, h^\pm}^{\sin(\phi_h - \phi_S)} \frac{P_T}{zM} (x, Q^2) = 2 \frac{\frac{4}{9} f_{1T}^{1u}(x, Q^2) \tilde{D}_{1, u}^{h^\pm}(Q^2) + \frac{1}{9} f_{1T}^{1d}(x, Q^2) \tilde{D}_{1, d}^{h^\pm}(Q^2)}{\sum_q e_q^2 f_q^q(x, Q^2) \tilde{D}_{1, q}^{h^\pm}(Q^2)}, \]

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- Same choices and approach as
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\[ \tilde{D}_{1, q}^{h^\pm}(Q^2) = \int_{0.2}^1 dz D_{1, q}^{h^\pm}(z, Q^2) \]
The weighted Sivers asym. in SIDIS and DY: Fit results

- The asymmetry for $h^-$ and $h^+$ is simultaneously fitted.
- Sivers 1st $k_T^2$-moment parametrisation:

$$xf_{1T}^{q(1)}(x) = a_q x^{b_q} (1 - x)^{c_q},$$

- Error bands: $1\sigma$, only stat. error of the data and fit.

Fit of the $P_T/z$-weighted Sivers asymmetry in SIDIS [F. Bradamante (COMPASS), arXiv:1702.0062 [hep-ex], proc. of SPIN 2016].

The 1st $k_T^2$-moment of the Sivers function at $Q^2 = Q^2_{\text{SIDIS}}(x)$. 

Jan Matoušek (Prague & Trieste)
The weighted Sivers asym. in SIDIS and DY: Results

- $f^{q}_{1T}|_{DY} = -f^{q}_{1T}|_{SIDIS}$ [J. Collins, Phys.Lett. B536 (2002) 43]
- We assume valence quark dominance:
  \[
  A_{T}^{\sin \phi_{S}} \frac{q_{T}}{M_{p}}(x_{N}, Q^{2}) \approx 2 \frac{f^{(1)u}_{1T,p}(x_{N}, Q^{2})}{f^{u}_{1,p}(x_{N}, Q^{2})}.
  \]
- Collinear evolution of $f_{1}$, $Q^{2} = Q^{2}_{DY}(x_{N})$ from fit.
- No evolution of the Sivers function first moment between $Q^{2}_{SIDIS}(x)$ and $Q^{2}_{DY}(x_{N})$
- Another data taking planned for 2018!
The weighted Sivers asym. in SIDIS and DY: Results

- $f_{1T}^{\perp \perp q} \big|_{DY} = - f_{1T}^{\perp \perp q} \big|_{SIDIS}$ [J. Collins, Phys.Lett. B536 (2002) 43]
- We assume valence quark dominance:
  \[ A_T^{\sin \phi_S} \frac{q_T}{M_p} (x_N, Q^2) \approx 2 \frac{f_{1T,p}^{(1,u)}(x_N, Q^2)}{f_{1,p}^{u}(x_N, Q^2)} . \]
- Collinear evolution of $f_1$, $Q^2 = Q_{DY}^2(x_N)$ from fit.
- No evolution of the Sivers function first moment between $Q_{SIDIS}^2(x)$ and $Q_{DY}^2(x_N)$
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Weighted Sivers asymmetry in Drell–Yan measured in 2015 data and the projection from SIDIS. Statistical errors only.

Projection for combined 2015 and 2018 data (assuming 1.5 times larger statistics in 2018).
1 TSAs in the Drell–Yan process

2 Measurement

3 The weighted Sivers asym. in SIDIS and DY

4 Conclusion
The transverse momentum weighted asymmetries are interesting!
- A model-independent way to overcome the convolution over intrinsic $k_T$.
- Direct access to the $k_T^2$-moments of TMD PDFs.

$q_T$-weighted TSAs in single T-pol. Drell–Yan at COMPASS:
- First ever data collected.
- Sivers asymmetry: $A_T^{\sin \phi_S \frac{q_T}{M_N}}$ compatible with zero.
- Transversity asymmetry: $A_T^{\sin(2\phi - \phi_S) \frac{q_T}{M_\pi}}$ about $1.5\sigma$ below zero.

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Thank you for your attention!