Transverse Single Spin Asymmetries for Drell-Yan production

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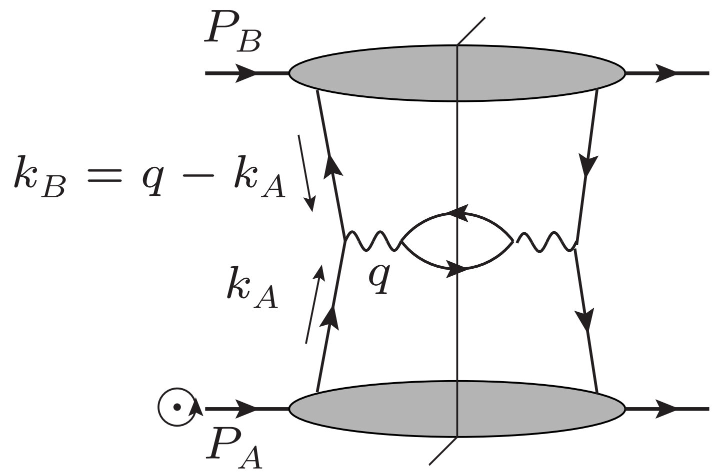
- Theme: Why study SSA for Drell-Yan?
- Theory: New understanding of gluon-induced dynamics in hard scattering.

  Notably: predicted change in sign of Sivers function between SIDIS and DY
- Experiment: Where to look? What does it test?

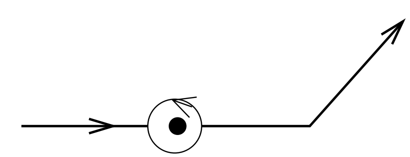
Drell-Yan in parton model (i.e., without QCD complications)



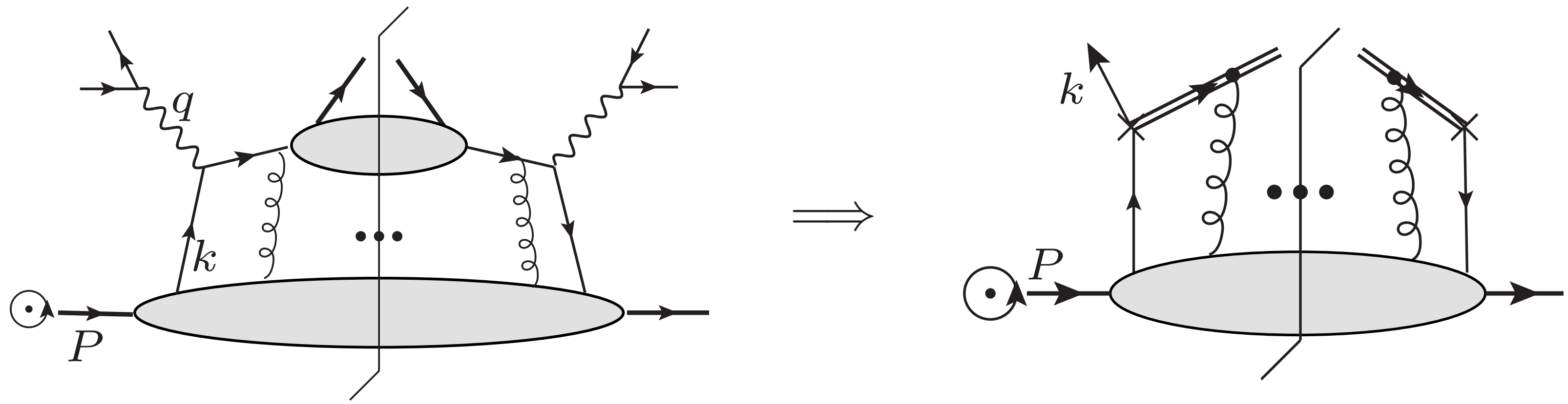
$$\frac{\mathrm{d}\sigma}{\mathrm{d}^4 q\, \mathrm{d}\Omega} \stackrel{?}{=} \sum_j \int \mathrm{d}^2 \boldsymbol{k}_{A\,\mathsf{T}}\ f_{j/h_A}(x_A, \boldsymbol{k}_{A\,\mathsf{T}})\ f_{\bar{j}/h_B}(x_B, \boldsymbol{q}_{\mathsf{T}} - \boldsymbol{k}_{A\,\mathsf{T}})\ \frac{\mathrm{d}\hat{\sigma}_{j\bar{j}}}{\mathrm{d}\Omega}$$

- $f(x, \boldsymbol{k}_{\mathsf{T}})$ is said to be "number density of partons"
- Sivers function is its (transverse) SSA:

$$f(x, \boldsymbol{k}_{\mathsf{T}}) = f_{\text{unpol.}}(x, k_{\mathsf{T}}) + \text{norm.} \sin(\phi_k - \phi_s)) f_{\text{Sivers}}(x, k_{\mathsf{T}})$$

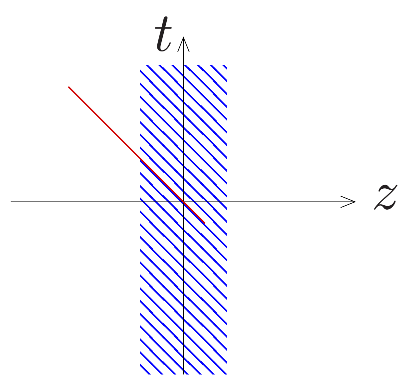
Positive Sivers function $\Longrightarrow$ preferred $\boldsymbol{k}_{\mathsf{T}}$ is 

Wilson line in QCD pdf is target's view of struck quark

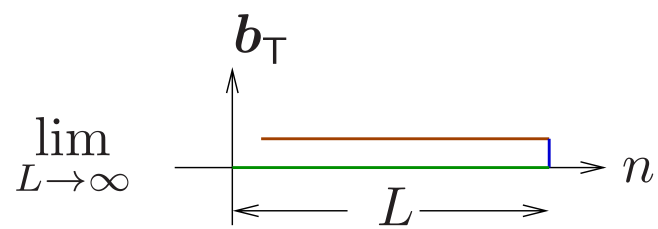


Coordinate space:

Target rest frame

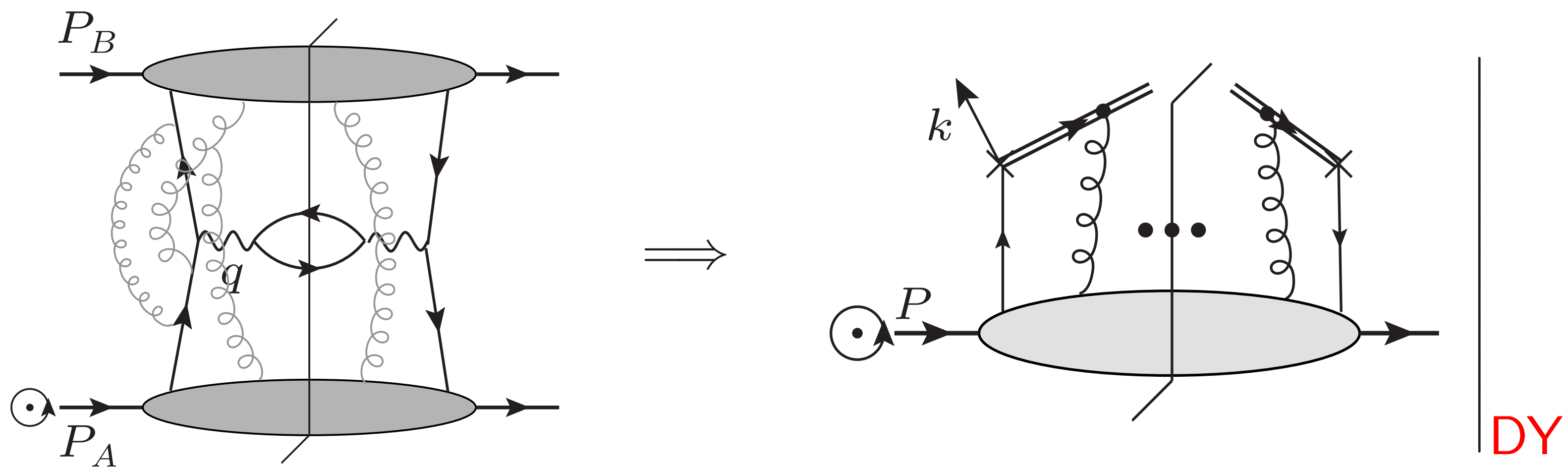


side view

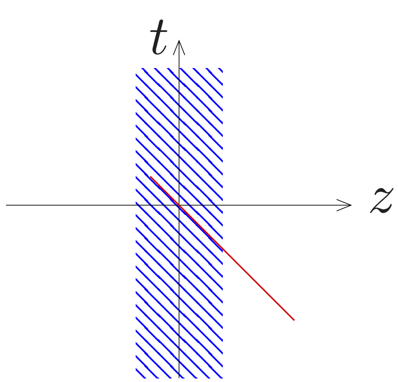


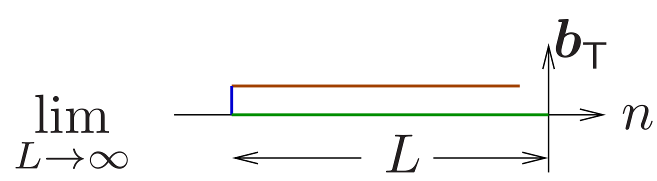
N.B. SSA and interference: Burkhardt's talk

Drell-Yan has different pdfs



with past-pointing WLs:





(Need cancellation of f.s.i.; *inclusive* Drell-Yan only.)
(Proof of TMD factorization — JCC's "Foundations of perturbative QCD".)

Experimentally accessible consequence of WL: Sign change of Sivers function

Relate pdfs in SIDIS and DY by TP transformation

Changes:

- Wilson lines:

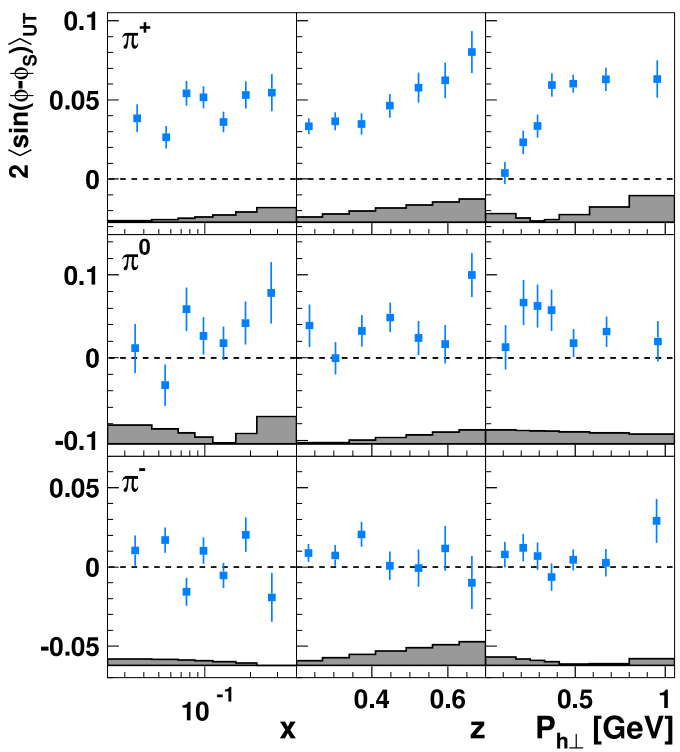
$$\text{Future-pointing for SIDIS pdfs} \quad \stackrel{TP}{\Longleftrightarrow} \quad \text{past-pointing for DY pdfs}$$

- States:

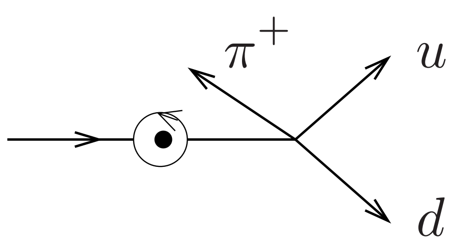
$$|\mathbf{P}, \boldsymbol{s}_\mathsf{T}\rangle \quad \stackrel{P}{\Longleftrightarrow} \quad |-\mathbf{P}, \boldsymbol{s}_\mathsf{T}\rangle \quad \stackrel{T}{\Longleftrightarrow} \quad |\mathbf{P}, -\boldsymbol{s}_\mathsf{T}\rangle$$

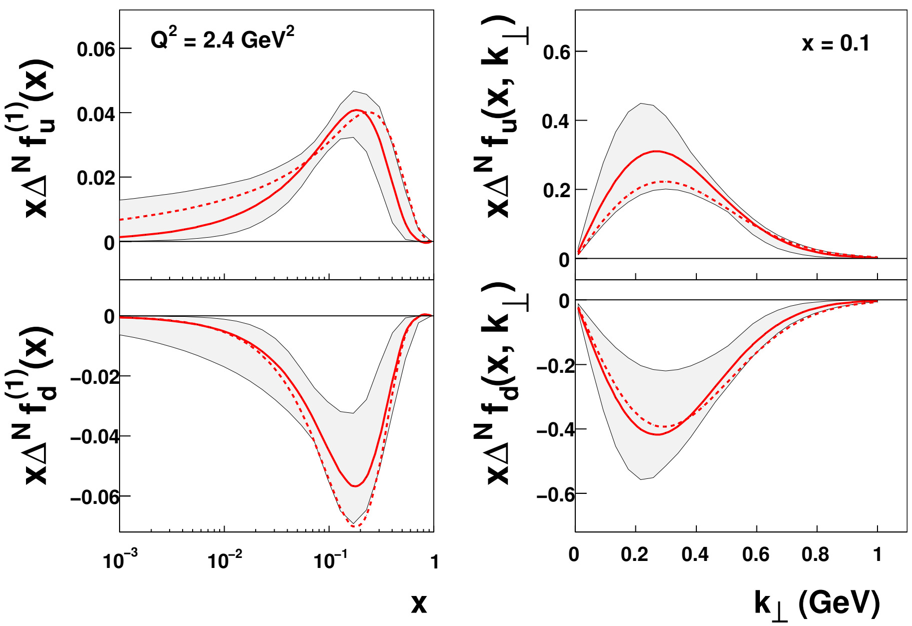
- Hence for pdfs:
  - normal $\text{pdf}_{\mathrm{DY}} =$ normal $\text{pdf}_{\mathrm{DIS}}$
  - But $\text{Sivers}_{\mathrm{DY}} = -\text{Sivers}_{\mathrm{DIS}}$

Extract Sivers function from SIDIS



(HERMES, Phys. Rev. Lett. 103 (2009) 152002)





(Anselmino et al., Eur. Phys. J. A39 (2009) 89)

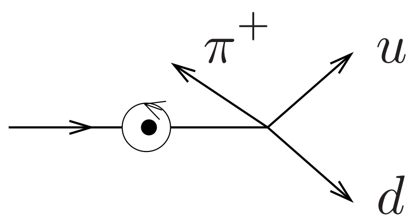
Data range:

$0.05 \lesssim x \lesssim 0.3,\ p_T \lesssim 1\,\mathrm{GeV}$

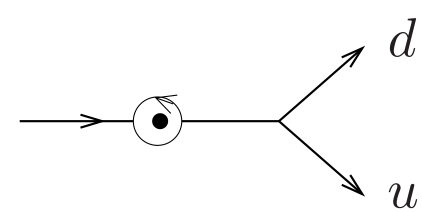
Prediction for DY

To have a prediction, $x_{\text{in polarized proton}}$ *must be in Hermes region*

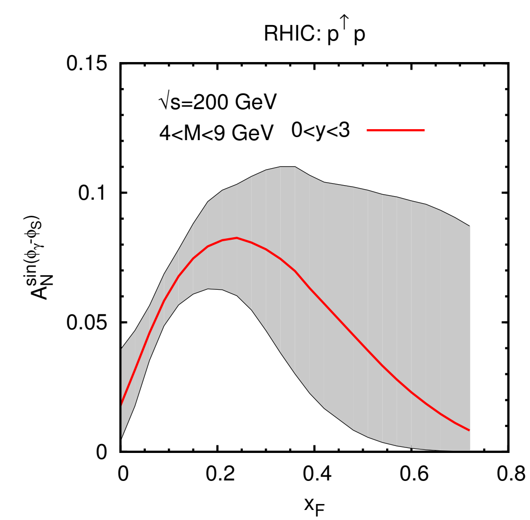
SIDIS



DY



Prediction *w/o (CSS) evolution for TMDs*



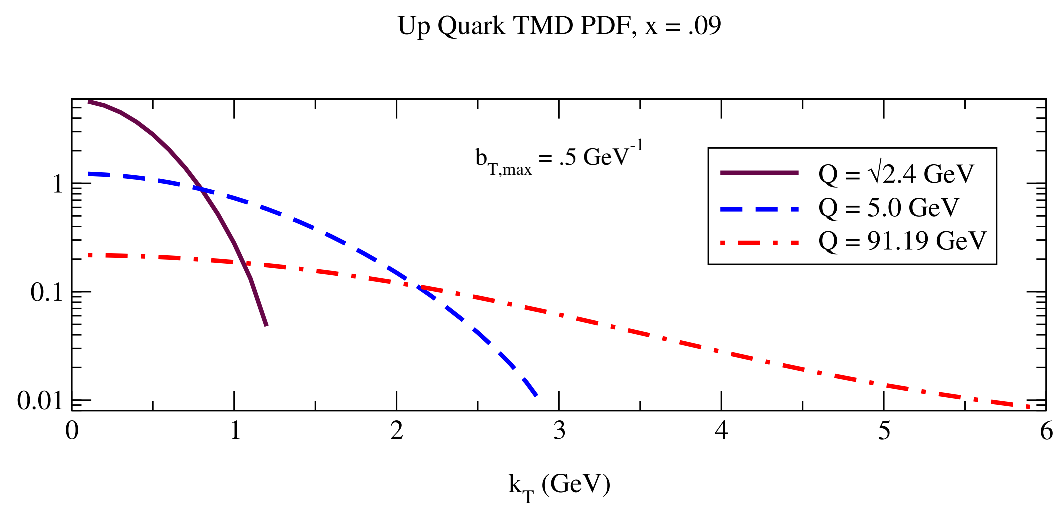
(Anselmino et al. Phys.Rev. D79 (2009) 054010)

For $\mathrm{d}\sigma \,/\, \mathrm{d}q\,\mathrm{d}\Omega$: distribution $\propto \sin(\phi_q - \phi_s)(1 + \cos^2\theta)$ + Boer-Mulders term

QCD issues

- Drell-Yan is clean, theoretically. (Cw. $p^{\uparrow}p \to \pi X$)
- Full TMD factorization proof now exists. (Issue of direction of Wilson line is recent.)

$\Longrightarrow$ *Evolution*, e.g., à la CSS. Cf. unpolarized case:



$f_{u/p}(x = 0.09, \boldsymbol{k}_{\mathrm{T}})$ (GeV^{-2}), from Aybat & Rogers arXiv:1101.5057 & Rogers talk here

N.B. Perturbative & non-perturbative evolution kernels already known

What if experiment disagrees?

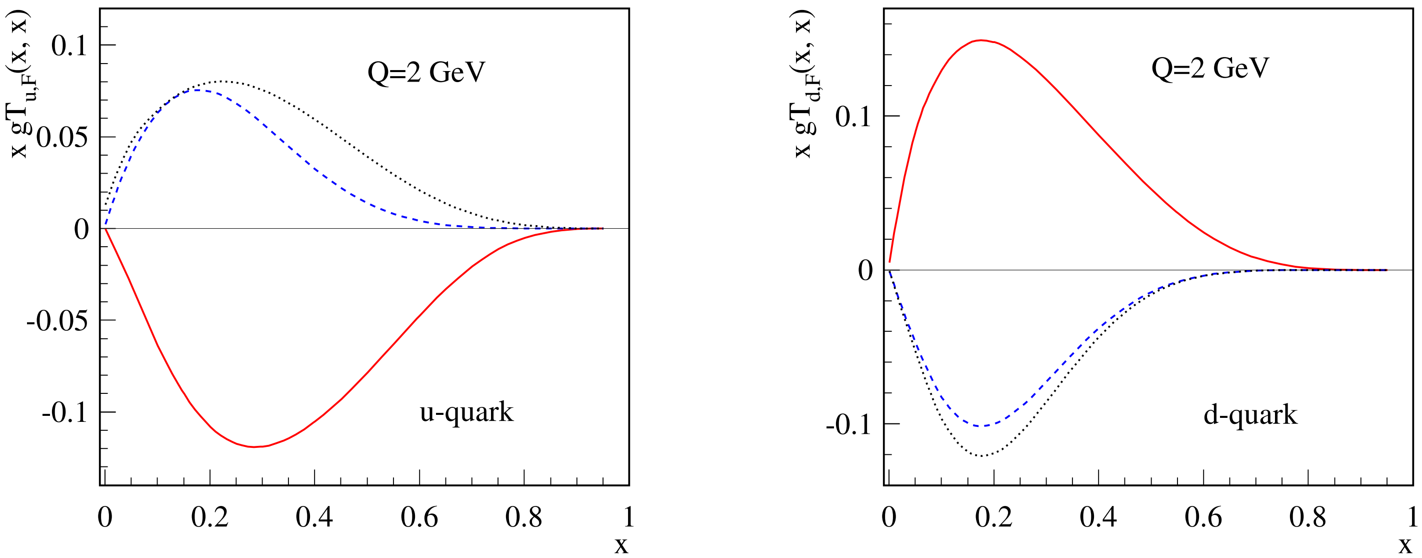
Solid QCD theory (I think).

But . . .

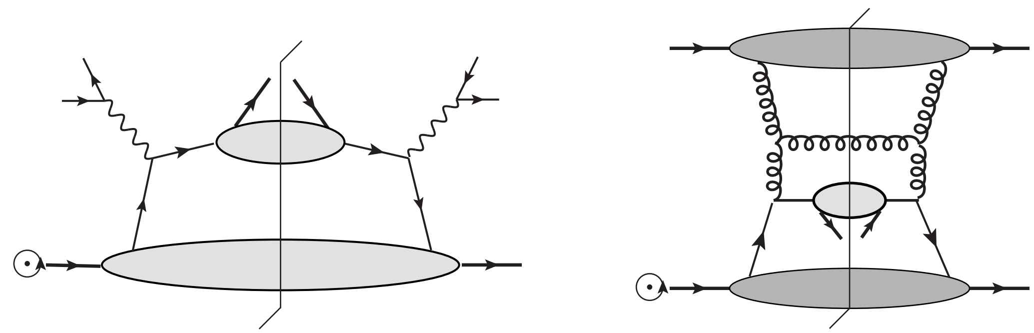
SSA in SIDIS v. $p^{\uparrow}p \to \pi X$ has ***wrong*** sign

Kang, Qiu, Vogelsang, and Yuan, arXiv:1103.1591):

Twist-3 correlation function from: SIDIS (blue) v. $p^{\uparrow}p \to \pi X$ (red/solid)

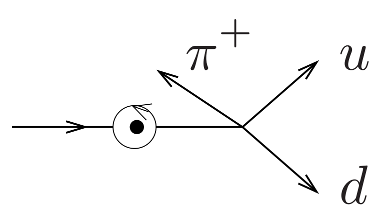
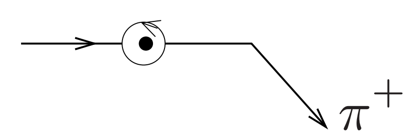
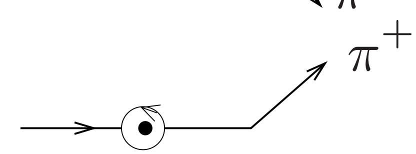


SSA in SIDIS v. $p^\uparrow p \to \pi X$ has *wrong* sign



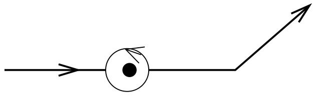
- SIDIS data + TMD factorization $\Longrightarrow$ Sivers function $\Longrightarrow$ Twist-3 function
- Predict SSA of $p^\uparrow p \to \pi X$ using Qiu-Sterman factorization,

  with initial-state imag. part with gluon dominating final-state term
- Preferred configurations

SIDIS	$p^\uparrow p \to \pi X$
	$\Longrightarrow$ Predicted: 
	Reality: 

What if experiment disagrees for Drell-Yan?

- Usual mundane possibilities to rule out:
  - Experiment wrong
  - Theory calculations wrong
- Check signs carefully:

  Define sign convention for positive SSA graphically: 
- Don't forget to include CSS evolution
- Cross check theorems in model calculations
- Check factorization derivations critically
- Is Q large enough?
  - Scaling test in experiment: Increase s and Q keeping x_A and x_B fixed
- Is Sivers function used where determined by SIDIS?
- If all checks passed: Crisis for QCD hard scattering

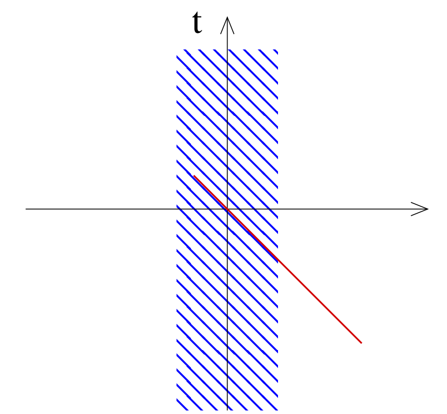
Reliability of theoretical framework

QCD

Kinematic approximations

Disentangle gluons into Wilson lines

Cancellation of spectator interactions



factorization

TMD, incl. Sivers

Cancellation of soft ints.

Collinear factorization

Any problems with Sivers function impact issues critical to all kinds of factorization.

(Unpolarized) factorization survived many tests, so probability of failure is low.

Wilson lines encode space-time locations of color flow relative to hard scattering.

Reliability of predictions

- Classic example of predictive power of QCD:
  - Measure non-perturbative functions from one set of data
  - Add in perturbative calculations, etc.
  - Predict other data

- SSA for Drell-Yan particularly needs:

Sivers for valence $u/p^{\uparrow}$	from SIDIS
Unpolarized TMD for valence u/p	from SIDIS and DY fits
Unpolarized TMD for sea $\bar{u}/p$	from DY fits
Non-pert. unpolarized CSS kernel $K(k_{\mathsf{T}})$	from DY fits
Perturbative functions	from QCD calculations

- For non-perturbative functions: range of use should correspond to range of measurement

Conclusions

- Sivers function gives stress test of our understanding of QCD parton dynamics in hard scattering, especially of space-time locations of color flows

  (Key issues were hidden until recently!)

- SSA in Drell-Yan is clean test case with predictions deduced from SIDIS data and unpolarized Drell-Yan

  But remember CSS evolution (or equivalent) in making predictions.

- Disquieting data for $p^{\uparrow}p \to \pi X$

- But than $p^{\uparrow}p \to \pi X$ is harder for theory than Drell-Yan