Extraction of Sivers functions from SIDIS and Drell-Yan data with TMD evolution

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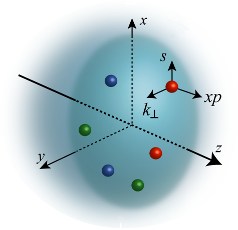
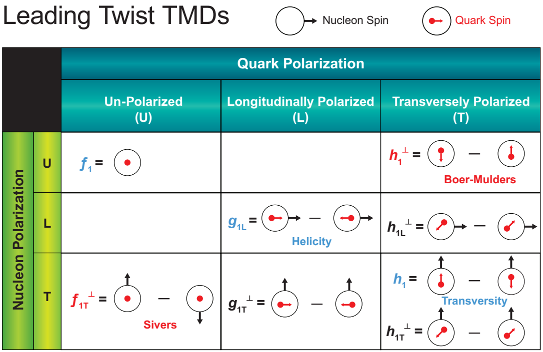
Based on work in collaboration with Alexei Prokudin and Alexey Vladimirov

arXiv:2012.05135

Transverse Momentum Dependent distributions



Dudek *et al.* Eur. Phys. J. A 48 (2012)



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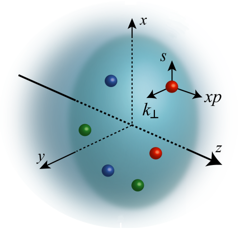

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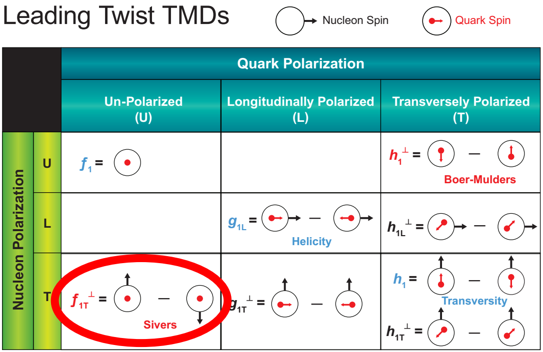

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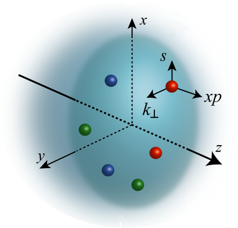

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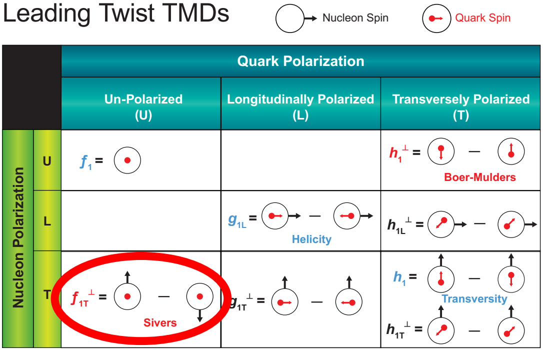
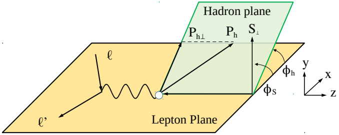
$$f_{1T}^{\perp SIDIS} = -f_{1T}^{\perp DY}$$



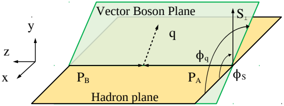
Accardi *et al.* Eur. Phys. J. A 52 (2016)

Single Spin Asymmetries

SIDIS



Drell-Yan, $W^{\pm}/Z$ production



$$\frac{d\sigma}{d\mathcal{PS}}=\sigma_0\left\{F_{UU,T}+|S_\perp|\sin(\phi_h-\phi_S)F_{UT,T}^{\sin(\phi_h-\phi_S)}\right\}$$

$$\frac{d\sigma}{d\mathcal{PS}}=\sigma_0\left\{F_{UU}^1+|S_T|\sin(\varphi-\phi_S)F_{TU}^1\right\}$$

$$A_{UT}^{\sin(\phi_h-\phi_S)}\equiv\frac{F_{UT,T}^{\sin(\phi_h-\phi_S)}}{F_{UU,T}}=-M\frac{\mathcal{B}_1^{\text{SIDIS}}\left[f_{1T}^\perp D_1\right]}{\mathcal{B}_0^{\text{SIDIS}}[f_1 D_1]}$$

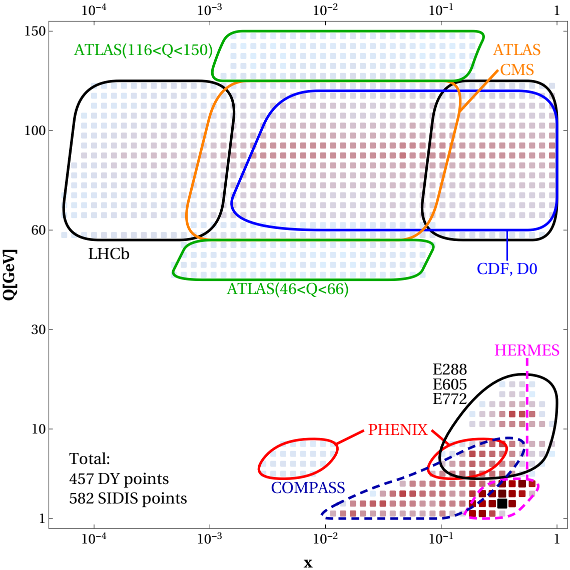
$$A_{TU}\equiv\frac{F_{TU}^1}{F_{UU}^1}=-M\frac{\mathcal{B}_1^{\text{DY}}[f_{1T}^\perp\ f_2]}{\mathcal{B}_0^{\text{DY}}[f_1\ f_2]}$$

$$\mathcal{B}_n^{\text{SIDIS}}[fD]\equiv\sum_q e_q^2\int_0^\infty\frac{bdb}{2\pi}b^n J_n\left(\frac{b|P_{hT}|}{z}\right)\times f_{q\leftarrow h_1}(x,b;\mu,\zeta_1)D_{q\to h_2}(z,b;\mu,\zeta_2)$$

$$\mathcal{B}_n^{\text{DY}}[f_1\ f_2]\equiv\sum_q e_q^2\int_0^\infty\frac{bdb}{2\pi}b^n J_n(b|q_T|)\times f_{1;q\leftarrow h_1}(x_1,b;\mu,\zeta_1)f_{2;\bar{q}\leftarrow h_2}(x_2,b;\mu,\zeta_2)$$

Pictures from Echevarria *et al.* arXiv:2009.10710

Unpolarized TMD



SV19: Scimemi, Vladimirov

arXiv:1912.06532

DY:	457 points
SIDIS:	582 points
TOTAL:	1039 points

NNLO:χ^2_{global}/N_{pt}=0.95

N^{3}LO:χ^2_{global}/N_{pt}=1.05

Scimemi, Vladimirov arXiv:1912.06532

Evolution

- TMD distributions depend on ultra-violet μ and rapidity ζ renormalization scales and the evolution is dictated by a pair of differential equations
- We use the ζ-prescription (the reference scale $(\mu, \zeta) = (\mu, \zeta_\mu(b))$ is selected from equipotential line of the field anomalous dimension that passes through the saddle point)
- The reference TMD distribution is independent on μ and the solution of evol. equations can be written in simpler form

$$f_{1T,q\leftarrow h}^{\perp}(x,b;\mu,\zeta) = \left(\frac{\zeta}{\zeta_\mu(b)}\right)^{-\mathcal{D}(b,\mu)} f_{1T,q\leftarrow h}^{\perp}(x,b)$$

- The function $f_{1T,q\leftarrow h}^{\perp}(x,b) = f_{1T,q\leftarrow h}^{\perp}(x,b;\mu,\zeta_\mu(b))$ on rhs is the **optimal Sivers** function
- $\zeta_\mu(b)$ is a calculable function of the universal non-perturbative Collins-Soper kernel $\mathcal{D}(b,\mu)$, parametrized as

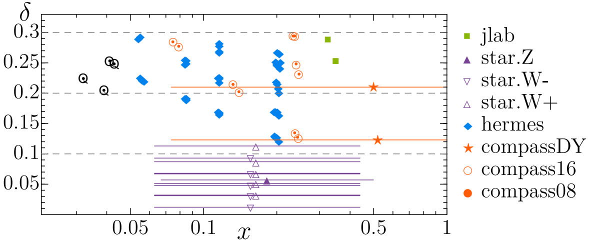
$$\mathcal{D}(b,\mu) = \mathcal{D}_{\text{resum}}(b^*,\mu) + c_0 b b^*, \qquad b^* = b/\sqrt{1+\left(b/(2\text{ GeV}^{-1})\right)^2}$$

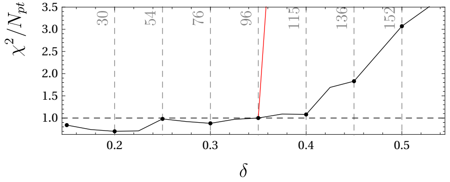
- N^3LO expressions are used for $\zeta_\mu(b)$ and $\mathcal{D}_{\text{resum}}$

Data selection

- TMD factorization applies in the limit of large Q and small relative transverse momentum δ. Selection criteria:

$$\langle Q\rangle > 2\text{ GeV} \qquad \text{and} \qquad \delta^{\text{SIDIS}}=\frac{|P_{h\perp}|}{zQ},\ \delta^{\text{DY}}=\frac{|q_T|}{Q} < 0.3$$





DY:	13/14 pt
SIDIS:	63/388 pt
TOTAL:	76/402 pt

Parametrization of Sivers function

- We do not use small-b matching for Sivers functions (presence of unknown twist-3 distributions, besides Qiu-Sterman function)
- Optimal Sivers function is a generic NP function, extracted from the data, parametrized as

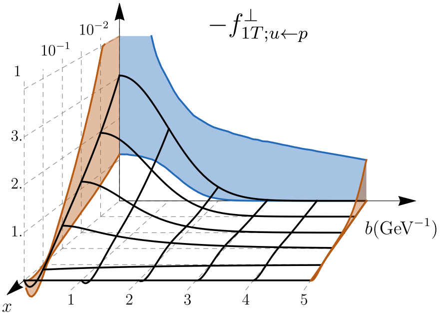
$$f_{1T;q\leftarrow h}^{\perp}(x,b) = N_q \frac{(1-x)x^{\beta_q}(1+\epsilon_q x)}{n(\beta_q,\epsilon_q)} \exp\left(-\frac{r_0 + x r_1}{\sqrt{1+r_2 x^2 b^2}} b^2\right)$$

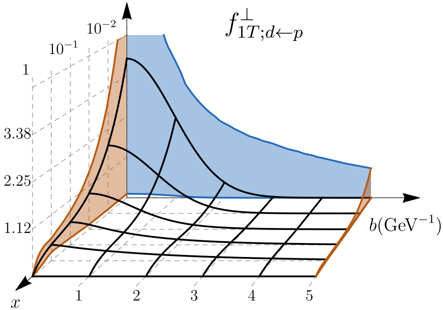
$$n(\beta,\epsilon)=(3+\beta+\epsilon+\epsilon\beta)\beta!/(\beta+3)! \Rightarrow \int_0^1 dx f_{1T;q\leftarrow h}^{\perp}(x,0)=N_q$$

- Separate functions for u, d, s, single *sea* Sivers function for $\bar{u}$, $\bar{d}$ and $\bar{s}$; $\beta_s = \beta_{sea}$ and $\epsilon_s = \epsilon_{sea} = 0$, since small-$x$ behavior is not restricted by data
- 12 free parameters in total
- QS function is then obtained from the small-b limit of the extracted Sivers function

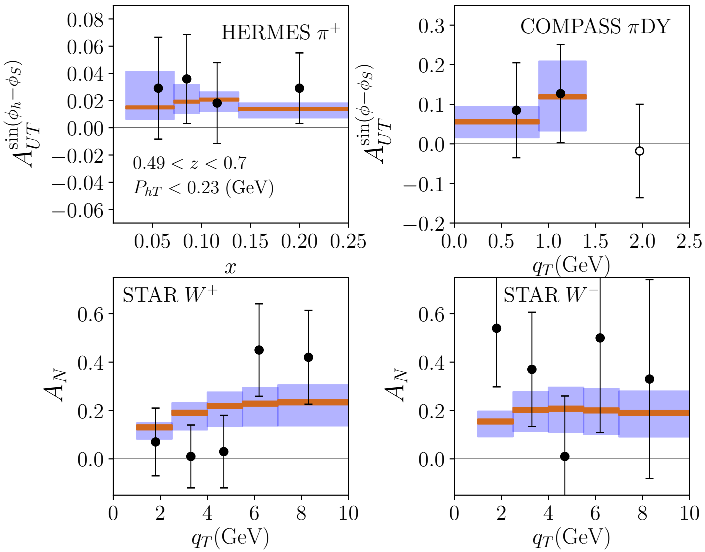
Fit result

Name	χ^2/N_{pt}[SIDIS]	χ^2/N_{pt}[DY]	χ^2/N_{pt}[total]
SIDIS at NNLO	0.88	1.29 no fit	0.95
SIDIS+DY at NNLO	0.90	0.94	0.91
SIDIS at N^{3}LO	0.87	1.23 no fit	0.93
SIDIS+DY at N^{3}LO	0.88	0.90	0.88





Description of the data

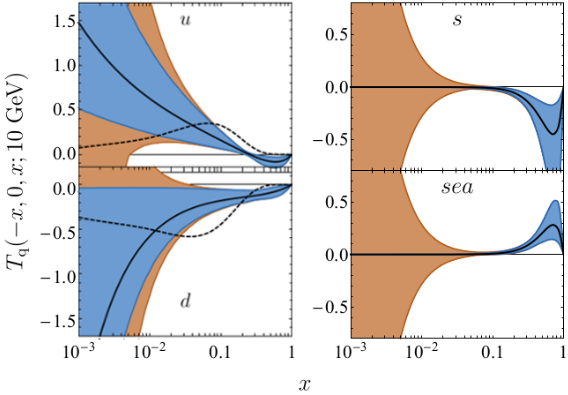


Qiu-Sterman function

$$T_q(-x,0,x;\mu_b) = -\frac{1}{\pi} f^{\perp}_{1T;q\leftarrow h}(x,b)$$

$G^{(+)} = \pm(|T_u| + |T_d|)$ - gluon QS function

$$-\frac{\alpha_s(\mu_b)}{4\pi^2}\int_x^1 \frac{dy}{y}\left[\frac{\bar{y}}{N_c} f^{\perp}_{1T;q\leftarrow h}\left(\frac{x}{y},b\right) + \frac{3y^2\bar{y}}{2x} G^{(+)}\left(-\frac{x}{y},0,\frac{x}{y};\mu_b\right)\right] + \mathcal{O}(a_s^2, b^2)$$



Dashed line - JAM20 results (Cammarota *et al.*

Conclusions

- We performed the extraction of the Sivers function that consistently utilizes previously extracted unpolarised proton and pion TMDs, and uses SIDIS, pion-induced Drell-Yan, and $W^{\pm}/Z$-bozon production experimental data
- The extraction is performed at N^{3}LO perturbative precision within the ζ-prescription that allows us to unambiguously relate the Sivers function and QS function
- Our results compare well in magnitude with the existing extractions
- We confirm the signs of Sivers functions for u and d quarks while we also obtain non negligible Sivers functions for anti-quarks
- The analysis was done with `artemide` package
- The fitting codes and the results of the extraction (in the form of replica-distributions for model parameters) are publicly available