Towards improved hadron femtography with hard exclusive reactions

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The key take-away messages of this Presentation

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

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

To find such an analog, it is helpful 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 of a spin and two momenta

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

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 on 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

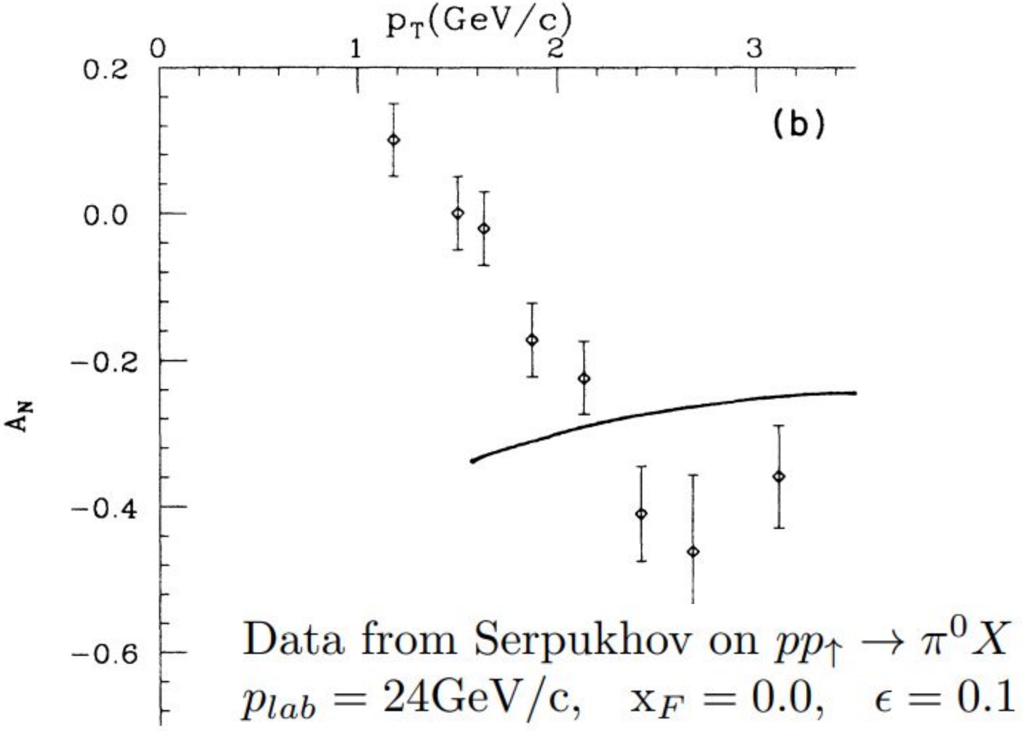
$$A_N d\sigma(pp_\uparrow \longrightarrow \pi X)$$

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

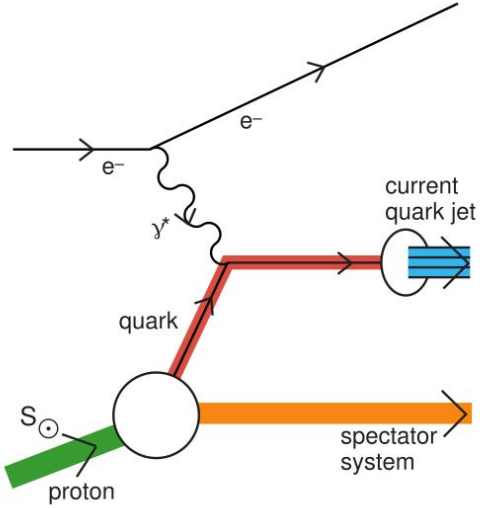
Refutation of the possibility of a T-odd function: Collins 1993

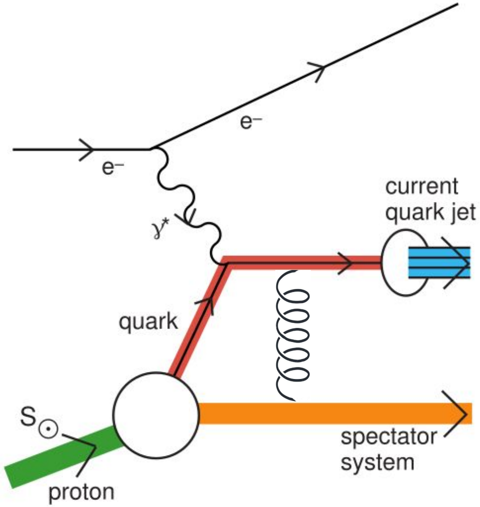
$$\hat{f}_{a/A}(x, k_\perp; LR)$$
$$= -\int \frac{dy^- d^2y_\perp}{(2\pi)^3} e^{-ixp^+y^- + ik_\perp \cdot y_\perp} \langle p, R| \mathcal{T}^\dagger \bar{\psi}_a(0, y^-, y_\perp) \mathcal{T} \frac{\gamma^+}{2} \mathcal{T}^\dagger \psi_a(0) \mathcal{T} |p, L\rangle^*$$
$$= -\int \frac{dy^- d^2y_\perp}{(2\pi)^3} e^{-ixp^+y^- + ik_\perp \cdot y_\perp} \langle p, R| \bar{\psi}_a(0, -y^-, -y_\perp) PT \frac{\gamma^+}{2} PT \psi_a(0) |p, L\rangle^*$$
$$= -\hat{f}_{a/A}(x, k_\perp; LR) \qquad \therefore \qquad = 0$$

"there is no dependence of the transverse momentum distribution on the spin of the incoming hadron. This contradicts Sivers's suggestion."

J. Collins, Nuclear Physics B, Volume 396, Issue 1, 10 May 1993

Phenomenological Approach to T-odd Functions: Brodsky, Hwang, Schmidt 2002





SIDIS (**S**emi-**I**nclusive **D**eep **I**nelastic **S**cattering) without and with gluon exchange between outgoing quark and remnant leading to interference terms and a non-zero single spin asymmetry.

Physics Letters B 530, 99 – 107 (2002)

Wilson lines introduced to symmetry calculation
Retraction of refutation by Collins, 2002

J. Collins, Physics Letters B 536 (2002)

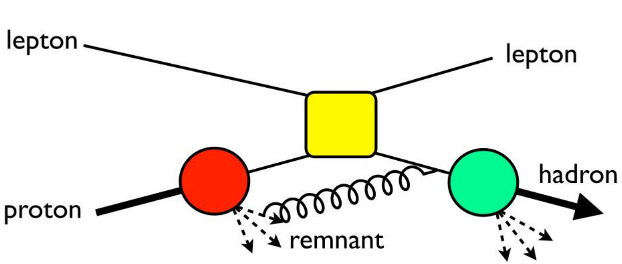
"Under time-reversal the future-pointing Wilson lines are replaced by past-pointing Wilson lines, so that the correct version of the proof gives…"

$$\int \frac{dy^- d^2 y_T}{(2\pi)^3} e^{-ixp^+y^- + ik_T \cdot y_T} \langle p|\overline{\psi}(0, y^-, y_T) W^\dagger_{y\infty} \frac{\gamma^+}{2} W_{0\infty} \psi(0)|p\rangle$$

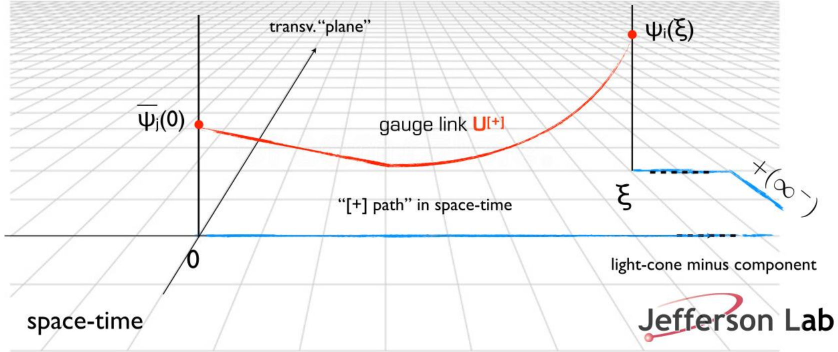
"Since, as we will see, the past-pointing Wilson lines are appropriate for factorization in the Drell–Yan process, the correct result is not that the Sivers asymmetry vanishes, but that it has opposite signs in DIS and in Drell–Yan…"

$$f_{1T}^{\perp}(x, k_T, \zeta)|_{\mathrm{DIS}} = -f_{1T}^{\perp}(x, k_T, \zeta)|_{\mathrm{DY}}$$

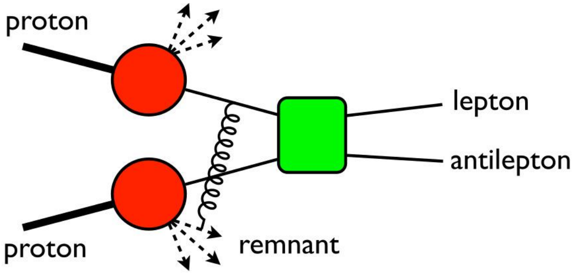
SIDIS



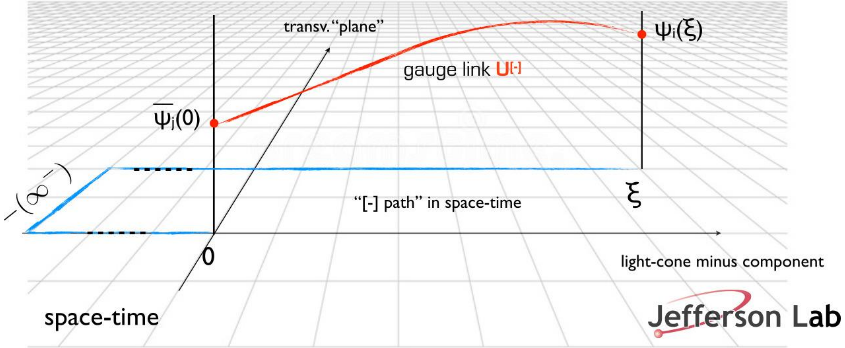
$$\Phi(k,P) = \mathrm{F.T.}\langle P|\overline{\psi_j}(0)\ U^{[+]}(0,\xi)\ \psi_i(\xi)|P\rangle$$



Drell-Yan



$$\Phi(k,P) = \mathrm{F.T.}\langle P|\overline{\psi_j}(0)\ U^{[-]}(0,\xi)\ \psi_i(\xi)|P\rangle$$



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

Ingredients for a single-spin asymmetry generated by a bound state T-odd spin-momentum correlation

- A scattering process of a bound state in a gauge theory.
- The bound state must include spin such that one can measure the triple product of a spin with the momentum of the target and the momentum of a constituent.

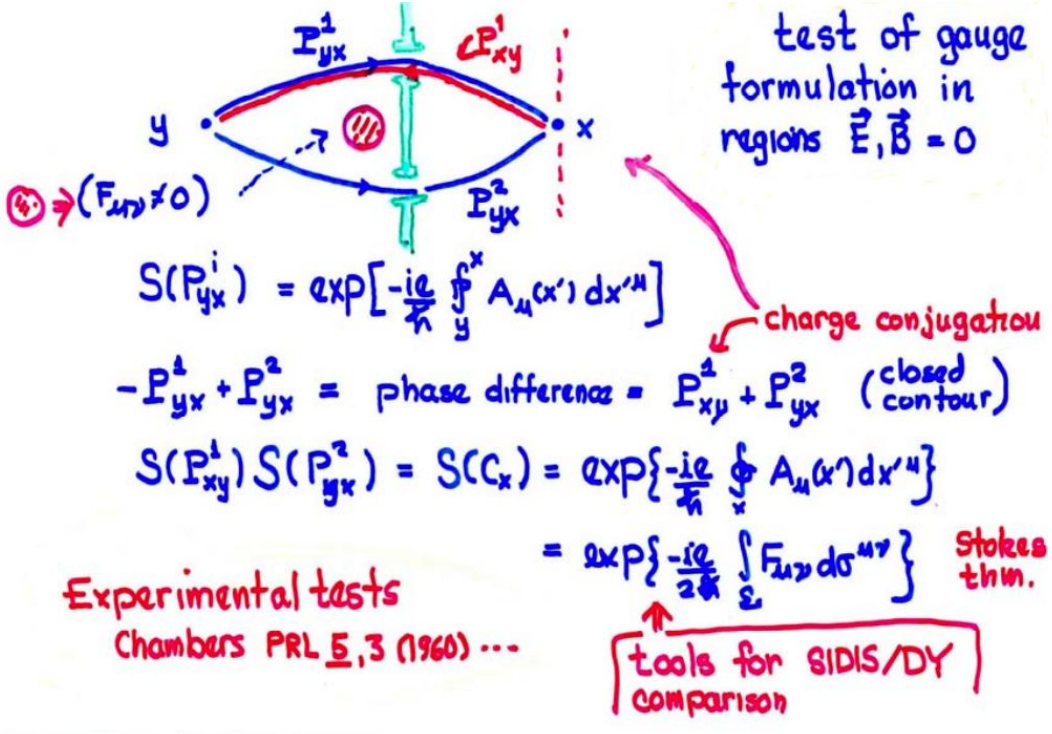
$$i\vec{S}_{\text{target}} \cdot \vec{P}_{\text{target}} \times \vec{P}_{\text{constituent}}$$

- The observable must be sensitive to a component of the constituent momentum that's not collinear with the target momentum
In QCD, this will involve a TMD (Transverse Momentum Dependent) PDF (Parton Distribution Function)

Aspects of single-spin asymmetries generated by a bound state T-odd spin-momentum correlation

- They arise from the **interference** of final-state QCD Coulomb **phases in S and P waves**
- They arise from **interference between states** with an **exchange of a gauge boson and those without an exchange**
- There is a **crossing in the partonic legs** of the Feynman diagram between Final State Interaction and Initial State Interaction rescattering of photons or gluons
- **They infer a process-dependent sign change** as they are T-odd (not so of double spin asymmetries)

QFT generalization: Aharonov-Bohm and Wilson Lines



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

The Aharonov-Bohm effect and Wilson lines 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.

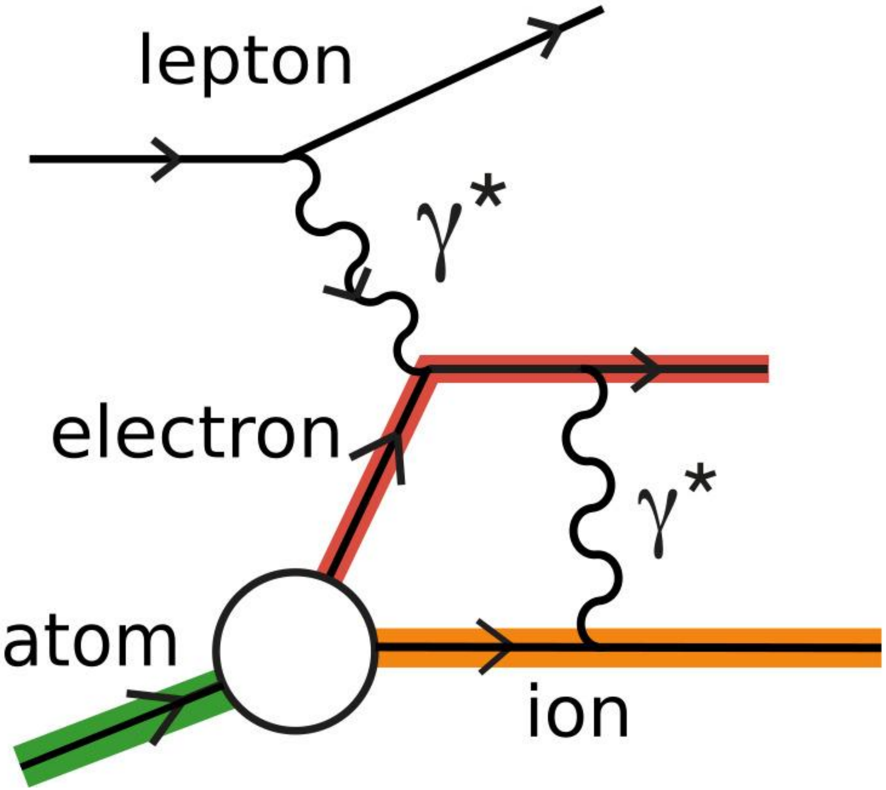
Such a single spin asymmetry in QED should be calculable and observable.

Finding a T-odd function sign change analog in QED

- We need a QED SIDIS analog where we have replaced the proton with another bound state
- We need a QED Drell-Yan analog, replacing the proton with another bound state
- The initial state interaction is between the remnant and incoming lepton
- The final state interaction is between the remnant and outgoing electron

The calculation of such a system is likely to involve semi-classical techniques from atomic theory which merge the phenomenological framework with the symmetry based framework.

A atomic analog of SIDIS

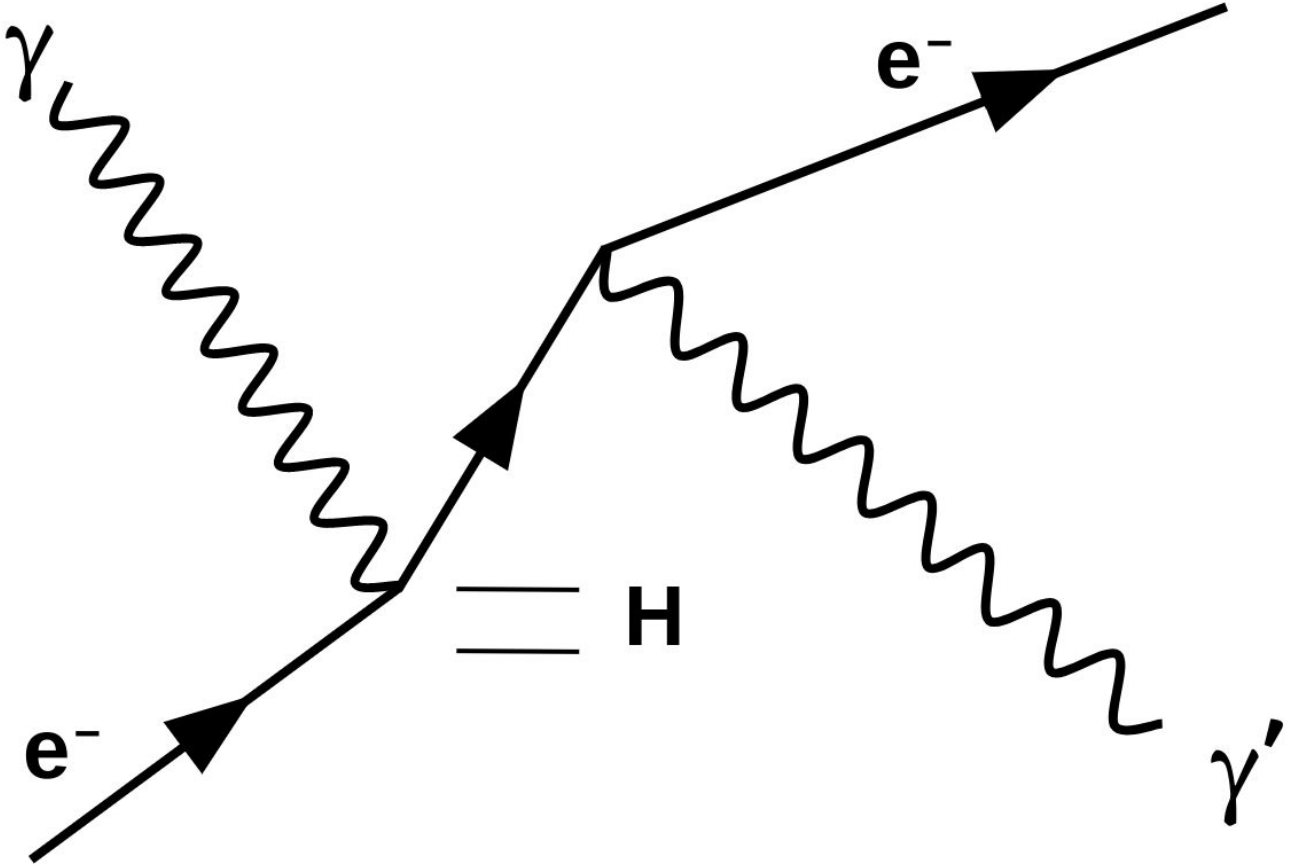


Here, we look at a possible QED SIDIS analog where we have replaced the proton with an atom.

The final state interaction is between the positive ion and outgoing electron.

Notice, like SIDIS, the gauge interaction is between opposite-sign charges.

Hydrogen as the bound state



Here, we have the simplest of bound atomic states, Hydrogen.

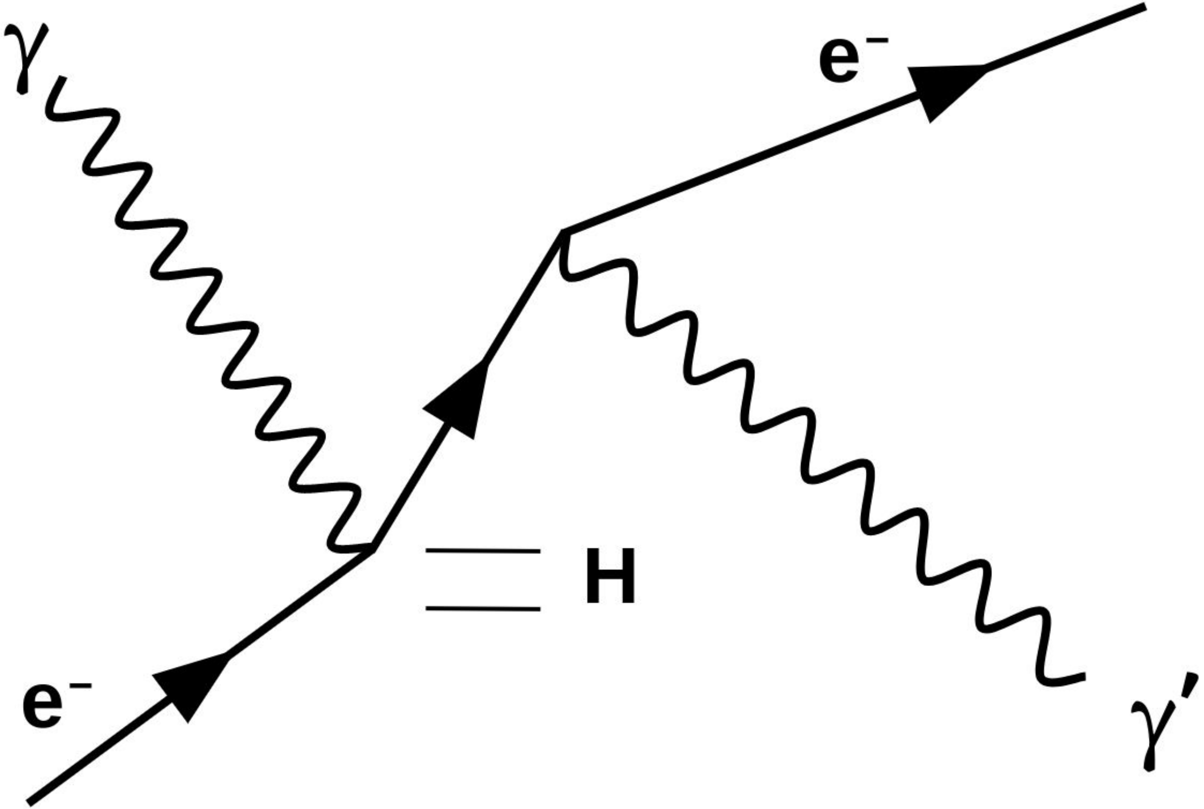
Note, we have replaced the incoming virtual photon with a real photon.

Compton Scattering with H bound state as perturbation

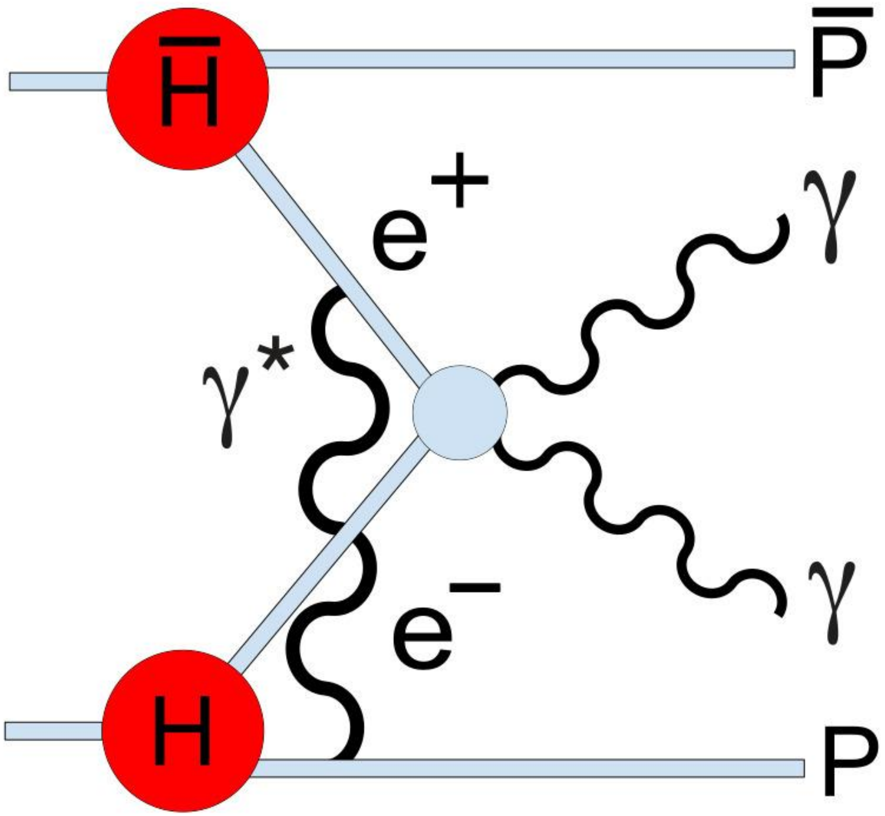
Note, we have replaced the incoming virtual photon with a real photon.

In QED, there is no need for virtuality in calculating this atomic deep inelastic scattering analog.

Experimentally this will prove useful.



An atomic analog of Drell-Yan

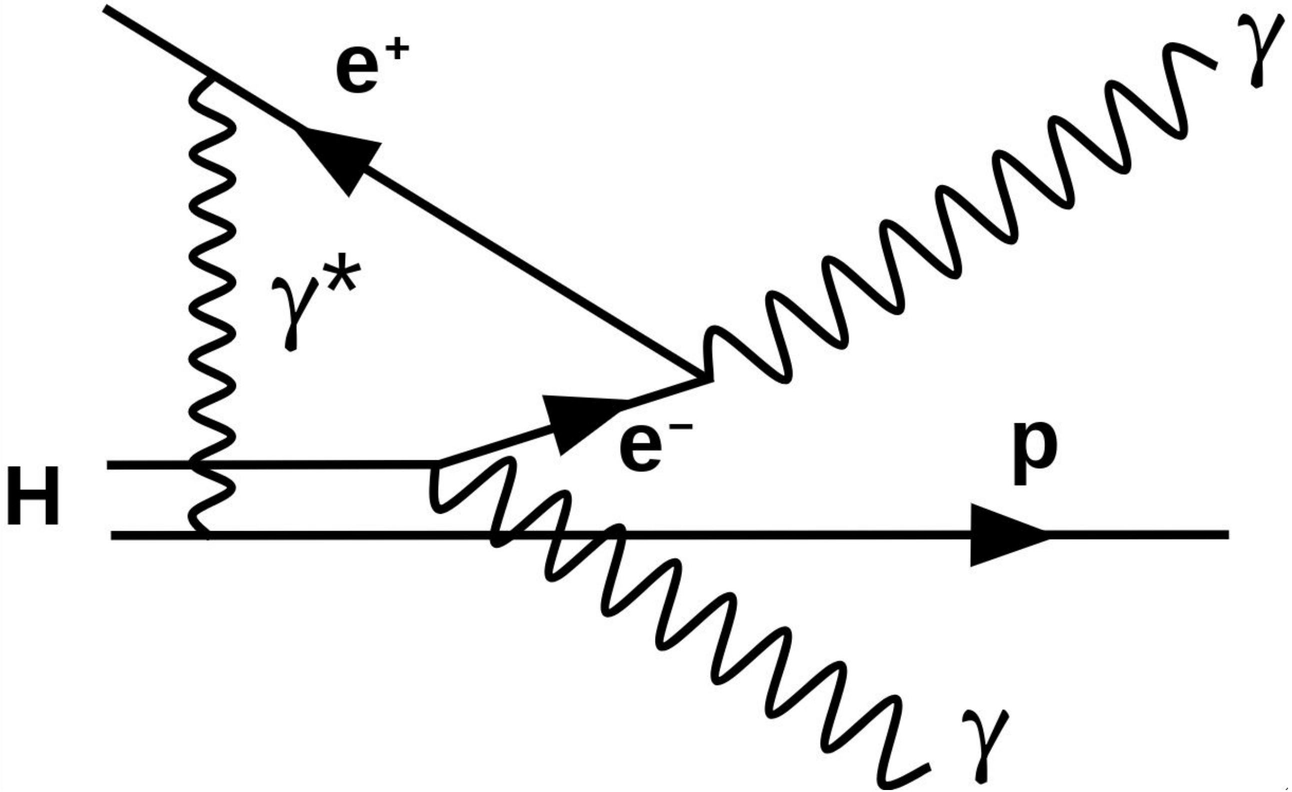


Here, we look at a possible QED Drell-Yan analog where we have replaced protons with Hydrogen and Anti-Hydrogen.

The initial state interaction is between the remnant Hydrogen ion (proton) and the positron.

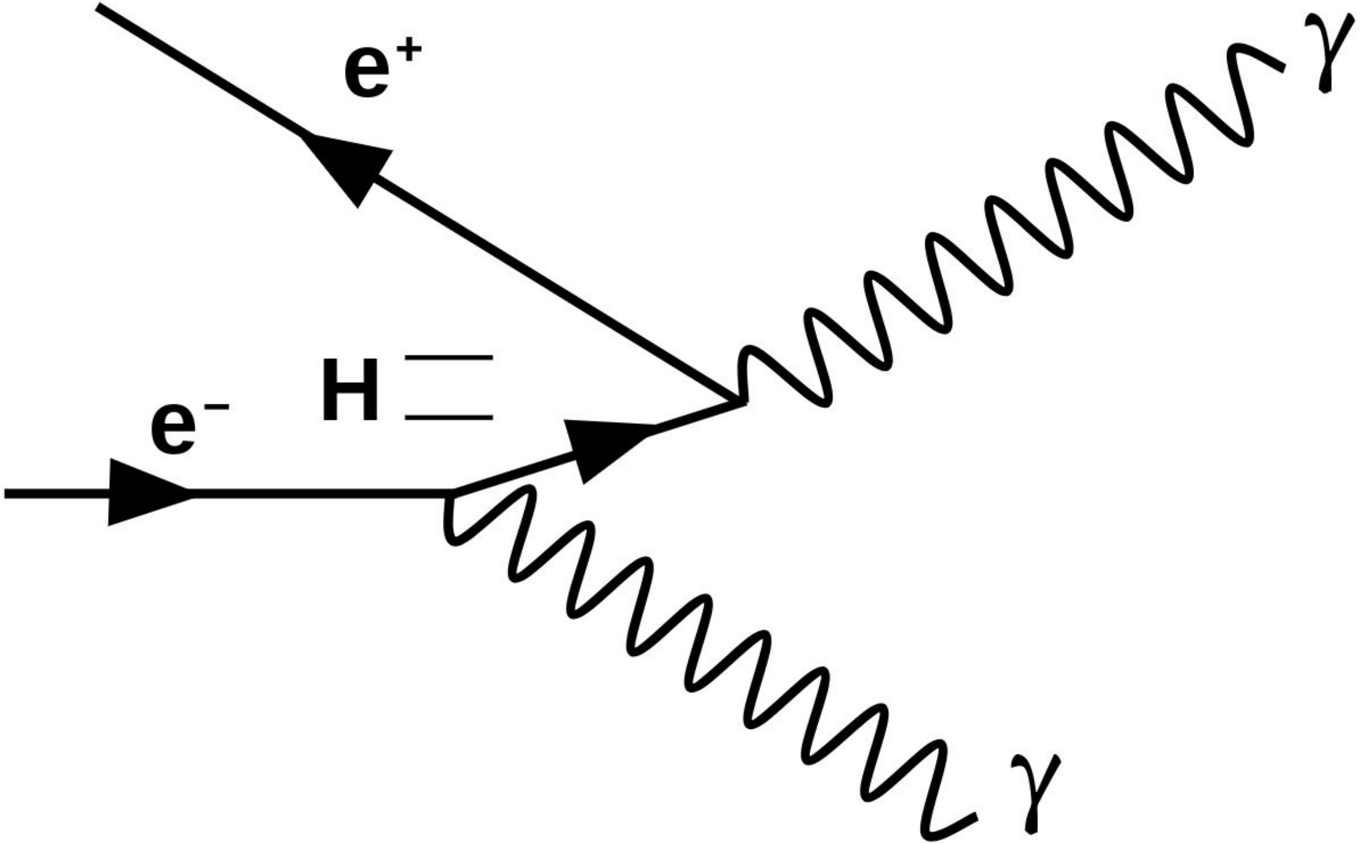
Notice, like Drell-Yan, the gauge interaction is between same-sign charges.

A positron-Hydrogen analog of Drell-Yan



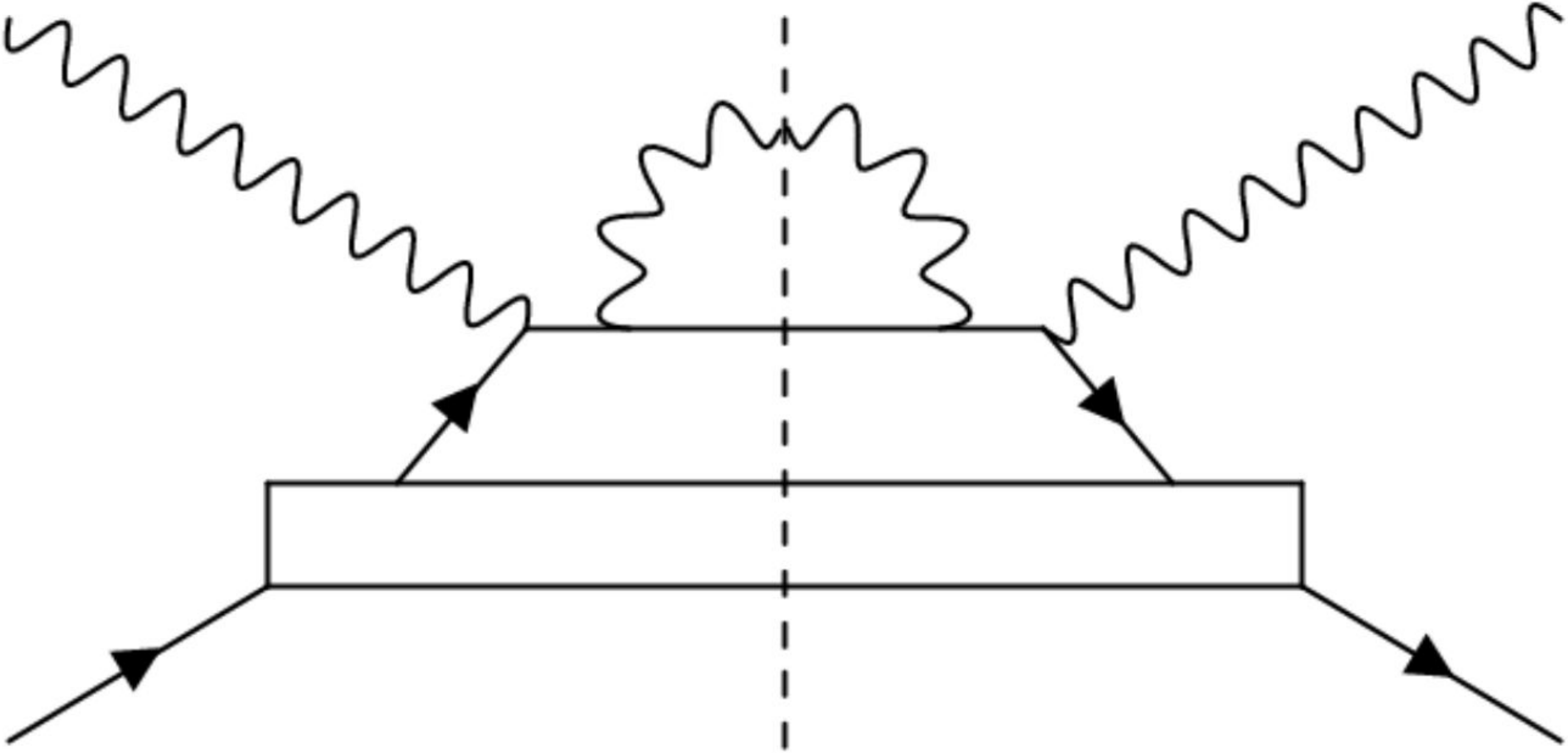
We have replaced Anti-Hydrogen with a positron.

Positron-electron annihilation with H as a perturbation



Here we present positron electron annihilation with a perturbation in the form of the bound state of the electron in Hydrogen.

Compton cut diagram with bound state perturbation



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