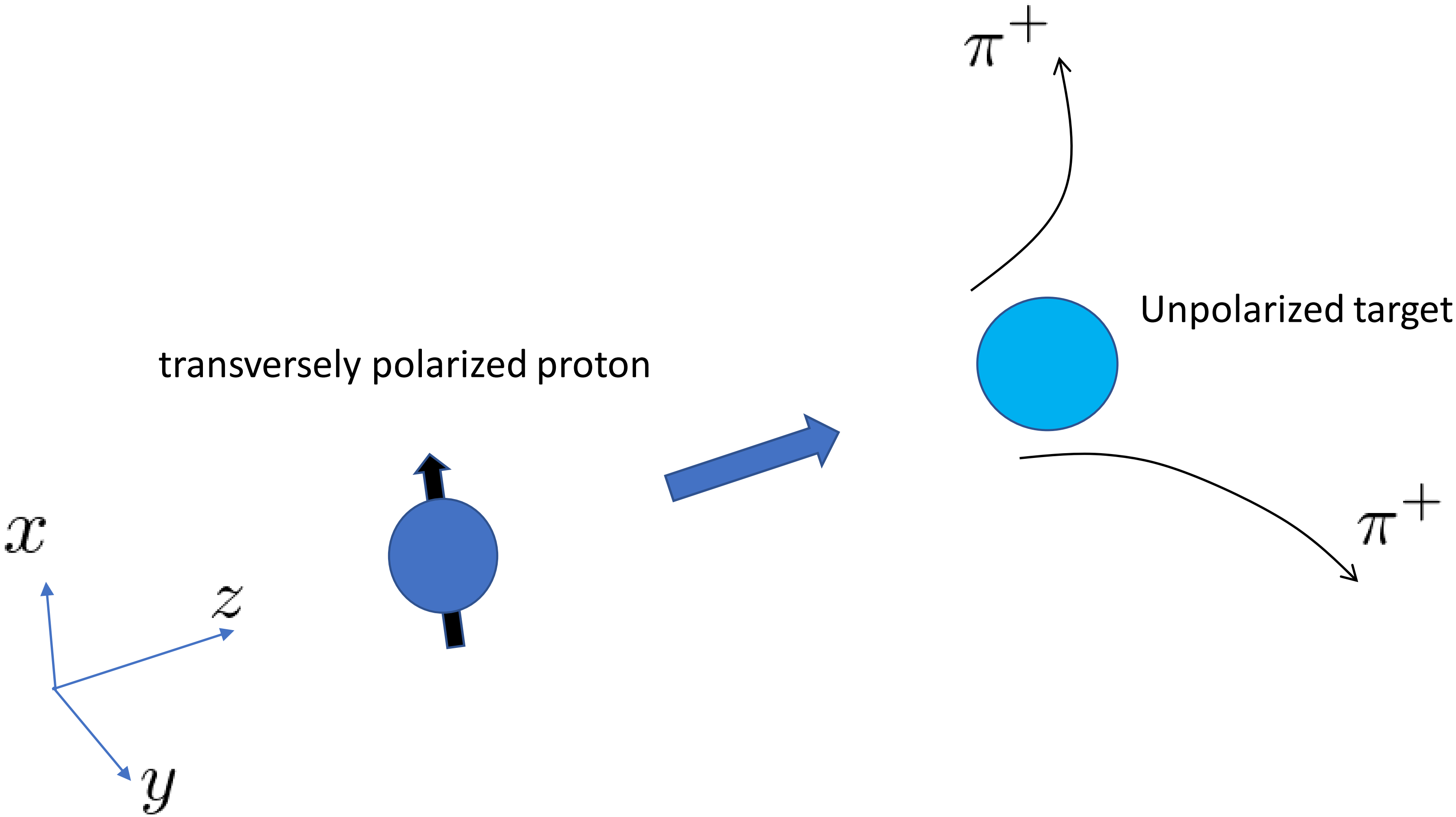
Computing the gluon Sivers function at small-x

Yoshitaka Hatta

(BNL)

Based on Phys. Lett. B790 (2019) 361, with Xiaojun Yao and Yoshikazu Hagiwara

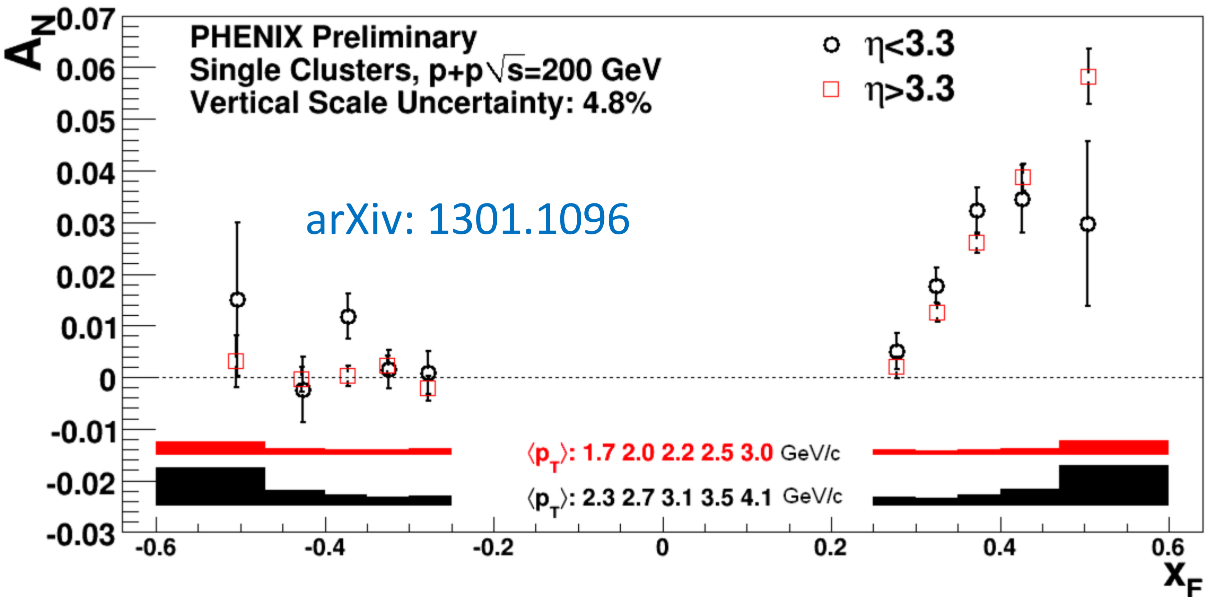
Transverse Single Spin Asymmetry (SSA)



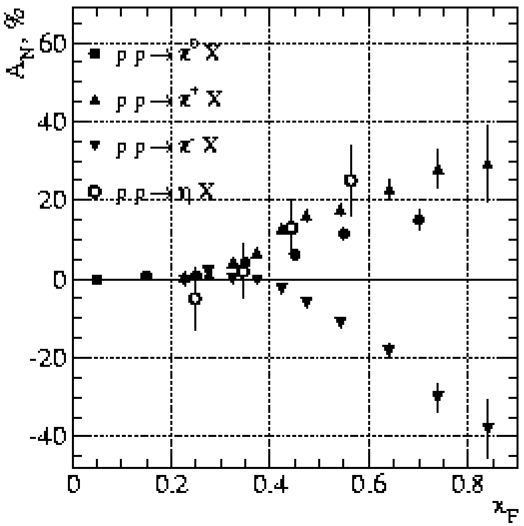
Production of hadrons is left-right asymmetric!

SSA in $p^{\uparrow}p$: experiments

$$A_N = \frac{d\sigma^L - d\sigma^R}{d\sigma^L + d\sigma^R}$$



arXiv: 1301.1096



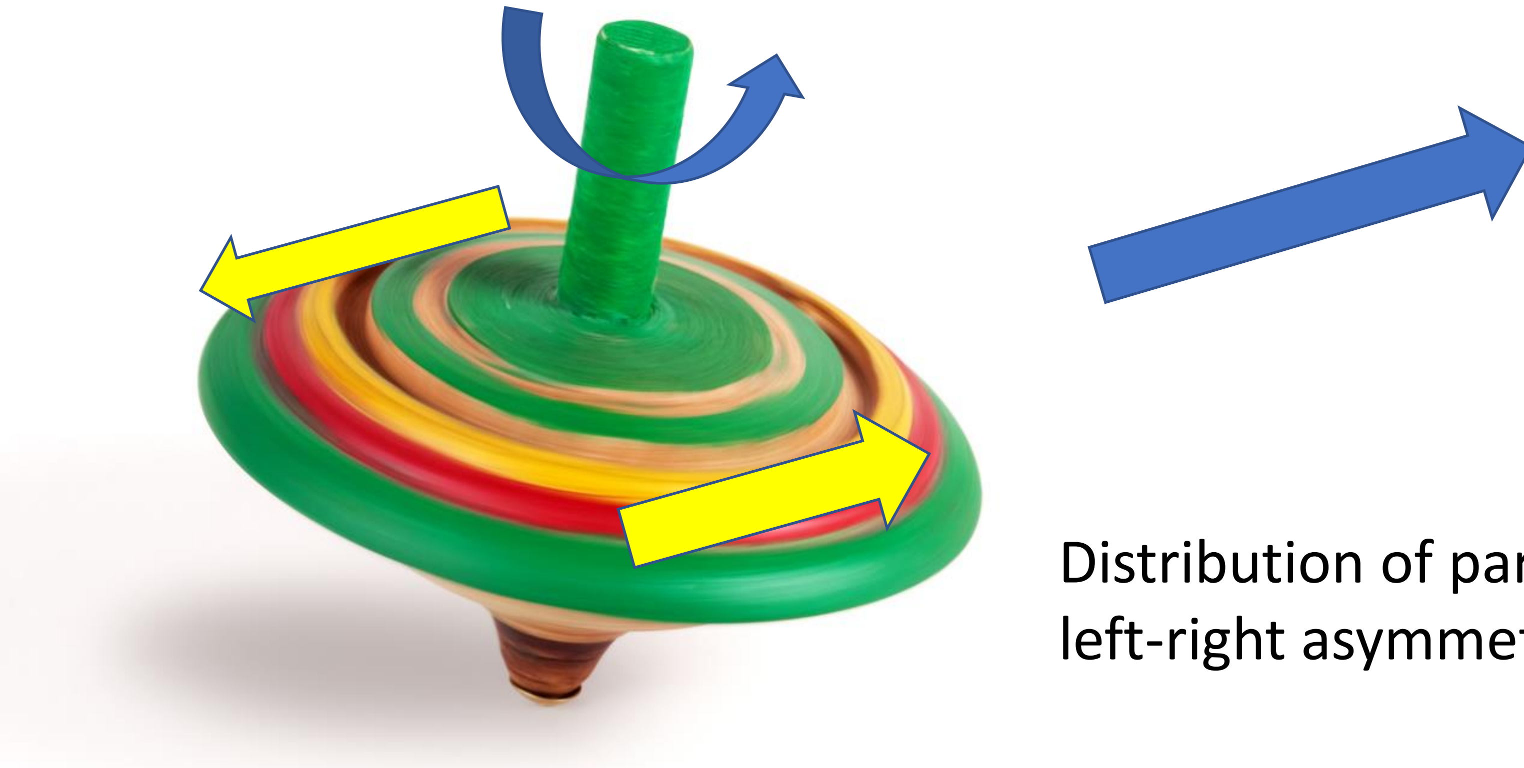
E704 (Fermilab, 1991)

$$x_F = \frac{2p_z}{\sqrt{s}}$$

Enhanced in the forward region $x_F \to 1$

Sivers function

Sivers (1990)



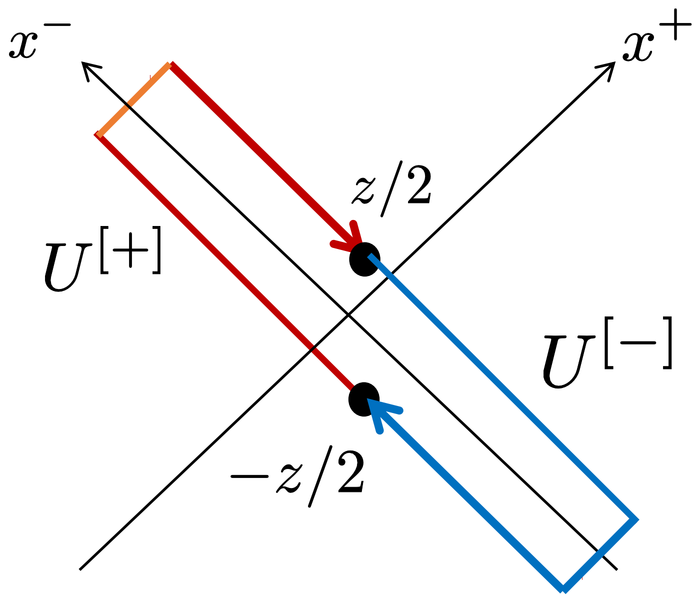
Distribution of partons can be left-right asymmetric

$$f(x,\vec{k}_\perp) = f_1(x,|k_\perp|) + (\vec{k}_\perp \times \vec{S}_\perp)^z f_{1T}^\perp(x,|k_\perp|)$$

One of the possible origins of single spin asymmetry

Universality up to a sign

$$f_{1T}^{\perp}(x, k_\perp) \sim F.T.\langle PS_\perp|\bar{\psi}(z/2)\gamma^+ U^{[\pm]}\psi(-z/2)|PS_\perp\rangle$$



$U^{[+]}$ or $U^{[-]}$,

Sivers function flips signs (Collins 1993)

→Opposite signs when used in SIDIS (initial state interaction) and Drell-Yan (final state interaction)

Gluon Sivers function

There are two ways to make it gauge invariant

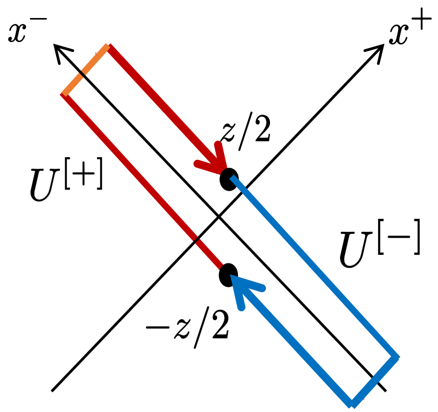
Bomhof, Mulders, Pijlman (2006)
Dominguez, Marquet, Xiao, Yuan (2011)

Weizsacker-Williams distribution

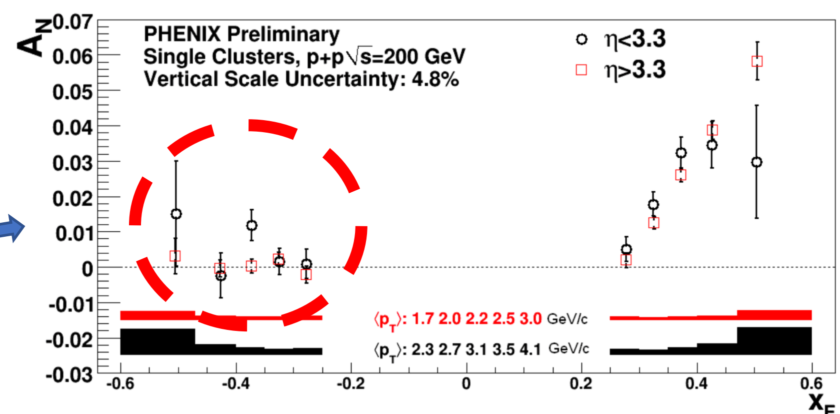
$$\mathrm{Tr}[F(-z/2)U^{[+]}F(z/2)U^{[+]}]$$

Dipole distribution

$$\mathrm{Tr}[F(-z/2)U^{[+]}F(z/2)U^{[-]}]$$



Expected to be dominant in
- SSA of high-mass states
- SSA in the backward region



Proposals to study at EIC, RHIC, AFTER@LHC

e.g., Zheng, Aschenauer, Lee, Xiao, Yin (2018)

Little constraints from theory. Factorization often assumed. $f_{1T}^{\perp}(x, k_\perp) \approx A(x)B(k_\perp)$

Evolution of the Sivers function $f_{1T}^{\perp}(x, k_{\perp})$

Q^2 evolution → usual TMD evolution

Small-x evolution→ ??

$$f(x, \vec{k}_{\perp}) = f_1(x, |k_{\perp}|) + (\vec{k}_{\perp} \times \vec{S}_{\perp})^z f_{1T}^{\perp}(x, |k_{\perp}|)$$

BFKL, BK

??

In general, spin effects are suppressed at small-x.

→ sub-eikonal effects, double logarithmic resummation $(\alpha_s \ln^2 1/x)^n$

→ Talk by Matt Sievert on Friday

Spin-dependent Odderon

Jian Zhou (2013)

BFKL and BK→ Evolution of the dipole S-matrix

$$\langle PS|\mathrm{tr}\, U(r_\perp)U^\dagger(0_\perp)|PS\rangle$$

This cannot depend on spin S^μ if longitudinally polarized (parallel to P^μ)

However, it can depend on S^μ if transversely polarized!

$$\langle PS|\mathrm{tr}\, U(r_\perp)U^\dagger(0_\perp)|PS\rangle = P(r_\perp) + iS_\perp \times r_\perp Q(r_\perp)$$

real
Pomeron

imaginary
Odderon

Dipole gluon Sivers and Odderon

Boer, Echevarria, Mulders, Zhou (2015)

$$f_{1T}^{\perp}(x, k_\perp) \propto \frac{k_\perp^2}{x} \widetilde{Q}(x, k_\perp)$$

Fourier transform of Odderon

Small-x evolution of (dipole) gluon Sivers → evolution of Odderon in QCD

Single logarithmic, well understood in the literature including saturation effects

Bartels (1979); Kwiecinski, Praszalowicz (1980)
Kovchegov, Szymanowski, Wallon (2003)
YH, Iancu, Itakura, McLerran (2004)

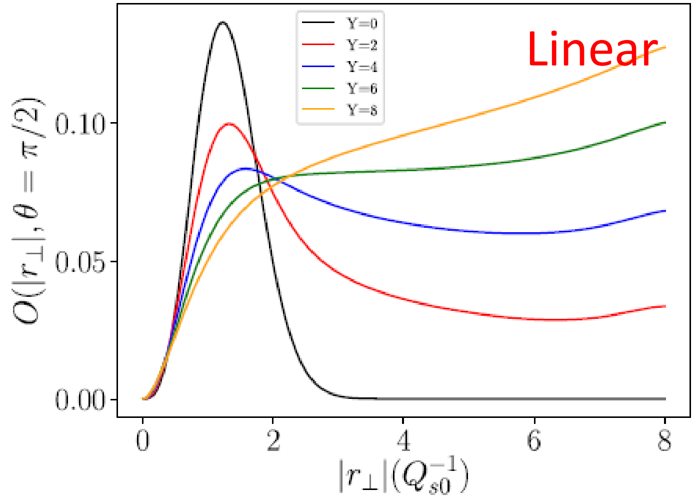
$$\frac{\partial}{\partial Y} O(x_\perp, y_\perp) = \frac{\bar{\alpha}_s}{2\pi} \int d^2 z_\perp \frac{(x_\perp - y_\perp)^2}{(x_\perp - z_\perp)^2 (z_\perp - y_\perp)^2} \Big[O(x_\perp, z_\perp) + O(z_\perp, y_\perp) - O(x_\perp, y_\perp) \\ - O(x_\perp, z_\perp) N(z_\perp, y_\perp) - N(x_\perp, z_\perp) O(z_\perp, y_\perp) \Big] ,$$

Initial condition anti-symmetric $O(x_\perp, y_\perp) = -O(y_\perp, x_\perp)$
Bartels-Vacca-Lipatov solution in the linear regime. Regge intercept exactly unity.

Numerical results (1)

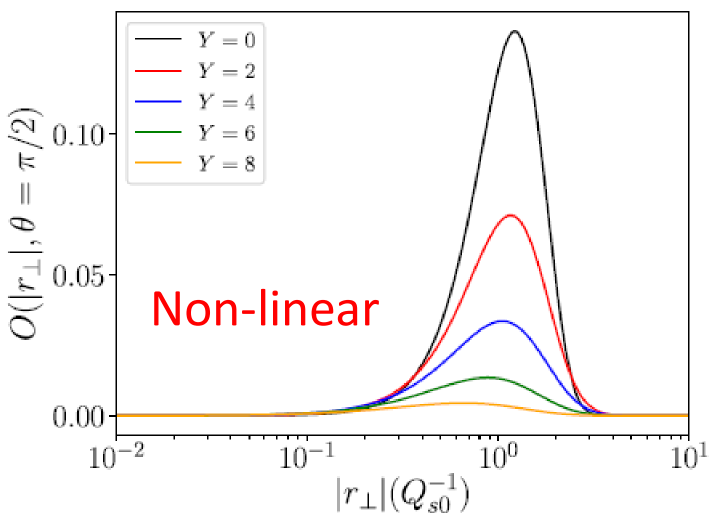
Initial condition

$$O(|r_\perp|,\theta) = \kappa\, Q_{s0}^3 |r_\perp|^3 \sin\theta\, e^{-r_\perp^2 Q_{s0}^2},$$



BLV solution → Odderon amplitude constant?
Strongly dependent on $r_\perp$

Sudakov-like suppression at small-$r_\perp$

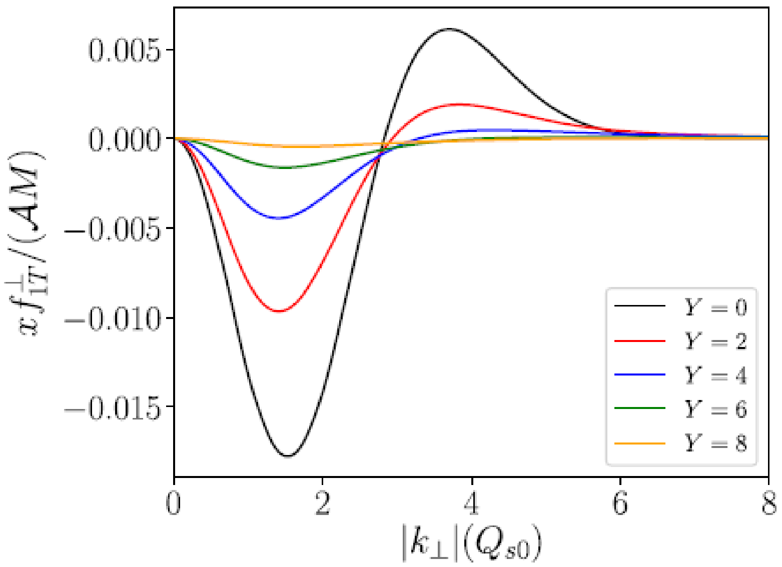


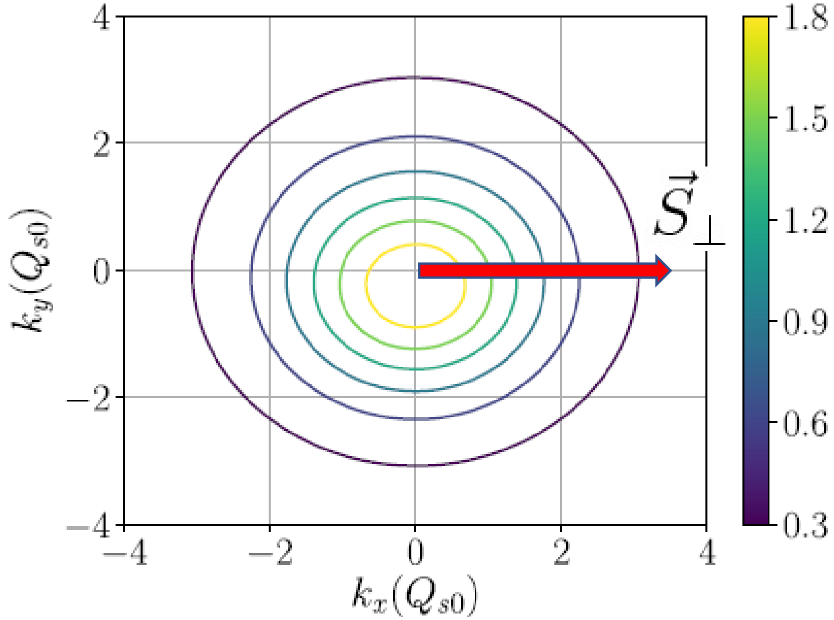
Suppression due to the nonlinear terms

Peak position does not move.
(No geometric scaling)

See, also, Lappi, Ramnath, Rummukainen, Weigert (2016)

Numerical results (2)





Always there is a node in $k_\perp$

Factorization $f_{1T}^{\perp}(x, k_\perp) \approx A(x)B(k_\perp)$ holds approximately, unlike in unpolarized TMDs

(Good news for phenomenology)

SSA in open charm production

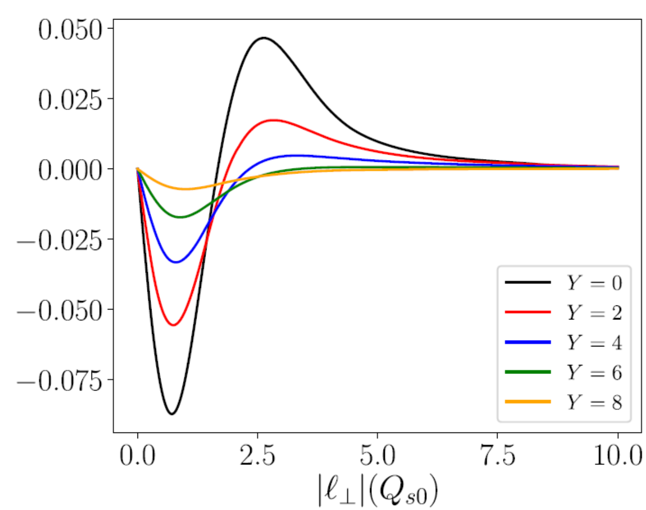
SIDIS $ep^{\uparrow} \to DX$

$$\frac{d\sigma}{dx_B dz dQ^2 dy d^2\ell_\perp} = \frac{\alpha_{\rm em}^2 e_c^2}{2\pi^4 x_B Q^2} \mathcal{A} \int \frac{d^2k_\perp}{(2\pi)^2} H(k_\perp, \ell_\perp, Q^2) \epsilon^{ij} S_{\perp i} k_{\perp j} \widetilde{Q}(|k_\perp|)$$

$$H(k_\perp, \ell_\perp, Q^2) = \left[1 - y + \frac{y^2}{2}\right]\left\{(z^2 + (1-z)^2)\left[\frac{\ell_\perp - k_\perp}{\rho + (\ell_\perp - k_\perp)^2} - \frac{\ell_\perp}{\rho + \ell_\perp^2}\right]^2 + m_c^2\left(\frac{1}{\rho + (\ell_\perp - k_\perp)^2} - \frac{1}{\rho + \ell_\perp^2}\right)^2\right\} + 4(1-y)z^2(1-z)^2 Q^2\left(\frac{1}{\rho + (\ell_\perp - k_\perp)^2} - \frac{1}{\rho + \ell_\perp^2}\right)^2$$

Integral dominated by $k_\perp \sim l_\perp$

Node in $\widetilde{Q}(k_\perp)$ → node in $\frac{d\sigma}{d^2 l_\perp}$



Summary

- Quark Sivers→ most well-studied TMD, rich phenomenology
  Gluon Sivers→ relatively unexplored, interesting at EIC.
- Related to Odderon at small-x, single-logarithmic evolution
- Suppressed at very small-x due to saturation effects
- Factorization of x and $k_\perp$ looks reasonably OK
- SSA of open charm at EIC. Predict a node (nodes) in $P_{h\perp}$

Different signs in SIDIS and Drell-Yan	← initial/final state effects
Different signs for D^0 and $\bar{D}^0$	← C-oddness
Different signs in different $P_{h\perp}$ regions	← Node in $k_\perp$