T-odd effects in QCD and beyond
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Author:
Dylan Manna, University of Michigan

Co-authors:
Andrea Signori, University of Pavia &
Christine Aidala, University of Michigan

The key take-away messages of this Presentation are:

- The generality of T-odd Transverse Momentum Dependent (TMD) Parton Distribution Functions (PDF's) and the associated T-odd function sign change in any quantum gauge theory.

- The possibility of finding analogs of T-odd sign changes outside of QCD, i.e., in QED.

To find such an analog, it is useful to understand the history of the problem.

A brief history of T-odd functions in TMD PDF's

1990 Sivers introduced a T-odd function through a triple product

$$\Delta^N G_{a/p\uparrow}(x_a, k_T; \mu^2) \neq 0$$

Phys. Rev. D 41, 83 (1990)

1993 Collins argued any T-odd function must have zero value based on a PT symmetry

$$\hat{f}_{a/A}(x, k_\perp; \alpha, \alpha') = 0$$

Nuclear Physics B 396, 161–182 (1993)

2002 Brodsky, Hwang, Schmidt introduced a T-odd function based a model of QCD which respects Time reversal symmetry

$$\psi_{n/p}(x_i, \vec{k}_{\perp i}, \lambda_i) \neq 0$$

Physics Letters B 530, 99–107 (2002)

2002 Collins shows T-odd TMD's can be non-zero by adding Wilson lines to his earlier symmetry argument

$$f_{1T}^{\perp}(x, k_T, \xi) \neq 0$$

Physics Letters B 536, 43–48 (2002)

Phenomenological Approach to T-odd Functions: Sivers 1990

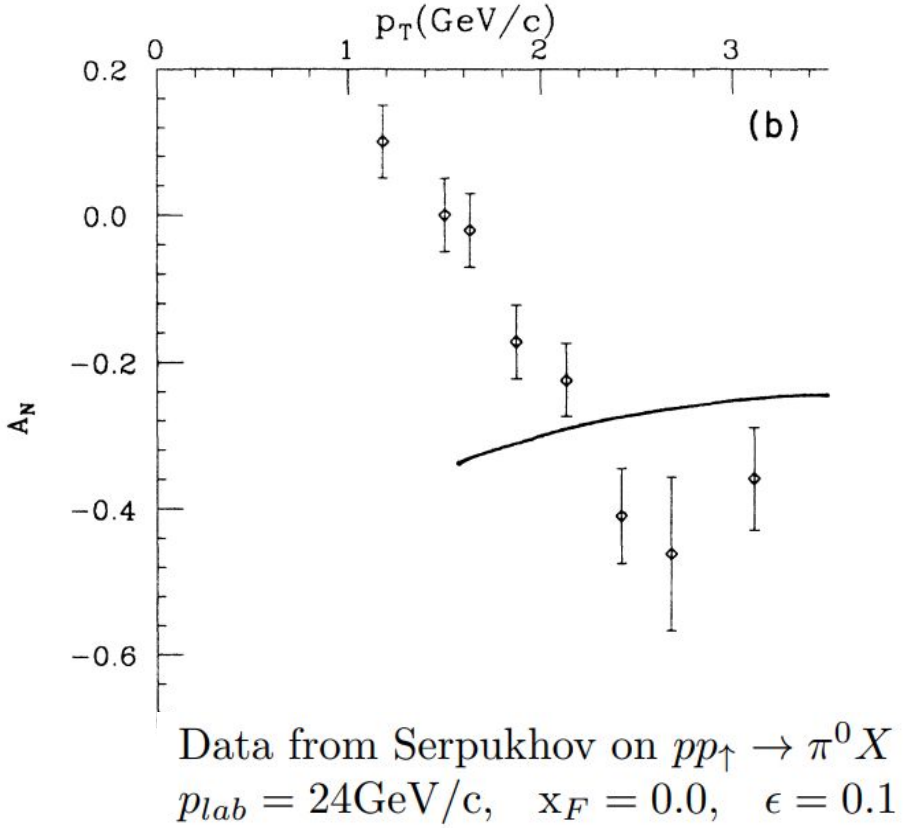
$$A_N d\sigma(pp_\uparrow \longrightarrow \pi X)$$

Perturbative effects are too small to describe the measured data

A new non-perturbative effect is described by the Sivers T-odd TMD PDF

$$\Delta^N G_{a/p_\uparrow}(x_a, k_T; \mu^2)$$

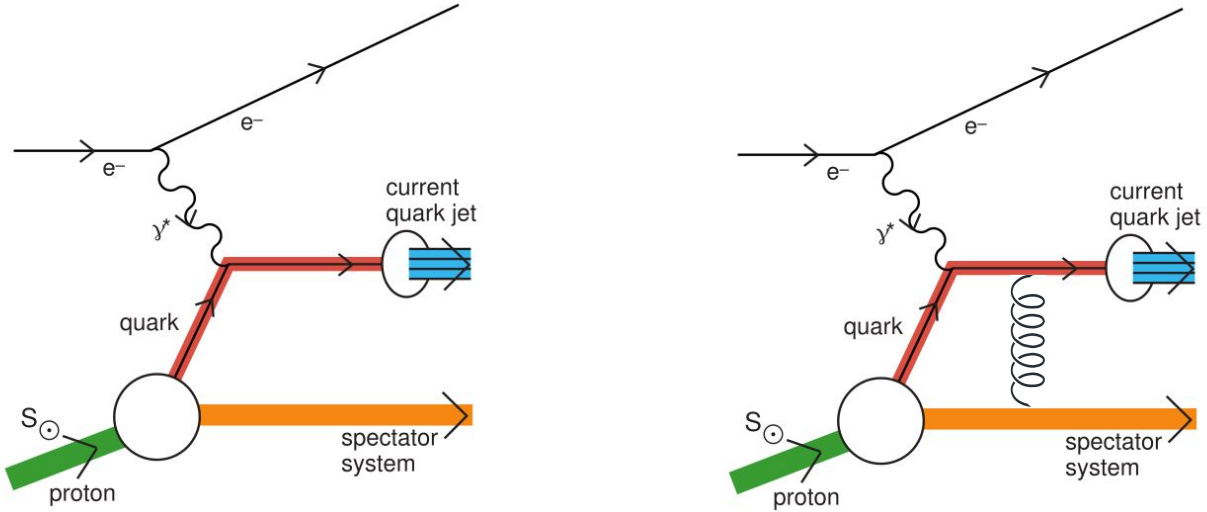
D. Sivers, Phys. Rev. D 41, 83 (1990)



Protvino Inst. High Energy Phys., Serpukhov, 1987

Phenomenological Approach to T-odd Functions

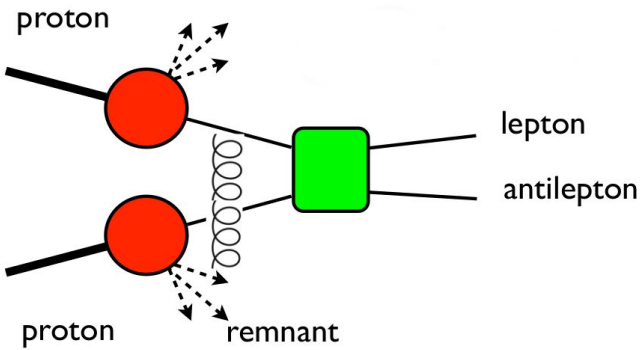
Brodsky, Hwang, Schmidt 2002

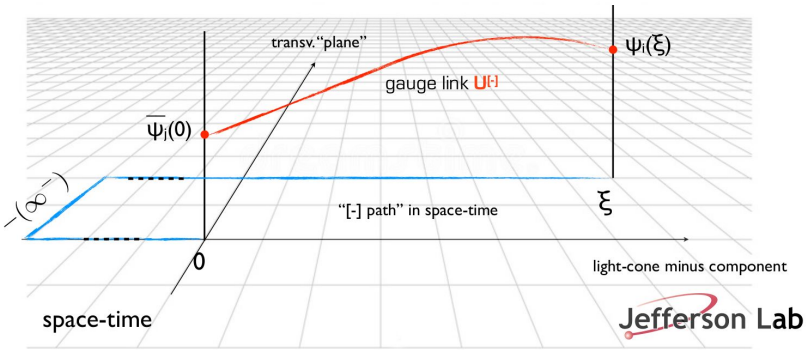


Physics Letters B 530, 99–107 (2002)

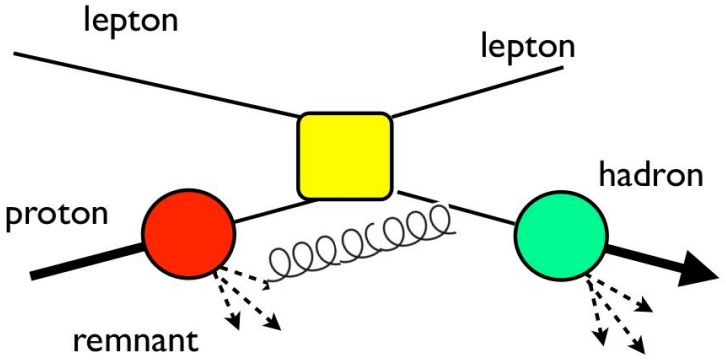
SIDIS without and with gluon exchange between outgoing quark and remnant leading to interference terms and a non-zero single spin asymmetry

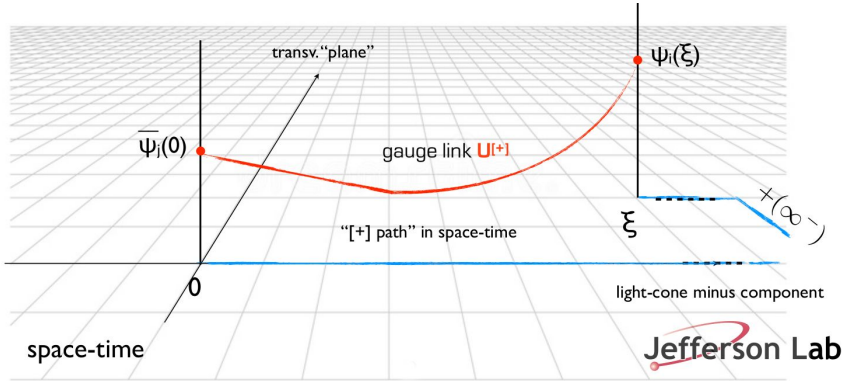
Drell-Yan





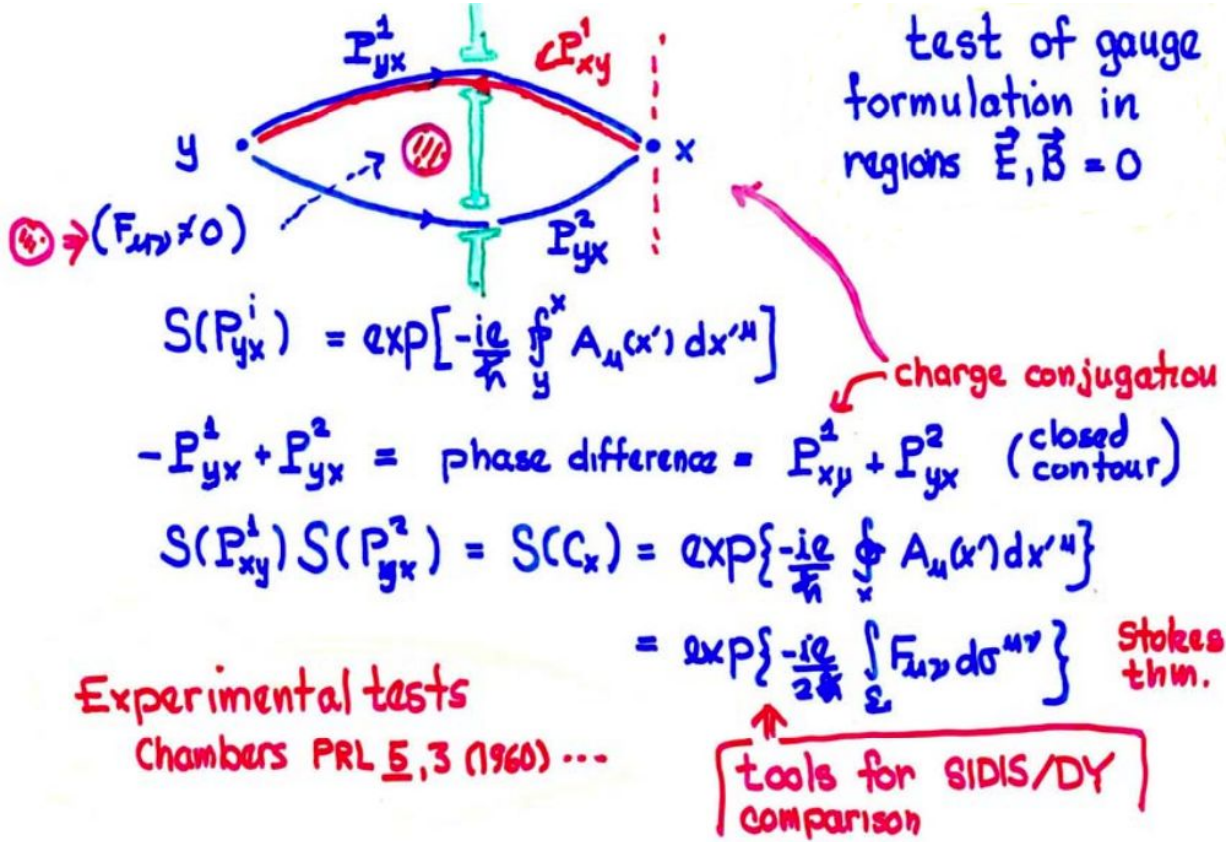
SIDIS





A. Signori, TMD physics between RHIC and JLab, RHIC & AGS users' group meeting 2018

QED generalization: Aharanov-Bohm and Wilson Loops



D. Sivers, arXiv:1109.2521 [hep-ph]

The Aharanov-Bohm effect and Wilson loops both give rise to interference terms in the phase of the wave functions.

Both QED and QCD are gauge theories that admit single spin asymmetries due to interference between amplitudes with and without photons and gluons respectively.

Such a single spin asymmetry in QED should be calculable and observable.

Summary

- the history of single spin asymmetries in T-odd functions
- two approaches: phenomenological and symmetry based
- generality in gauge invariant QFT’s
- testing the prediction in QCD processes is a formal U.S. Nuclear Science Advisory Committee milestone
- necessary ingredients in any QFT process for T-odd sign change
- utilizing parallel phenomenology in QED
- searching for analogs of T-odd sign change in atomic physics