Weighted transverse spin asymmetries in 2015 COMPASS Drell–Yan data

Jan Matoušek
University and INFN of Trieste

On behalf of the COMPASS Collaboration

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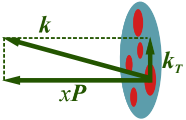
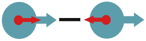
Outline

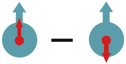
Nucleon structure: Transverse momentum dependent PDFs



Number density.



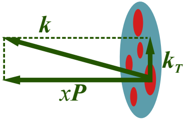
Helicity.



Transversity.

- Parton distribution functions (PDFs)
  - Structure in longitudinal momentum space.
  - $f(x, Q^2)$, the dependence on Q^2 calculable.
- Transverse Momentum Dependent (TMD) PDFs:
  - If parton intrinsic $\boldsymbol{k}_\mathrm{T}$ is not integrated over,
  - "three-dimensional" objects $f(x, k_\mathrm{T}^2, Q^2)$.

		Parent hadron polarization		
		Unpolarised	Longitudinal	Transverse
Parton polar.	U	$f_1(x, k_\mathrm{T}^2)$ (number density)		$f_{1T}^{\perp}(x, k_\mathrm{T}^2)$ (Sivers)
	L		$g_1(x, k_\mathrm{T}^2)$ (helicity)	$g_{1T}(x, k_\mathrm{T}^2)$
	T	$h_1^{\perp}(x, k_\mathrm{T}^2)$ (Boer–Mulders)	$h_{1L}^{\perp}(x, k_\mathrm{T}^2)$	$h_1(x, k_\mathrm{T}^2)$ (transversity) $h_{1T}^{\perp}(x, k_\mathrm{T}^2)$

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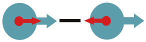
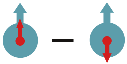

Helicity.


Transversity.

Sivers PDF.

Boer–Mulders PDF.

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  - Structure in longitudinal momentum space.
  - $f(x, Q^2)$, the dependence on Q^2 calculable.
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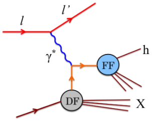
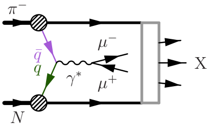
Nucleon structure: SIDIS and Drell–Yan processes



SIDIS on transversely polarised nucleons

- COMPASS 2007, 2010: $\mu \mathrm{p}^{\uparrow} \to \mu' h X$.
- Structure functions F:
  $F = \mathrm{PDF}_{q,\mathrm{p}} \otimes \mathrm{FF}_{q\to h}$.
- For example:
  - $F_{\mathrm{UU}}^{\cos\phi_h}$ and $F_{\mathrm{UU}}^{\cos 2\phi_h}$ linked to $h_{1,\mathrm{p}}^{\perp}$,
  - $F_{\mathrm{UT,T}}^{\sin(\phi_h-\phi_S)} = f_{1\mathrm{T},\mathrm{p}}^{\perp} \otimes D_{1,q}^{h^{\pm}}$.
  - $F_{\mathrm{UT}}^{\sin(\phi_h+\phi_S)} = h_{1,\mathrm{p}} \otimes H_1^{\perp,h^{\pm}}$,



Drell–Yan on transversely polarised nucleons

- COMPASS 2015, 2018: $\pi^- \mathrm{p}^{\uparrow} \to \mu^- \mu^+ X$.
  (1st ever polarised Drell–Yan)
- $F = \mathrm{PDF}_{q,\mathrm{p}} \otimes \mathrm{PDF}_{\bar{q},\pi^-}$.
- For example:
  - $F_{\mathrm{U}}^{\cos 2\phi} = h_{1,\pi}^{\perp} \otimes h_{1,\mathrm{p}}^{\perp}$,
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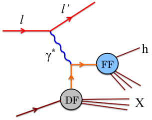
A sign change predicted for Sivers and Boer–Mulders functions:

$$f_{1\mathrm{T}}^{\perp q}\big|_{\mathrm{SIDIS}} = -f_{1\mathrm{T}}^{\perp q}\big|_{\mathrm{DY}}$$

$$h_{1}^{\perp q}\big|_{\mathrm{SIDIS}} = -h_{1}^{\perp q}\big|_{\mathrm{DY}}$$

[J. Collins, Phys.Lett. B536 (2002) 43]

Nucleon structure: SIDIS and Drell–Yan processes



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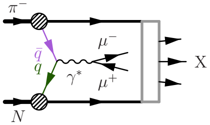

Drell–Yan on transversely polarised nucleons

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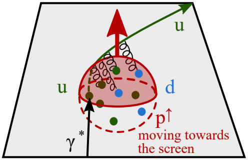

Sivers effect in SIDIS (as described by [M. Burkardt, Nucl.Phys. A735 (2004) 185].

A sign change predicted for Sivers and Boer–Mulders functions:

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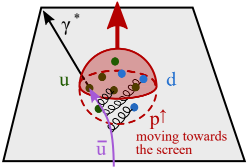
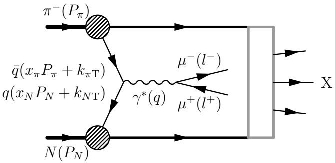


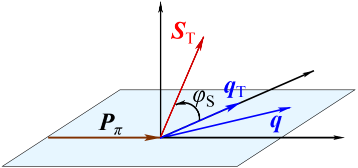
Sivers effect in Drell–Yan drawn in the same manner.

Outline

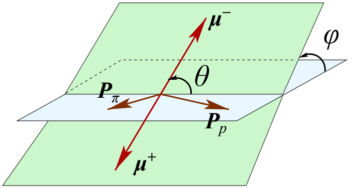
- Cross-section, LO TMD approach [S. Arnold, A. Metz, M. Schlegel, Phys.Rev. D79 (2009) 034005]:

$$\frac{\mathrm{d}\sigma_{\mathrm{DY}}}{\mathrm{d}x_\pi\,\mathrm{d}x_N\,\mathrm{d}q_{\mathrm{T}}^2\,\mathrm{d}\phi_{\mathrm{S}}\,\mathrm{d}\cos\theta\,\mathrm{d}\phi} = C_0\Big\{(1+\cos^2\theta)F_{\mathrm{U}}^{1} + \sin^2\theta\,\cos 2\phi\,F_{\mathrm{U}}^{\cos 2\phi}$$
$$+ |\boldsymbol{S}_{\mathrm{T}}|\Big[(1+\cos^2\theta)\sin\phi_{\mathrm{S}}\,F_{\mathrm{T}}^{\sin\phi_{\mathrm{S}}}$$
$$+ \sin^2\theta\,\sin(2\phi+\phi_{\mathrm{S}})F_{\mathrm{T}}^{\sin(2\phi+\phi_{\mathrm{S}})}$$
$$+ \sin^2\theta\,\sin(2\phi-\phi_{\mathrm{S}})F_{\mathrm{T}}^{\sin(2\phi-\phi_{\mathrm{S}})}\Big]\Big\},$$





ϕ_{S} angle in target frame.



ϕ angle in Collins–Soper frame.

Transverse spin asymmetries in Drell–Yan: Structure functions

- The structure functions $F_X^{[mod]}$ can be interpreted as convolutions of TMD PDFs.
- In particular, for COMPASS 2015 ($\pi^- \mathrm{p}^\uparrow \to \mu^- \mu^+ X$) we have

$$F_{\mathrm{U}}^{1} = \mathcal{C}\Big[f_{1,\pi}\, f_{1,\mathrm{p}}\Big], \qquad \text{(number densities)}$$

$$F_{\mathrm{U}}^{\cos 2\phi} = \mathcal{C}\Big[\frac{2(\boldsymbol{q}_\mathbf{T}\cdot\boldsymbol{k}_{\boldsymbol{\pi}\mathbf{T}})(\boldsymbol{q}_\mathbf{T}\cdot\boldsymbol{k}_{\mathbf{pT}}) - q_\mathrm{T}^2(\boldsymbol{k}_{\boldsymbol{\pi}\mathbf{T}}\cdot\boldsymbol{k}_{\mathbf{pT}})}{q_\mathrm{T}^2 M_\pi M_\mathrm{p}}\, h_{1,\pi}^\perp\, h_{1,\mathrm{p}}^\perp\Big], \qquad \text{(Boer–Mulders functions)}$$

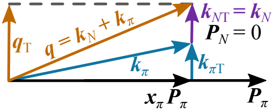
$$F_{\mathrm{T}}^{\sin\phi_\mathrm{S}} = -\mathcal{C}\Big[\frac{\boldsymbol{q}_\mathbf{T}\cdot\boldsymbol{k}_{\mathbf{pT}}}{q_\mathrm{T} M_\mathrm{p}}\, f_{1,\pi}\, f_{1\mathrm{T},\mathrm{p}}^\perp\Big], \qquad \text{(Sivers function and number density)}$$

(Boer–Mulders function and pretzelosity)

$$F_{\mathrm{T}}^{\sin(2\phi+\phi_\mathrm{S})} = -\mathcal{C}\Big[\frac{2(\boldsymbol{q}_\mathbf{T}\cdot\boldsymbol{k}_{\mathbf{pT}})\big[2(\boldsymbol{q}_\mathbf{T}\cdot\boldsymbol{k}_{\boldsymbol{\pi}\mathbf{T}})(\boldsymbol{q}_\mathbf{T}\cdot\boldsymbol{k}_{\mathbf{pT}}) - q_\mathrm{T}^2(\boldsymbol{k}_{\boldsymbol{\pi}\mathbf{T}}\cdot\boldsymbol{k}_{\mathbf{pT}})\big] - q_\mathrm{T}^2 k_{\mathrm{pT}}^2(\boldsymbol{q}_\mathbf{T}\cdot\boldsymbol{k}_{\boldsymbol{\pi}\mathbf{T}})}{2q_\mathrm{T}^3 M_\pi M_\mathrm{p}^2}\, h_{1,\pi}^\perp\, h_{1\mathrm{T},\mathrm{p}}^\perp\Big],$$

$$F_{\mathrm{T}}^{\sin(2\phi-\phi_\mathrm{S})} = -\mathcal{C}\Big[\frac{\boldsymbol{q}_\mathbf{T}\cdot\boldsymbol{k}_{\boldsymbol{\pi}\mathbf{T}}}{q_\mathrm{T} M_\pi}\, h_{1,\pi}^\perp\, h_{1,\mathrm{p}}\Big]. \qquad \text{(Boer–Mulders function and trasversity)}$$

- The convolution $\mathcal{C}$ of the TMDs runs over intrinsic transverse momenta.



Transverse momenta in target frame.

- Transverse spin asymmetries (TSAs):

$$A_{\mathrm{T}}^{\sin\Phi}(x_\pi, x_N, q_{\mathrm{T}}^2) = \frac{F_{\mathrm{T}}^{\sin\Phi}(x_\pi, x_N, q_{\mathrm{T}}^2)}{F_{\mathrm{U}}^{1}(x_\pi, x_N, q_{\mathrm{T}}^2)} = \frac{\mathcal{C}\left[w(\boldsymbol{k}_{\pi\mathrm{T}}, \boldsymbol{k}_{\mathrm{pT}})\, f_\pi\, f_{\mathrm{p}}\right]}{\mathcal{C}\left[f_{1,\pi}\, f_{1,\mathrm{p}}\right]}, \qquad \Phi = \phi_{\mathrm{S}}, 2\phi \pm \phi_{\mathrm{S}}.$$

- To solve the convolution over intrinsic transverse momenta one can assume Gaussian dependence of the TMDs on k_{T}.
- For example, Sivers asymmetry integrated over $\boldsymbol{q}_{\mathrm{T}}$ in the Gaussian model

$$A_{\mathrm{T}}^{\sin\phi_{\mathrm{S}}}(x_\pi, x_N) \overset{\text{Gauss.}}{=} -a_{\mathrm{G}} \frac{\sum_q e_q^2\left[f_{1,\pi}^{\bar{q}}(x_\pi)\, f_{1\mathrm{T,p}}^{\perp(1)q}(x_N) + (q \leftrightarrow \bar{q})\right]}{\sum_q e_q^2\left[f_1^q(x_\pi) f_1^{\bar{q}}(x_N) + (q \leftrightarrow \bar{q})\right]} \approx -a_{\mathrm{G}} \frac{f_{1\mathrm{T}}^{\perp(1)\mathrm{u}}(x_N),}{f_{1,\mathrm{p}}^{\mathrm{u}}(x_N)}.$$

- where the approximate equality neglects sea quarks, as $\pi^- = |\bar{\mathrm{u}}\mathrm{d}\rangle$, $\mathrm{p} = |\mathrm{uud}\rangle$
- the Gaussian factor a_{G} and the first k_{T}^2-moment of the Sivers function are

$$a_{\mathrm{G}} = \frac{\sqrt{\pi} M_{\mathrm{p}}}{\sqrt{\langle \boldsymbol{k}_{\pi\mathrm{T}} \rangle^2 + \langle \boldsymbol{k}_{\mathrm{pT}} \rangle_S^2}} \qquad f_{1\mathrm{T}}^{\perp(1)q}(x) = \int \mathrm{d}^2\boldsymbol{k}_{\mathrm{T}} \frac{k_{\mathrm{T}}^2}{2M^2} f_{1\mathrm{T}}^{\perp q}(x, k_{\mathrm{T}}^2).$$

Transverse spin asymmetries in Drell–Yan

- Transverse spin asymmetries (TSAs):

$$A_{\mathrm{T}}^{\sin\Phi}(x_\pi, x_N, q_{\mathrm{T}}^2) = \frac{F_{\mathrm{T}}^{\sin\Phi}(x_\pi, x_N, q_{\mathrm{T}}^2)}{F_{\mathrm{U}}^{1}(x_\pi, x_N, q_{\mathrm{T}}^2)} = \frac{\mathcal{C}\left[w(\boldsymbol{k}_{\boldsymbol{\pi}\mathbf{T}}, \boldsymbol{k}_{\mathbf{pT}})\, f_\pi\, f_{\mathrm{p}}\right]}{\mathcal{C}\left[f_{1,\pi}\, f_{1,\mathrm{p}}\right]}, \qquad \Phi = \phi_{\mathrm{S}}, 2\phi \pm \phi_{\mathrm{S}}.$$

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Transverse spin asymmetries in Drell–Yan: Weighting with q_{T}

- The integration of F_{U}^{1} over $\mathrm{d}^2\boldsymbol{q}_{\mathbf{T}}$ can be done with no assumptions:

$$\int \mathrm{d}^2\boldsymbol{q}_{\mathbf{T}}\, F_{\mathrm{U}}^{1} = \int \mathrm{d}^2\boldsymbol{q}_{\mathbf{T}}\, \mathcal{C}\left[f_{1,\pi} f_{1,\mathrm{p}}\right] = \frac{1}{N_{\mathrm{c}}}\sum_q e_q^2 \left[f_{1,\pi}^{\bar{q}}(x_\pi) f_{1,\mathrm{p}}^{q}(x_{\mathrm{p}}) + (q \leftrightarrow \bar{q})\right].$$

- On the contrary, the integration of $F_{\mathrm{T}}^{\sin\phi_{\mathrm{S}}}$ over $\mathrm{d}^2\boldsymbol{q}_{\mathbf{T}}$ can not be solved,

$$\int \mathrm{d}^2\boldsymbol{q}_{\mathbf{T}}\, F_{\mathrm{T}}^{\sin\phi_{\mathrm{S}}} = -\int \mathrm{d}^2\boldsymbol{q}_{\mathbf{T}}\, \mathcal{C}\left[\frac{\boldsymbol{q}_{\mathbf{T}}\cdot\boldsymbol{k}_{\mathbf{pT}}}{q_{\mathrm{T}} M_{\mathrm{p}}} f_{1,\pi} f_{1\mathrm{T},\mathrm{p}}^{\perp}\right] = \ ?$$

Popular solution: Gaussian model for the $\boldsymbol{k}_{\mathbf{T}}$ dependence shown on the previous slide.

Like in SIDIS (previous talk), weighting with transverse momentum (here q_{T}) is a way out:

- With the weight $q_{\mathrm{T}}/M_{\mathrm{p}}$, the integral of the structure function $F_{\mathrm{T}}^{\sin\phi_{\mathrm{S}}}$ over $\mathrm{d}^2\boldsymbol{q}_{\mathbf{T}}$ can be solved, getting

$$\int \mathrm{d}^2\boldsymbol{q}_{\mathbf{T}}\, \frac{q_{\mathrm{T}}}{M_{\mathrm{p}}} F_{\mathrm{T}}^{\sin\phi_{\mathrm{S}}} = -\int \mathrm{d}^2\boldsymbol{q}_{\mathbf{T}}\, \frac{q_{\mathrm{T}}}{M_{\mathrm{p}}}\, \mathcal{C}\left[\frac{\boldsymbol{q}_{\mathbf{T}}\cdot\boldsymbol{k}_{\mathbf{pT}}}{q_{\mathrm{T}} M_{\mathrm{p}}} f_{1,\pi} f_{1\mathrm{T},\mathrm{p}}^{\perp}\right]$$

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

- And similarly for the other asymmetries.
- Also quite popular, e.g. [A. Efremov *et al.*, Phys.Lett. B612 (2005) 233], [A. Sissakian *et al.*, Eur.Phys.J. C46 (2006) 147], [Z. Wang *et al.*, Phys.Rev. D95 (2017) 094004]

Transverse spin asymmetries in Drell–Yan: Weighting with q_T

- The integration of F_U^1 over $d^2\boldsymbol{q_T}$ can be done with no assumptions:

$$\int d^2\boldsymbol{q_T} F_U^1 = \int d^2\boldsymbol{q_T}\, \mathcal{C}\left[f_{1,\pi} f_{1,p}\right] = \frac{1}{N_c}\sum_q e_q^2 \left[f_{1,\pi}^{\bar{q}}(x_\pi) f_{1,p}^{q}(x_p) + (q \leftrightarrow \bar{q})\right].$$

- On the contrary, the integration of $F_T^{\sin\phi_S}$ over $d^2\boldsymbol{q_T}$ can not be solved,

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

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Like in SIDIS (previous talk), weighting with transverse momentum (here q_T) is a way out:

- With the weight q_T/M_p, the integral of the structure function $F_T^{\sin\phi_S}$ over $d^2\boldsymbol{q_T}$ can be solved, getting

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

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

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Weighted transverse spin asymmetries in Drell–Yan

q_{T}-weighted TSAs = direct measurement of TMD PDF k_{T}^2-moments.
Instead of convolutions of TMD PDFs, we have products.

In addition, in COMPASS kinematics (valence region) and in π^-p reaction one can neglect sea quarks, as $\pi^- = |\bar{\mathrm{u}}\mathrm{d}\rangle$, $\mathrm{p} = |\mathrm{uud}\rangle$.

q_{T}-weighted Sivers asymmetry

$$A_{\mathrm{T}}^{\sin\phi_{\mathrm{S}} \frac{q_{\mathrm{T}}}{M_{\mathrm{p}}}}(x_\pi, x_N) = -2\frac{\sum_q e_q^2 \left[f_{1,\pi}^{\bar{q}}(x_\pi)\, f_{1\mathrm{T},\mathrm{p}}^{\perp(1)q}(x_N) + (q \leftrightarrow \bar{q})\right]}{\sum_q e_q^2 \left[f_1^{\bar{q}}(x_\pi)\, f_1^{q}(x_N) + (q \leftrightarrow \bar{q})\right]} \approx -2\frac{f_{1\mathrm{T}}^{\perp(1)\mathrm{u}}(x_N)}{f_{1,\mathrm{p}}^{\mathrm{u}}(x_N)}.$$

q_{T}-weighted asymmetry induced by proton transversity and pion Boer–Mulders function:

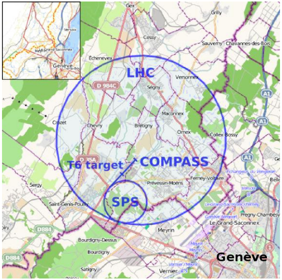
$$A_{\mathrm{T}}^{\sin(2\phi-\phi_{\mathrm{S}}) \frac{q_{\mathrm{T}}}{M_\pi}}(x_\pi, x_N) \approx -2\frac{h_{1,\pi}^{\perp(1)\bar{\mathrm{u}}}(x_\pi)\, h_{1,\mathrm{p}}^{\mathrm{u}}(x_N)}{f_1^{\bar{\mathrm{u}}}(x_\pi)\, f_{1,\mathrm{p}}^{\mathrm{u}}(x_N)}.$$

q_{T}-weighted asymmetry induced by proton pretzelosity and pion Boer–Mulders function:

$$A_{\mathrm{T}}^{\sin(2\phi+\phi_{\mathrm{S}}) \frac{q_{\mathrm{T}}^3}{2M_\pi M_{\mathrm{p}}^2}}(x_\pi, x_N) \approx -2\frac{h_{1,\pi}^{\perp(1)\bar{\mathrm{u}}}(x_\pi)\, h_{1\mathrm{T},\mathrm{p}}^{\perp(2)\mathrm{u}}(x_N)}{f_1^{\bar{\mathrm{u}}}(x_\pi)\, f_{1,\mathrm{p}}^{\mathrm{u}}(x_N)}.$$

Outline

- 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 (NH_3) target polarisation ≈ 73%, 2 oppositely-pol. cells.
  - 190 GeV/c π^- beam, about 10^9 π^-/spill of 10 s
  - Hadron absorber – μ filter, ensures reasonable detector occupancies.
  - Two-stage spectrometer, about 350 detector planes, μ identification.



Location of the site at CERN's SPS

[Wikimedia Commons]

Measurement of the weighted asymmetries: Spectrometer

COMPASS

- 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 (NH_3) target polarisation ≈ 73%, 2 oppositely-pol. cells.
  - 190 GeV/c π^- beam, about 10^9 π^-/spill of 10 s
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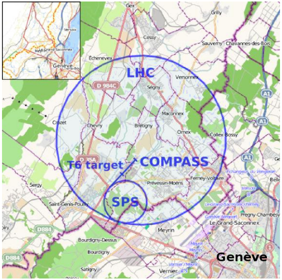

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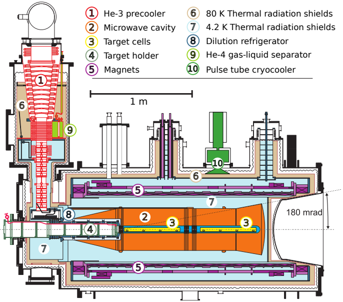

Polarised target cryostat.

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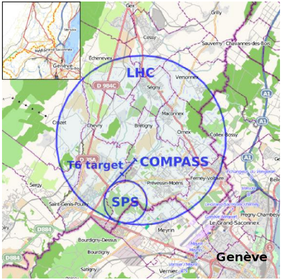

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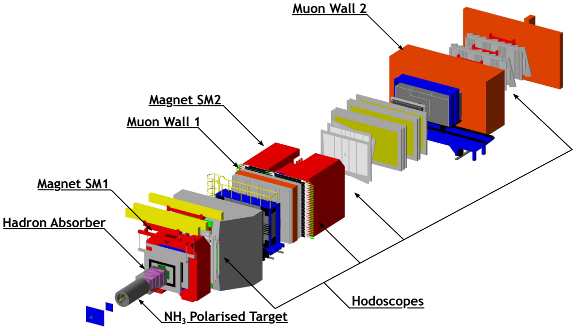
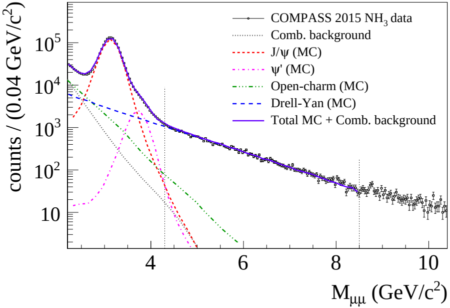
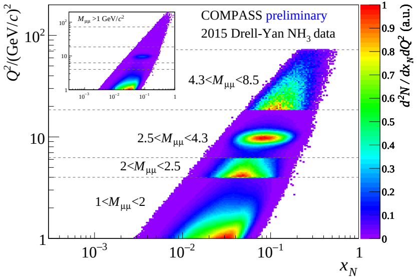


COMPASS Drell–Yan setup.

Measurement of the weighted asymmetries: Event selection



2015 data and reconstructed MC.



Kinematic coverage in x_N and Q^2

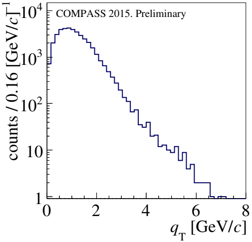
Event selection is almost the same for weighted and “standard” TSAs

[COMPASS, Phys.Rev.Lett. 119(11), 112002 (2017)]

(more on them and other aspects of COMPASS DY by C. Riedl on Thursday).

- $\mu^+\mu^-$ pairs (μ candidates: $X/X_0 > 30$).
- Vertex reconstructed in the target.
- $M_{\mu\mu} \in [4.3, 8.5]$ GeV/c^2.

Measurement of the weighted asymmetries: Distribution of q_T



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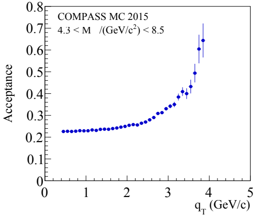
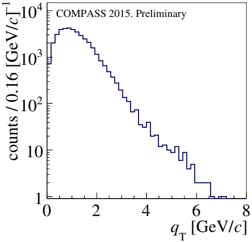


Acceptance in q_T.
The shape is due to resolution. Impact on the weighted TSAs is under control.



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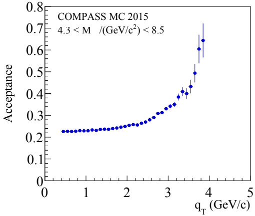

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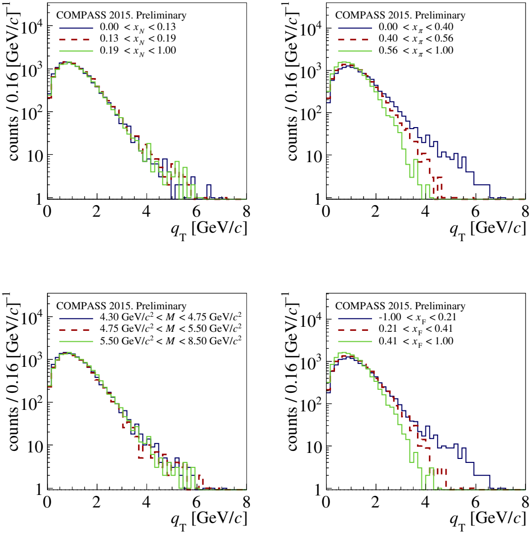
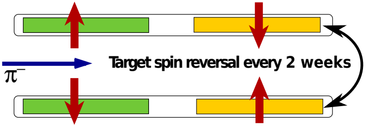
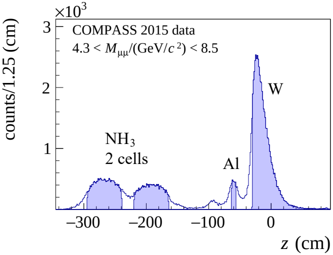


Distributions of q_{T} in the kinematic bins.

Measurement of the weighted asymmetries: Extraction



Two-cell target with polarisation reverasals.



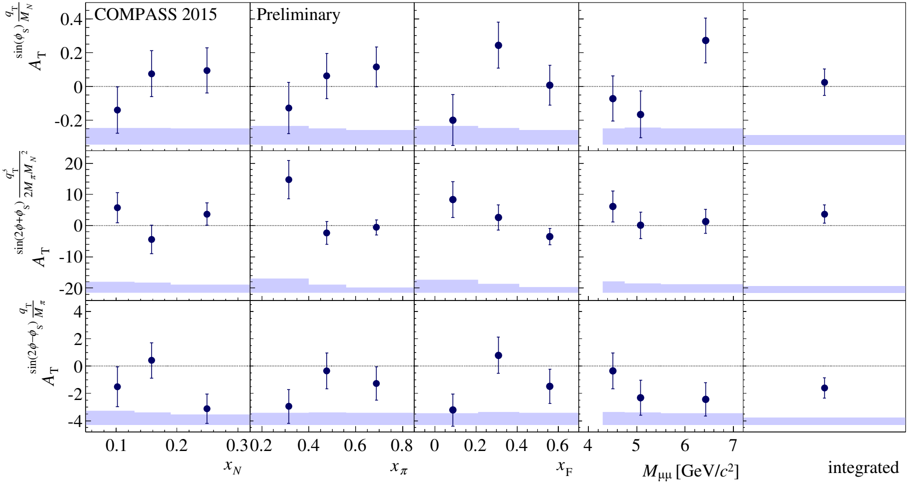
Primary vertex distribution.

- Polarised target with 2 cells, and alternating periods with opposite polarisation $\uparrow\downarrow, \downarrow\uparrow$.
- "Standard" transverse spin asymmetries
  – Extended Unbinned Maximum Likelihood method
- q_{T}-weighted asymmetries:

$$A_{\mathrm{T}}^{\sin\Phi W_\Phi}(x_\pi, x_N) = \frac{\int \mathrm{d}^2\boldsymbol{q}_{\mathbf{T}} W_\Phi\, F_{\mathrm{T}}^{\sin\Phi}(x_\pi, x_N)}{\int \mathrm{d}^2\boldsymbol{q}_{\mathbf{T}} F_{\mathrm{U}}^{1}(x_\pi, x_N)}, \qquad \Phi = \phi_{\mathrm{S}}, 2\phi \pm \phi_{\mathrm{S}}.$$

- Only the spin-dependent part of the cross-section is weighted!
  → different method from the standard ones:
- Modified double ratio method, where the acceptance $a(\Phi)$ is cancelled (used also in the weighted SIDIS analysis).
- Asymmetries corrected for the target composition (dilution factor).

Measurement of the weighted asymmetries: Results



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 8 % from dilution factor calculation.
From 2018 we expect at least 1.5 times more statistics.

Outline

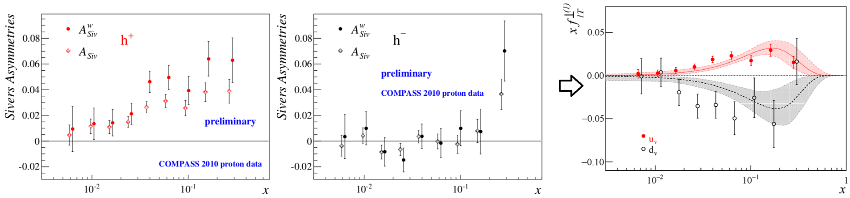
Weighted Sivers asymmetry in SIDIS and DY: Strategy

- How can we compare the Sivers function in SIDIS and Drell–Yan?
- A straightforward way – COMPASS has measured the weighted asymmetries:

$$\mathrm{DY}: \quad A_{\mathrm{T}}^{\sin\phi_{\mathrm{S}} \frac{q_{\mathrm{T}}}{M_{\mathrm{P}}}}(x_N) \approx -2 \frac{f_{1\mathrm{T}}^{\perp(1)\mathrm{u}}(x_N),}{f_{1,\mathrm{p}}^{\mathrm{u}}(x_N)}.$$

$$\mathrm{SIDIS}: \quad A_{\mathrm{UT,T},h^\pm}^{\sin(\phi_{\mathrm{h}}-\phi_{\mathrm{S}}) \frac{P_{\mathrm{T}}}{zM}}(x) \approx 2 \frac{\frac{4}{9} f_{1\mathrm{T}}^{\perp(1)\mathrm{u}}(x,Q^2)\, \tilde{D}_{1,\mathrm{u}}^{h^\pm}(Q^2) + \frac{1}{9} f_{1\mathrm{T}}^{\perp(1)\mathrm{d}}(x,Q^2)\, \tilde{D}_{1,\mathrm{d}}^{h^\pm}(Q^2)}{\sum_{q=\mathrm{u,d,s,\bar{u},\bar{d},\bar{s}}} e_q^2\, f_1^q(x,Q^2) \tilde{D}_{1,q}^{h^\pm}(Q^2)}.$$

- where $\tilde{D}_{1,q}^{h^\pm}(Q^2) = \int_{0.2}^{1} \mathrm{d}z\, D_{1,q}^{h^\pm}(z,Q^2)$ is an integrated FF.



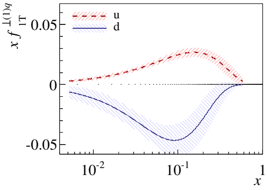
Weighted Sivers asymmetry in SIDIS and the Sivers function extracted from it point-by-point (previous talk of A. Martin).

Projection of the weighted Sivers asymmetry in Drell–Yan

- For this exercise we use a parametrizetion

$$x f_{1T}^{\perp(1)q}(x) = a_q \, x^{b_q} \, (1-x)^{c_q}.$$

- Otherwise same way as in the previous talk.
- No evolution of the Sivers function first moment between $Q^2_{\text{SIDIS}}(x)$ and $Q^2_{\text{DY}}(x_N)$.
- The signficance of the "standard" Sivers asymmetry is better – about 1σ (Thursday, C. Riedl).



Sivers function 1st moment from SIDIS.(stat. errors).
[COMPASS, J.Phys.Conf.Ser. 938, (2017) 012012]

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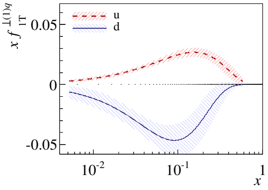

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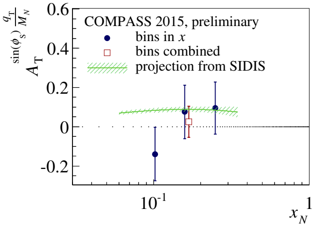

Weighted Sivers asymmetry in Drell–Yan measured in 2015 data and the projection from SIDIS. Statistical errors only.

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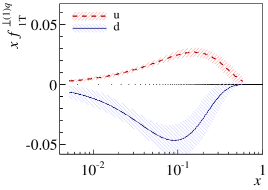

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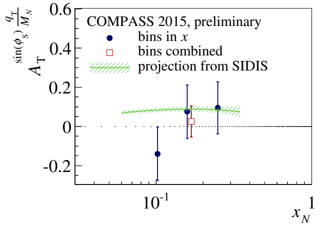

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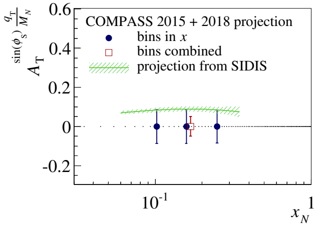

Projection for combined 2015 and 2018 data (assuming 1.5 times larger event sample in 2018 than in 2015).

Outline

Boer–Mulders function in SIDIS and Drell–Yan: Overview

COMPASS

- The situation of Boer–Mulders function is more complicated...
- SIDIS:

$$A_{UU}^{\cos 2\phi_h} \propto h_{1,p}^{\perp q} \otimes H_{1,q}^{\perp h} \quad \text{or}^1 \quad A_{UU}^{\cos 2\phi_h \frac{P_T^2}{4M_p M_h}} \propto h_{1,p}^{\perp(1)q} \times H_{1,q}^{\perp(1)h}, \quad (+\,\text{Cahn effect})$$

$$A_{UT}^{\sin(\phi_h+\phi_S)} \propto h_{1,p}^{q} \otimes H_{1,q}^{\perp h} \quad \text{or} \quad A_{UT}^{\sin(\phi_h+\phi_S)\frac{P_T}{M_h}} \propto h_{1,p}^{q} \times H_{1,q}^{\perp(1)h}$$

$$h_{1,p}^{\perp q}\big|_{\text{SIDIS}} = -h_{1,p}^{\perp q}\big|_{\text{DY}}$$

- Drell–Yan:

$$A_{U}^{\cos 2\phi} \propto h_{1,\pi}^{\perp q} \otimes h_{1,p}^{\perp q} \quad \text{or}^2 \quad A_{U}^{\cos 2\phi \frac{q_T^2}{4M_\pi M_p}} \propto h_{1,\pi}^{\perp(1)q} \times h_{1,p}^{\perp(1)q}$$

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- All the four asymmetries have to be measured to check the sign change!
- The Boer–Mulders function of π is interesting by itself
(the only nontrivial TMD PFD in π apart from f_1).

[1] [D. Boer, P. Mulders, Phys.Rev. D57 (1998) 5780], [A. Kotzinian, P. Mulders, Phys.Lett. B406 (1997) 373]
[2] [A. Sissakian *et al.*, Eur.Phys.J. C46 (2006) 147], [Z. Wang *et al.*, Phys.Rev. D95 (2017) 094004]

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COMPASS

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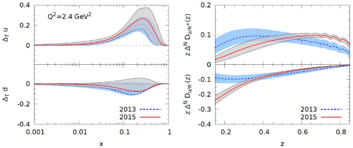
- Global fits available.



Global fit (HERMES, COMPASS, BELLE),
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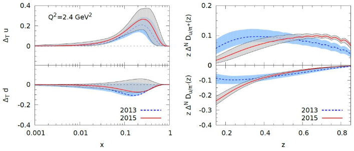

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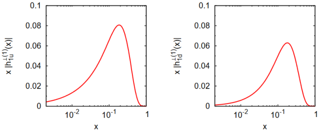

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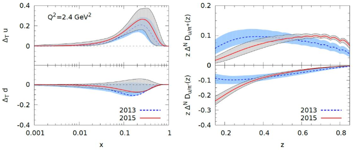

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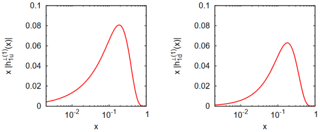

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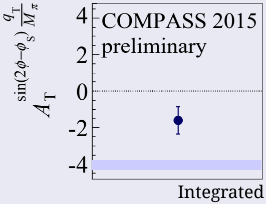
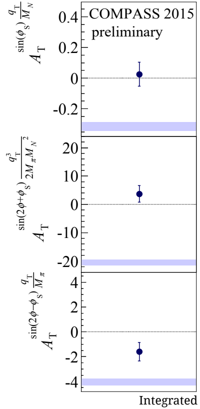
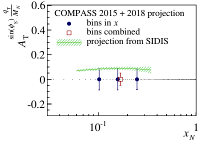


Outline

Conclusion

- COMPASS took the first ever polarised Drell–Yan data in 2015 in
$$\pi^- \mathrm{p}^{\uparrow} \to \mu^- \mu^+ X$$
and it is taking more right now!
We expect at least 1.5 times more in 2018 than in 2015.
- The transverse momentum weighted asymmetries:
    - A way to overcome the convolution over intrinsic $\boldsymbol{k}_{\mathbf{T}}$.
    - Direct access to the k_{T}^2-moments of TMD PDFs.
    - Price to pay: larger statistical uncertainty.
- q_{T}-weighted TSAs in Drell–Yan
    - $A_{\mathrm{T}}^{\sin\phi_{\mathrm{S}}\frac{q_{\mathrm{T}}}{M_N}} \to$ 1st moment of Sivers function of u in p.
    - $A_{\mathrm{T}}^{\sin(2\phi-\phi_{\mathrm{S}})\frac{q_{\mathrm{T}}}{M_\pi}} \to$ Transversity of u in p and 1st moment of Boer–Mulders function of ū in π.
- "Standard" TSAs and more to be presented on Thursday (C. Riedl).





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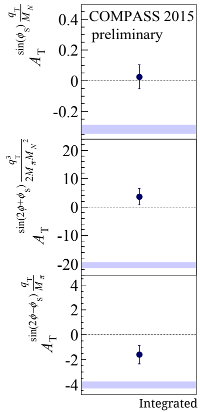
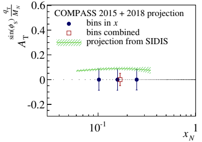
- The transverse momentum weighted asymmetries:
  - A way to overcome the convolution over intrinsic $\boldsymbol{k}_\mathrm{T}$.
  - Direct access to the k_T^2-moments of TMD PDFs.
  - Price to pay: larger statistical uncertainty.
- q_T-weighted TSAs in Drell–Yan
  - $A_\mathrm{T}^{\sin\phi_\mathrm{S}\,\frac{q_\mathrm{T}}{M_N}}$ → 1st moment of Sivers function of u in p.
  - $A_\mathrm{T}^{\sin(2\phi-\phi_\mathrm{S})\,\frac{q_\mathrm{T}}{M_\pi}}$ → Transversity of u in p and 1st moment of Boer–Mulders function of ū in π.
- "Standard" TSAs and more to be presented on Thursday (C. Riedl).



Thank you for your attention!



Fit of the weighted Sivers asymmetry in SIDIS

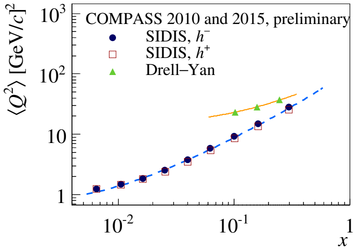
- SIDIS events as function of x, with standard event selection:
  $\mu + \mathrm{p}^{\uparrow} \rightarrow \mu' + h^{\pm} + X$, h^{+} and h^{-} with $z > 0.2$.
- Neglecting Sivers function of sea quarks we write

$$A_{\mathrm{UT,T},h^{\pm}}^{\sin(\phi_{\mathrm{h}}-\phi_{\mathrm{S}})\frac{P_{\mathrm{T}}}{zM}}(x,Q^2) = 2\,\frac{\frac{4}{9}\,f_{1\mathrm{T}}^{\perp(1)\mathrm{u}}(x,Q^2)\,\tilde{D}_{1,\mathrm{u}}^{h^{\pm}}(Q^2) + \frac{1}{9}\,f_{1\mathrm{T}}^{\perp(1)\mathrm{d}}(x,Q^2)\,\tilde{D}_{1,\mathrm{d}}^{h^{\pm}}(Q^2)}{\sum_{q=\mathrm{u,d,s,\bar{u},\bar{d},\bar{s}}} e_q^2\, f_1^q(x,Q^2)\tilde{D}_{1,q}^{h^{\pm}}(Q^2)},$$

- where
- Sivers 1st k_{T}^2-moment – parametrisation:

$$x f_{1\mathrm{T}}^{\perp(1)q}(x) = a_q\, x^{b_q}\,(1-x)^{c_q}.$$

- PDFs and FFs from global fit results
  [CTEQ, Eur.Phys.J. C12 (2000) 375] [D. de Florian *et al.*, Phys.Rev. D75 (2007) 114010],
  collinear evolution with $Q^2 = \langle Q^2 \rangle(x)$.
- The asymmetry for h^{-} and h^{+} are simultaneously fitted.
- Error bands: 1σ, only statistical error of the data and fit.



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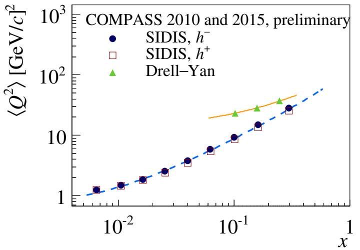

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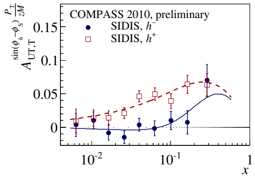

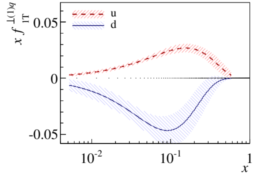

The 1st k_T^2-moment of the Sivers function at $Q^2 = Q^2_\mathrm{SIDIS}(x)$.