Measurement of q_{T}-weighted TSAs in 2015 COMPASS Drell–Yan data

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On behalf of the COMPASS Collaboration

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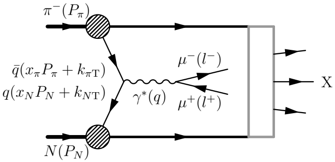
Outline

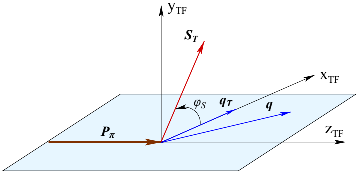
- π^- beam, NH_3 traget with T-polarized H nuclei

$$\pi^-(P_\pi) + \mathrm{p}(P_N, S) \to \mu^-(l^-) + \mu^+(l^+) + X.$$

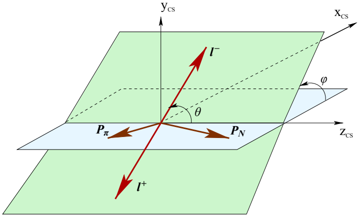
- Cross-section, LO TMD approach [S. Arnold, A. Metz, M. Schlegel, Phys.Rev. D79 (2009) 034005]:

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





Target frame.



Collins–Soper frame.

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

COMPASS

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

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

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

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

(Boer–Mulders function and pretzelosity)

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

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

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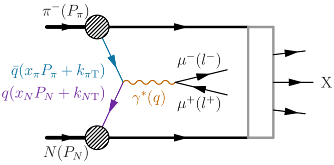
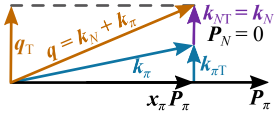
[1] Sign of Sivers func. opposite to Trento convention [M. Anselmino et al., Phys.Rev. D70 (2004) 117504].

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

$$\mathcal{C}[w(\boldsymbol{k_{\pi T}}, \boldsymbol{k_{pT}}, \boldsymbol{q_T}) f_\pi f_\mathrm{p}] = \frac{1}{N_\mathrm{c}} \sum_q e_q^2 \int \mathrm{d}^2\boldsymbol{k_{\pi T}} \mathrm{d}^2\boldsymbol{k_{pT}} \delta^{(2)}(\boldsymbol{q_T} - \boldsymbol{k_{\pi T}} - \boldsymbol{k_{pT}})$$
$$\times w(\boldsymbol{k_{\pi T}}, \boldsymbol{k_{pT}}, \boldsymbol{q_T}) \left[f_\pi^{\bar{q}}(x_\pi, k_{\pi T}^2) f_\mathrm{p}^q(x_\mathrm{p}, k_{\mathrm{p}T}^2) + f_\pi^q(x_\pi, k_{\pi T}^2) f_\mathrm{p}^{\bar{q}}(x_\mathrm{p}, k_{\mathrm{p}T}^2) \right].$$



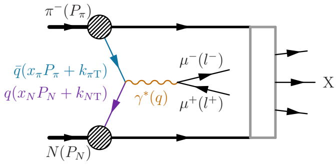
Drell–Yan reaction.



Transverse momenta in target frame.

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

$$\mathcal{C}[w(\boldsymbol{k}_{\pi\mathrm{T}},\boldsymbol{k}_{\mathrm{pT}},\boldsymbol{q}_{\mathrm{T}})f_\pi f_\mathrm{p}] = \frac{1}{N_\mathrm{c}}\sum_q e_q^2 \int \mathrm{d}^2\boldsymbol{k}_{\pi\mathrm{T}}\mathrm{d}^2\boldsymbol{k}_{\mathrm{pT}}\delta^{(2)}(\boldsymbol{q}_{\mathrm{T}}-\boldsymbol{k}_{\pi\mathrm{T}}-\boldsymbol{k}_{\mathrm{pT}})$$
$$\times w(\boldsymbol{k}_{\pi\mathrm{T}},\boldsymbol{k}_{\mathrm{pT}},\boldsymbol{q}_{\mathrm{T}})\left[f_\pi^{\bar{q}}(x_\pi,k_{\pi\mathrm{T}}^2)f_\mathrm{p}^{q}(x_\mathrm{p},k_{\mathrm{pT}}^2)+f_\pi^{q}(x_\pi,k_{\pi\mathrm{T}}^2)f_\mathrm{p}^{\bar{q}}(x_\mathrm{p},k_{\mathrm{pT}}^2)\right].$$



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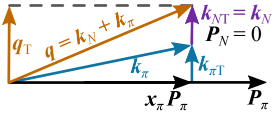


Transverse momenta in target frame.

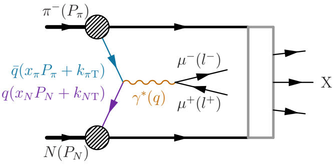
- Integration of F_U^1 over $\mathrm{d}^2\boldsymbol{q}_\mathrm{T}$

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

TSAs in the Drell–Yan process: The convolution

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

$$\mathcal{C}[w(\boldsymbol{k}_{\pi\mathrm{T}}, \boldsymbol{k}_{\mathrm{pT}}, \boldsymbol{q}_{\mathrm{T}}) f_\pi f_\mathrm{p}] = \frac{1}{N_\mathrm{c}} \sum_q e_q^2 \int \mathrm{d}^2\boldsymbol{k}_{\pi\mathrm{T}} \mathrm{d}^2\boldsymbol{k}_{\mathrm{pT}} \delta^{(2)}(\boldsymbol{q}_{\mathrm{T}} - \boldsymbol{k}_{\pi\mathrm{T}} - \boldsymbol{k}_{\mathrm{pT}})$$
$$\times w(\boldsymbol{k}_{\pi\mathrm{T}}, \boldsymbol{k}_{\mathrm{pT}}, \boldsymbol{q}_{\mathrm{T}}) \left[f_\pi^{\bar{q}}(x_\pi, k_{\pi\mathrm{T}}^2) f_\mathrm{p}^{q}(x_\mathrm{p}, k_{\mathrm{pT}}^2) + f_\pi^{q}(x_\pi, k_{\pi\mathrm{T}}^2) f_\mathrm{p}^{\bar{q}}(x_\mathrm{p}, k_{\mathrm{pT}}^2) \right].$$



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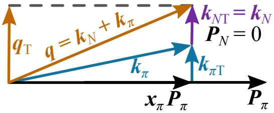

Transverse momenta in target frame.

- Integration of $F_\mathrm{T}^{\sin\phi_\mathrm{S}}$ over $\mathrm{d}^2\boldsymbol{q}_\mathrm{T}$:

$$\int \mathrm{d}^2\boldsymbol{q}_\mathrm{T} F_\mathrm{T}^{\sin\phi_\mathrm{S}} = -\int \mathcal{C}\left[\frac{\boldsymbol{q}_\mathrm{T} \cdot \boldsymbol{k}_{\mathrm{pT}}}{q_\mathrm{T} M_\mathrm{p}} f_{1,\pi} f_{1\mathrm{T,p}}^{\perp} \right]$$
$$= -\frac{1}{N_\mathrm{c}} \sum_q e_q^2 \int \mathrm{d}^2\boldsymbol{k}_{\pi\mathrm{T}} \mathrm{d}^2\boldsymbol{k}_{\mathrm{pT}} \frac{(\boldsymbol{k}_{\pi\mathrm{T}} + \boldsymbol{k}_{\mathrm{pT}}) \cdot \boldsymbol{k}_{\mathrm{pT}}}{|\boldsymbol{k}_{\pi\mathrm{T}} + \boldsymbol{k}_{\mathrm{pT}}| M_\mathrm{p}}$$
$$\times \left[f_{1,\pi}^{\bar{q}}(x_\pi, k_{\pi\mathrm{T}}^2)\, f_{1\mathrm{T,p}}^{\perp q}(x_\mathrm{p}, k_{\mathrm{pT}}^2) + (q \leftrightarrow \bar{q}) \right]$$
$$= \;?$$

Popular solution: Gaussian model for the $\boldsymbol{k}_\mathrm{T}$ dependence.

TSAs in the Drell–Yan process: The q_T-weighting

- Possible alternative: weighting with powers of the transverse momentum
- First developed for SIDIS:
  - [A. Kotzinian and P. Mulders, Phys.Lett. B406 (1997) 373]
  - [D. Boer and P. Mulders, Phys.Rev. D57 (1998) 5780]
- Recent COMPASS SIDIS measurement:
  - [F. Bradamante (COMPASS), arXiv:1702.0062 [hep-ex], proc. of SPIN 2016]
- Also suggested for Drell–Yan, e.g.:
  - [A. Efremov *et al.*, Phys.Lett. B612 (2005) 233]
  - [A. Sissakian *et al.*, Phys.Rev. D72 (2005) 054027]
  - [A. Sissakian *et al.*, Eur.Phys.J. C46 (2006) 147]
  - [Z. Wang *et al.*, Phys.Rev. D95 (2017) 094004]
- Example: integration of $F_T^{\sin\phi_S}$ over $d^2\boldsymbol{q_T}$ with weight $= q_T/M_p$,

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

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

$$\times\left[f_{1,\pi}^{\bar{q}}(x_\pi, k_{\pi T}^2)\, f_{1T,p}^{\perp q}(x_p, k_{pT}^2) + (q\leftrightarrow\bar{q})\right]$$

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

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

$$f_{1T}^{\perp(1)q}(x) = \int d^2\boldsymbol{k_T} \frac{k_T^2}{2M^2} f_{1T}^{\perp q}(x, k_T^2).$$

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- Example: integration of $F_{\mathrm{T}}^{\sin\phi_{\mathrm{S}}}$ over $\mathrm{d}^2\boldsymbol{q}_{\mathbf{T}}$ with weight $= q_{\mathrm{T}}/M_{\mathrm{p}}$,

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

$$= -\frac{1}{N_{\mathrm{c}} M_{\mathrm{p}}^2} \sum_q e_q^2 \int \mathrm{d}^2\boldsymbol{k}_{\boldsymbol{\pi}\mathbf{T}} \mathrm{d}^2\boldsymbol{k}_{\mathbf{pT}} (\boldsymbol{k}_{\boldsymbol{\pi}\mathbf{T}} + \boldsymbol{k}_{\mathbf{pT}}) \cdot \boldsymbol{k}_{\mathbf{pT}}$$

$$\times \left[f_{1,\pi}^{\bar{q}}(x_\pi, k_{\pi\mathrm{T}}^2)\, f_{1\mathrm{T,p}}^{\perp q}(x_{\mathrm{p}}, k_{\mathrm{pT}}^2) + (q \leftrightarrow \bar{q})\right]$$

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

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

$$f_{1\mathrm{T}}^{\perp(1)q}(x) = \int \mathrm{d}^2\boldsymbol{k}_{\mathbf{T}} \frac{k_{\mathrm{T}}^2}{2M^2} f_{1\mathrm{T}}^{\perp q}(x, k_{\mathrm{T}}^2).$$

- Single T-polarised Drell–Yan spin-dependent azimuthal modulations, integrated with the appropriate q_{T}-weights:

$$\int \mathrm{d}^2\boldsymbol{q}_{\mathbf{T}}\,\frac{q_{\mathrm{T}}}{M_{\mathrm{p}}}\,F_{\mathrm{T}}^{\sin\phi_{\mathrm{S}}} = -\frac{2}{N_{\mathrm{c}}}\sum_q e_q^2\,[f_{1,\pi}^{\bar{q}}(x_\pi)\,f_{1\mathrm{T,p}}^{\perp(1)q}(x_N) + (q\leftrightarrow\bar{q})] \approx \frac{2e_{\mathrm{u}}^2}{N_{\mathrm{c}}}\,f_{1,\pi}^{\bar{\mathrm{u}}}(x_\pi)f_{1\mathrm{T}}^{\perp(1)\mathrm{u}}(x_N),$$

$$\int \mathrm{d}^2\boldsymbol{q}_{\mathbf{T}}\,\frac{q_{\mathrm{T}}}{M_\pi}\,F_{\mathrm{T}}^{\sin(2\phi-\phi_{\mathrm{S}})} = -\frac{2}{N_{\mathrm{c}}}\sum_q e_q^2\,[h_{1,\pi}^{\perp(1)\bar{q}}(x_\pi)\,h_{1,\mathrm{p}}^{q}(x_N) + (q\leftrightarrow\bar{q})] \approx \frac{2e_{\mathrm{u}}^2}{N_{\mathrm{c}}}\,h_{1,\pi}^{\perp(1)\bar{\mathrm{u}}}(x_\pi)h_{1,\mathrm{p}}^{\mathrm{u}}(x_N),$$

$$\int \mathrm{d}^2\boldsymbol{q}_{\mathbf{T}}\,\frac{q_{\mathrm{T}}^3}{2M_\pi M_{\mathrm{p}}^2}\,F_{\mathrm{T}}^{\sin(2\phi+\phi_{\mathrm{S}})} = -\frac{2}{N_{\mathrm{c}}}\sum_q e_q^2\,[h_{1,\pi}^{\perp(1)\bar{q}}(x_\pi)\,h_{1\mathrm{T,p}}^{\perp(2)q}(x_N) + (q\leftrightarrow\bar{q})] \approx \frac{2e_{\mathrm{u}}^2}{N_{\mathrm{c}}}\,h_{1,\pi}^{\perp(1)\bar{\mathrm{u}}}(x_\pi)h_{1\mathrm{T,p}}^{\perp(2)\mathrm{u}}(x_N).$$

- q_{T}-weighted TSA = direct measurement of TMD PDF k_{T}^2-moments!

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

- Example: q_{T}-weighted Sivers asymmetry

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

TSAs in the Drell–Yan process: Weighted asymmetries in DY

COMPASS

- Single T-polarised Drell–Yan spin-dependent azimuthal modulations, integrated with the appropriate q_T-weights:

$$\int \mathrm{d}^2\boldsymbol{q_\mathrm{T}}\,\frac{q_\mathrm{T}}{M_\mathrm{p}}\,F_\mathrm{T}^{\sin\phi_\mathrm{S}} = -\frac{2}{N_\mathrm{c}}\sum_q e_q^2[f_{1,\pi}^{\bar{q}}(x_\pi)\,f_{1\mathrm{T},\mathrm{p}}^{\perp(1)q}(x_N) + (q \leftrightarrow \bar{q})] \approx \frac{2e_\mathrm{u}^2}{N_\mathrm{c}}f_{1,\pi}^{\bar{\mathrm{u}}}(x_\pi)f_{1\mathrm{T}}^{\perp(1)\mathrm{u}}(x_N),$$

$$\int \mathrm{d}^2\boldsymbol{q_\mathrm{T}}\,\frac{q_\mathrm{T}}{M_\pi}\,F_\mathrm{T}^{\sin(2\phi-\phi_\mathrm{S})} = -\frac{2}{N_\mathrm{c}}\sum_q e_q^2[h_{1,\pi}^{\perp(1)\bar{q}}(x_\pi)\,h_{1,\mathrm{p}}^{q}(x_N) + (q \leftrightarrow \bar{q})] \approx \frac{2e_\mathrm{u}^2}{N_\mathrm{c}}h_{1,\pi}^{\perp(1)\bar{\mathrm{u}}}(x_\pi)h_{1,\mathrm{p}}^{\mathrm{u}}(x_N),$$

$$\int \mathrm{d}^2\boldsymbol{q_\mathrm{T}}\,\frac{q_\mathrm{T}^3}{2M_\pi M_\mathrm{p}^2}\,F_\mathrm{T}^{\sin(2\phi+\phi_\mathrm{S})} = -\frac{2}{N_\mathrm{c}}\sum_q e_q^2[h_{1,\pi}^{\perp(1)\bar{q}}(x_\pi)\,h_{1\mathrm{T},\mathrm{p}}^{\perp(2)q}(x_N) + (q \leftrightarrow \bar{q})] \approx \frac{2e_\mathrm{u}^2}{N_\mathrm{c}}h_{1,\pi}^{\perp(1)\bar{\mathrm{u}}}(x_\pi)h_{1\mathrm{T},\mathrm{p}}^{\perp(2)\mathrm{u}}(x_N).$$

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

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

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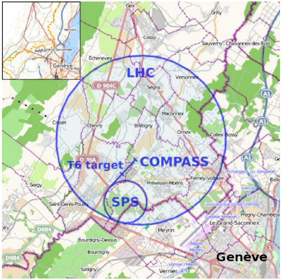
$$A_\mathrm{T}^{\sin\phi_\mathrm{S}\frac{q_\mathrm{T}}{M_\mathrm{p}}}(x_\pi, x_N) = -2\frac{\sum_q e_q^2\left[f_{1,\pi}^{\bar{q}}(x_\pi)\,f_{1\mathrm{T},\mathrm{p}}^{\perp(1)q}(x_N) + (q \leftrightarrow \bar{q})\right]}{\sum_q e_q^2\left[f_1^q(x_\pi)f_1^{\bar{q}}(x_N) + (q \leftrightarrow \bar{q})\right]}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

Outline

Measurement: Experimental apparatus

- 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

Image credit: Wikimedia Commons

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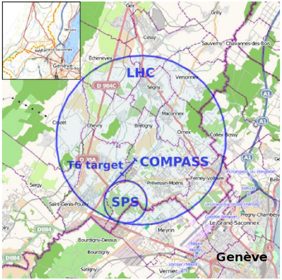

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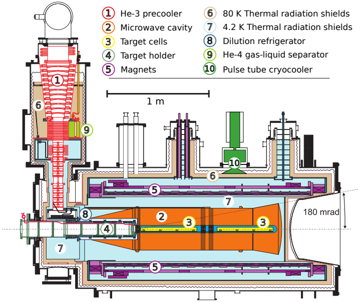
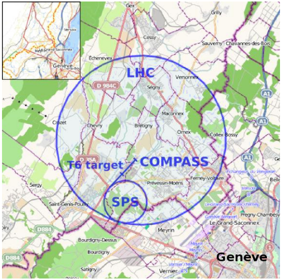


Polarised target cryostat.

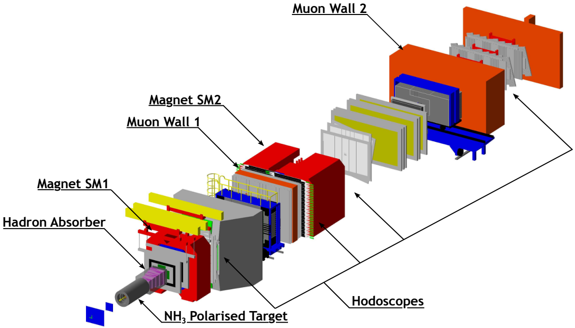
Measurement: Experimental apparatus

- COMPASS Collaboration: 24 institutions from 13 countries ($\approx$ 220 physicists).
- Experimental area: CERN Super Proton Synchrotron (SPS) North Area.
- Multi-purpose apparatus. Drell–Yan setup:
  - Transversely polarised p (NH_3) target polarisation $\approx 73\%$, 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.

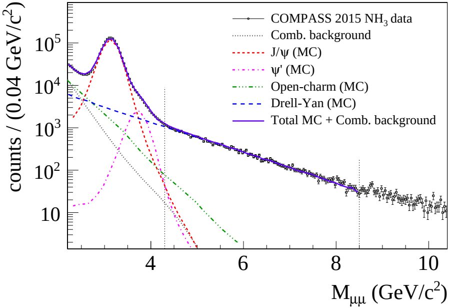


Location of the site at CERN's SPS

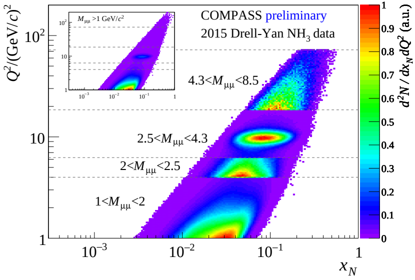
Image credit: Wikimedia Commons



COMPASS Drell–Yan setup.

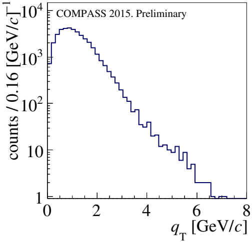


2015 data and reconstructed MC.

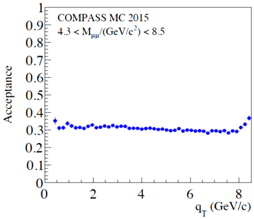


Kinematic coverage in x_N and Q^2

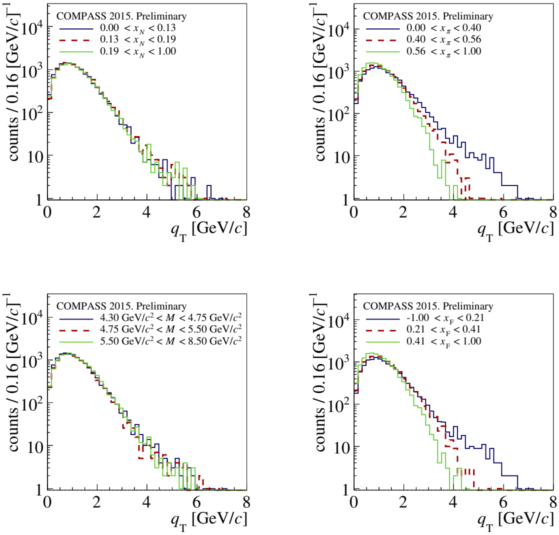
- The range $M_{\mu\mu} \in [4.3, 8.5]$ GeV$/c^2$ is selected.
- The same event selection as for the standard TSA analysis (previous talk of M. Pešek),
- except the cut on q_T, which we do not use
  (weighted asymmetry – must be integrated over the whole range of q_T).



Distribution of q_{T}.



Acceptance in q_{T}.



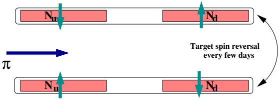
Distributions of q_{T} in the kinematic bins.

Measurement: q_T-weighted TSAs extraction

- Definition:

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

- Only the spin-dependent part is weighted!
  → we use different methods from the standard TSAs (no UML).
- Polarised target with 2 cells $c = {\rm U, D}$,
- and periods $p = 1, 2$ with opposite polarisation ↑↓, ↓↑.
- $N_{cp}(\Phi)$ – number of events
- $N_{cp}^W(\Phi)$ – sum of weights of events



Two-cell target, reversals every week.

- "Modified double ratio method":

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

- Used also in $P_{\rm T}/z$-weighted SIDIS analysis
  [F. Bradamante (COMPASS), arXiv:1702.0062 [hep-ex], proc. of SPIN 2016].
- Acceptance $a(\Phi)$ is canceled.
- $R_{\rm DM}^W(\Phi)$ is fitted in 8 bins of Φ.
- Separately in 9 pairs of periods.
- Statistically-weighted average is taken.

$$\tilde{D}_{\phi_{\rm S}} = 1,$$

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

$$\overline{S_{\rm T}} = \langle f_{\rm dil.}\rangle\langle P_{\rm targ.}\rangle.$$

Measurement: q_{T}-weighted TSAs extraction

COMPASS

- Definition:

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

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  → we use different methods from the standard TSAs (no UML).
- Polarised target with 2 cells $c = \mathrm{U}, \mathrm{D}$,
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- $N_{cp}(\Phi)$ – number of events
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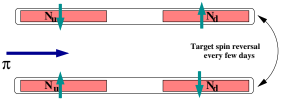

Two-cell target, reversals every week.

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

- Used also in P_{T}/z-weighted SIDIS analysis
  [F. Bradamante (COMPASS), arXiv:1702.0062 [hep-ex], proc. of SPIN 2016].
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- Separately in 9 pairs of periods.
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$$A_{\mathrm{T}}^{\sin\Phi W_\Phi}(x_\pi, x_N) = \frac{\int \mathrm{d}^2\boldsymbol{q}_{\mathbf{T}} W_\Phi\, F_{\mathrm{T}}^{\sin\Phi}(x_\pi, x_N)}{\int \mathrm{d}^2\boldsymbol{q}_{\mathbf{T}} F_{\mathrm{U}}^{1}(x_\pi, x_N)}, \qquad \Phi = \phi_{\mathrm{S}}, 2\phi \pm \phi_{\mathrm{S}}.$$

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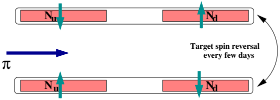

Two-cell target, reversals every week.

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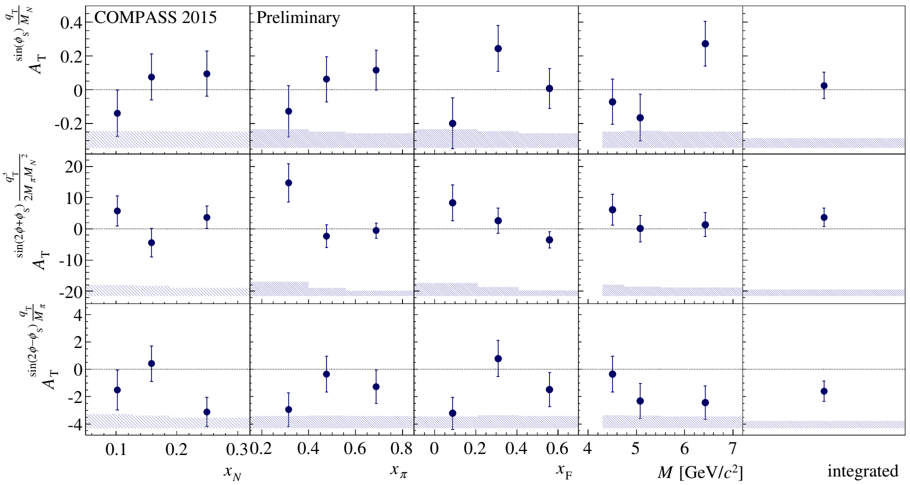


The q_T-weighted TSAs from the 2015 Drell–Yan run.
The combined systematic uncertainty is about $0.8\,\sigma_{\text{stat}}$..
(+ about 5% from the polarisation and dilution factor calculation.

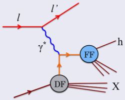
Outline

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

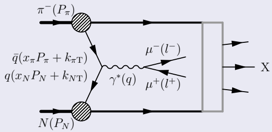
T-polarised SIDIS

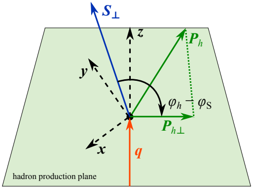
- COMPASS, $p^{\uparrow}$ 2010.
- TSA $= \mathrm{DF}_{q,N} \otimes \mathrm{FF}_{q\to h}$.
- P_T-weighted TSA $= \mathrm{DF}_{q,N} \times \mathrm{FF}_{q\to h}$.
- Sivers P_T-weighted asym. measured [F Bradamante (COMPASS), proc. of SPIN 2016, Urbana, USA]



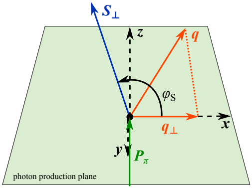
T-polarised Drell–Yan

- COMPASS, $p^{\uparrow}$ 2015 (1st ever).
- TSA $= \mathrm{DF}_{q,N} \otimes \mathrm{DF}_{\bar{q},h_{beam}}$.
- q_T-weighted $A = \mathrm{DF}_{q,N} \times \mathrm{DF}_{\bar{q},h_{beam}}$.
- Sivers q_T-weighted asym. measured!





γN frame



Target frame

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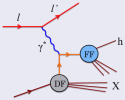

T-polarised Drell–Yan

- COMPASS, $p^{\uparrow}$ 2015 (1st ever).
- TSA $= \mathrm{DF}_{q,N} \otimes \mathrm{DF}_{\bar{q},h_{beam}}$.
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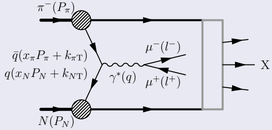
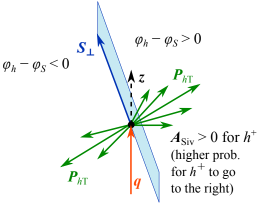
- Sivers q_T-weighted asym. measured!

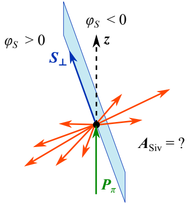




γN frame

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

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



Target frame

The weighted Sivers asym. in SIDIS and DY: Strategy

- Inspiration: weighted Sivers in SIDIS → DY [A. Efremov *et al.*, Phys.Lett. B612 (2005) 233]
- Fit of the P_{T}/z-weighted Sivers asymmetry in SIDIS,
- Calculation of the corresponding q_{T}-weighted Sivers asymmetry in DY.

- Reaction: $\mu + \mathrm{p}^{\uparrow} \to \mu' + h^{\pm} + X$.
- h^{+} and h^{-} with $z > 0.2$.
- u, d, s, ū, d̄, s̄ quarks.
- Sivers func. of sea quarks assumed zero.
- So we can write[2]

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

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

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

[2] Sign convention opposite to the Trento convention [M. Anselmino *et al.*, Phys.Rev. D70 (2004) 117504]

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- Sivers 1st $k_{\rm T}^2$-moment – parametrisation:

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

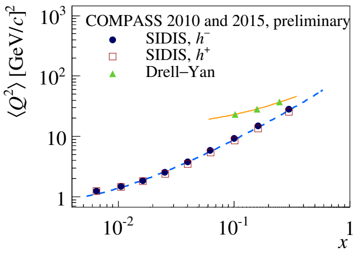
[2] Sign convention opposite to the Trento convention [M. Anselmino *et al.*, Phys.Rev. D70 (2004) 117504].

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

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

- Collinear evolution of PDFs and FFs, $Q^2 = Q^2_{\mathrm{SIDIS}}(x)$ from fit.
- Same choices and approach as [A. Martin *et al.*, Phys.Rev. D95 (2017) 094024].
- PDFs – from CTEQ 5D global fit [H. Lai *et al.* (CTEQ), Eur.Phys.J. C12 (2000) 375] (from LHAPDF library)
- The FFs from DSS 07 LO global fit [D. de Florian *et al.*, Phys.Rev. D75 (2007) 114010]

$$\tilde{D}_{1,q}^{h^{\pm}}(Q^2) = \int_{0.2}^{1} \mathrm{d}z D_{1,q}^{h^{\pm}}(z,Q^2)$$



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

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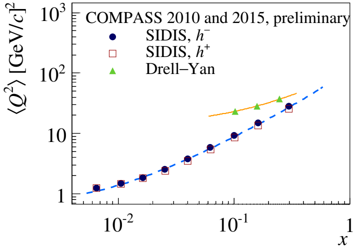

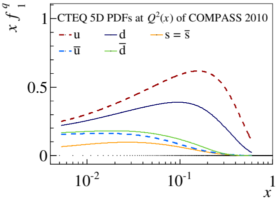

The weighted Sivers asym. in SIDIS and DY: PDFs and FFs

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

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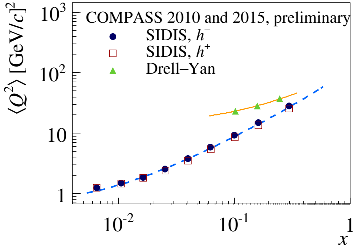
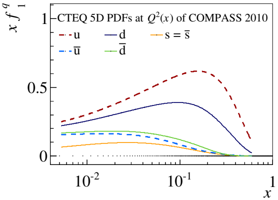
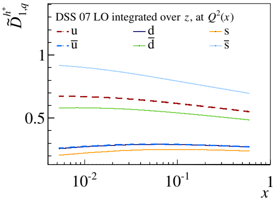




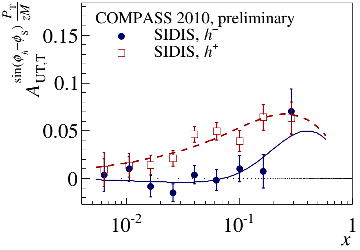


The weighted Sivers asym. in SIDIS and DY: Fit results

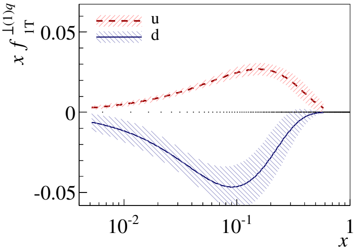
- The asymmetry for h^- and h^+ is simultaneously fitted.
- Sivers 1st k_T^2-moment parametrisation:

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

- Error bands: 1σ, 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].



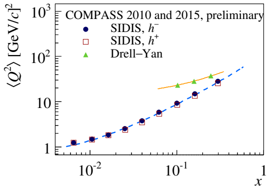
The 1st k_T^2-moment of the Sivers function at $Q^2 = Q^2_{SIDIS}(x)$.

The weighted Sivers asym. in SIDIS and DY: Results

- $f_{1T}^{\perp q}\big|_{DY} = -f_{1T}^{\perp q}\big|_{SIDIS}$ [J. Collins, Phys.Lett. B536 (2002) 43]
- We assume valence quark dominance:

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

- Collinear evolution of f_1, $Q^2 = Q^2_{\mathrm{DY}}(x_N)$ from fit.
- No evolution of the Sivers function first moment between $Q^2_{\mathrm{SIDIS}}(x)$ and $Q^2_{\mathrm{DY}}(x_N)$
- Another data taking planned for 2018!



- $f_{1T}^{\perp q}\big|_{\mathrm{DY}} = -f_{1T}^{\perp q}\big|_{\mathrm{SIDIS}}$ [J. Collins, Phys.Lett. B536 (2002) 43]
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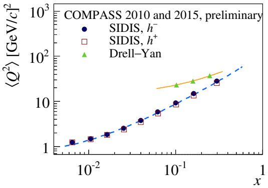

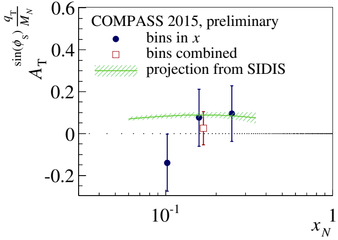

Weighted Sivers asymmetry in Drell–Yan measured in 2015 data and the projection from SIDIS. Statistical errors only.

The weighted Sivers asym. in SIDIS and DY: Results

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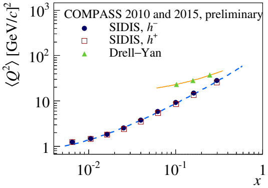

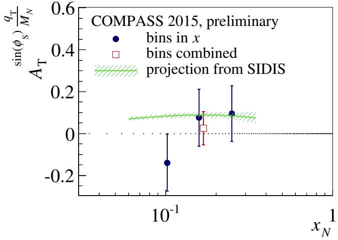

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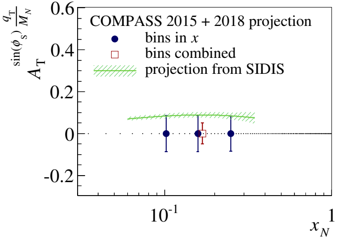

Projection for combined 2015 and 2018 data (assuming 1.5 times larger statistics in 2018).

Outline

Conclusion

- The transverse momentum weighted asymmetries are interesting!
  - A model-independent way to overcome the convolution over intrinsic $\boldsymbol{k}_{\mathbf{T}}$.
  - 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: $A_{\mathrm{T}}^{\sin\phi_{\mathrm{S}}\frac{q_{\mathrm{T}}}{M_N}}$ compatible with zero.
  - Transversity asymmetry: $A_{\mathrm{T}}^{\sin(2\phi-\phi_{\mathrm{S}})\frac{q_{\mathrm{T}}}{M_\pi}}$ about 1.5σ below zero.
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Thank you for your attention!