

ANOMALOUS DRELL-YAN ASYMMETRY FROM HADRONIC OR QCD VACUUM EFFECTS *

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The anomalously large $\cos(2\phi)$ asymmetry measured in the Drell-Yan process is discussed. Possible origins of this large deviation from the Lam-Tung relation are considered with emphasis on the comparison of two particular proposals: one that suggests it arises from a QCD vacuum effect and one that suggests it is a hadronic effect. Experimental signatures distinguishing these effects are discussed.

1. Introduction

Azimuthal asymmetries in the unpolarized Drell-Yan (DY) process differential cross section arise only in the following way

$$\frac{1}{\sigma} \frac{d\sigma}{d\Omega} \propto \left(1 + \lambda \cos^2 \theta + \mu \sin 2\theta \cos \phi + \frac{\nu}{2} \sin^2 \theta \cos 2\phi \right), \quad (1)$$

where ϕ is the angle between the lepton and hadron planes in the lepton center of mass frame (see Fig. 3 of Ref.¹). In the parton model (order α_s^0) quark-antiquark annihilation yields $\lambda = 1$, $\mu = \nu = 0$. The leading order (LO) perturbative QCD corrections (order α_s^1) lead to $\mu \neq 0$, $\nu \neq 0$ and $\lambda \neq 1$, such that the so-called Lam-Tung relation $1 - \lambda - 2\nu = 0$ holds. Beyond LO, small deviations from the Lam-Tung relation will arise. If one defines the quantity $\kappa \equiv -\frac{1}{4}(1 - \lambda - 2\nu)$ as a measure of the deviation from the Lam-Tung relation, it has been calculated^{2,3} that at order α_s^2 κ is small and negative: $-\kappa \lesssim 0.01$, for values of the muon pair's transverse momentum Q_T of up to 3 GeV/c.

Surprisingly, the data is incompatible with the Lam-Tung relation and with its small order- α_s^2 modification as well³. These data from CERN's NA10 Collaboration^{4,5} and Fermilab's E615 Collaboration⁶ are for $\pi^- N \rightarrow \mu^+ \mu^- X$, with $N = D$ and W . The π^- -beam energies range from 140 GeV

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up to 286 GeV and the invariant mass Q of the lepton pair is in the range $Q \sim 4 - 12$ GeV. The measured values for κ are an order of magnitude larger than the order- α_s^2 result and moreover, of opposite sign.

Several explanations have been put forward, but not all of them will be reviewed here. Some unlikely explanations would be: *i*) NNLO pQCD corrections could solve the discrepancy (but in that case the perturbative expansion itself would be questionable); *ii*) it could be a higher twist effect (but $Q^2 > 16$ GeV² seems too high and according to the Fermilab data the deviation disappears at high x_π , contrary to higher twist expectation; also, one would expect $\mu > \nu$, whereas in the data $\nu \gg \mu \approx 0$); *iii*) it could be a nuclear effect, since $\sigma(Q_T)_W/\sigma(Q_T)_D$ is an increasing function of Q_T (but according to Ref.⁵ $\nu(Q_T)$ shows no apparent nuclear dependence).

The two possible explanations that will be discussed and compared here are: *i*) a QCD vacuum effect³; *ii*) a hadronic effect, arising from non-collinear parton configurations¹. The following will largely be based on a recent comparative study performed in collaboration with A. Brandenburg, O. Nachtmann and A. Utermann⁷.

2. Explanation in terms of a QCD vacuum effect

Usually the DY process at $Q \sim 4 - 12$ GeV is described by collinear factorization. Collinear quarks inside unpolarized hadrons are unpolarized themselves, implying a trivial quark-antiquark spin density matrix:

$$\rho^{(q,\bar{q})} = \frac{1}{4} \{\mathbf{1} \otimes \mathbf{1}\}. \quad (2)$$

The QCD vacuum may alter this. The gluon condensate leads to a chromomagnetic field strength (Savvidy; Shifman, Vainshtein, Zakharov; ...)

$$\langle g^2 \mathbf{B}^a(x) \cdot \mathbf{B}^a(x) \rangle \approx (700 \text{ MeV})^4, \quad (3)$$

with gluon fields having a typical correlation length $a \approx 0.35$ fm in Euclidean space. Taking this to be an invariant length in Minkowski space⁸ leads to the picture of a fluctuating domain structure of the vacuum with typical domain size a , schematically depicted in Fig. 1. If a fast hadron, and with it a fast quark, traverses this domain structure, the time for traversing a vacuum domain is of the order of the correlation length: $t \approx a$. Due to the presence of a background chromomagnetic field the quark will acquire a transverse polarization (the Sokolov-Ternov effect). The time to build up transverse polarization is estimated^{8,9} to be much shorter than the time it takes to traverse the domain, i.e. $t \ll a$. The radiated gluons/photons are

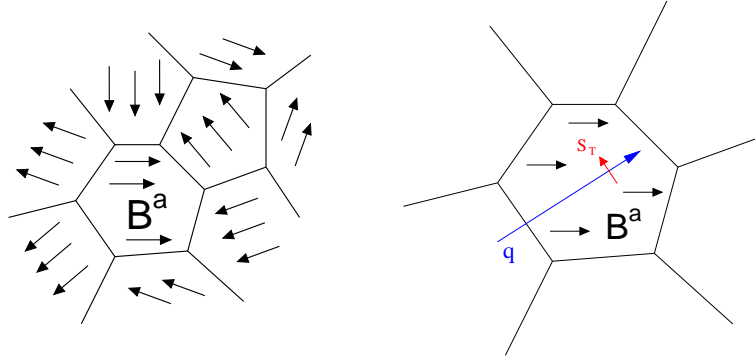


Figure 1. Left figure: cartoon of the chromomagnetic field domain structure of the QCD vacuum. Right figure: a fast quark traversing a domain.

just part of the cloud of virtual particles; in other words, they are included in the wave function. There will be no average polarization. However, if the quark will annihilate with an antiquark in a high energy scattering experiment, such as DY, the polarization of the quark and the antiquark may be correlated if they annihilate within a certain domain. Therefore, the QCD

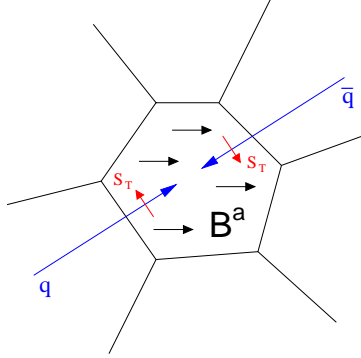


Figure 2. Annihilation of a quark and an antiquark inside the same domain.

vacuum can induce a spin correlation between an annihilating $q\bar{q}$ pair. The quark-antiquark spin density matrix Eq. (2) will then be modified into

$$\rho^{(q,\bar{q})} = \frac{1}{4} \{ \mathbf{1} \otimes \mathbf{1} + F_j \sigma_j \otimes \mathbf{1} + G_j \mathbf{1} \otimes \sigma_j + H_{ij} \sigma_i \otimes \sigma_j \}. \quad (4)$$

Only if $H_{ij} = F_i G_j$, then the spin density matrix factorizes. But this is not necessarily so, in which case it could be called entangled. Brandenburg,

Nachtmann & Mirkes³ demonstrated that the diagonal elements H_{11} and H_{22} can give rise to a deviation from the Lam-Tung relation:

$$\kappa \equiv -\frac{1}{4}(1 - \lambda - 2\nu) \approx \left\langle \frac{H_{22} - H_{11}}{1 + H_{33}} \right\rangle. \quad (5)$$

A simple assumption for the transverse momentum dependence of $(H_{22} - H_{11})/(1 + H_{33})$ produced a good fit to the data:

$$\kappa = \kappa_0 \frac{Q_T^4}{Q_T^4 + m_T^4}, \quad \text{with } \kappa_0 = 0.17 \text{ and } m_T = 1.5 \text{ GeV}. \quad (6)$$

Note that for this Ansatz κ approaches a constant value (κ_0) for large Q_T . In other words, the vacuum effect could persist out to large values of Q_T . The Q^2 dependence of the vacuum effect is not known, but there is also no reason to assume that the spin correlation due to the QCD vacuum effect has to decrease with increasing Q^2 .

3. Explanation as a hadronic effect

Usually if one assumes that factorization of soft and hard energy scales in a hard scattering process occurs, one implicitly also assumes factorization of the spin density matrix. In the present section this will indeed be assumed, but another common assumption will be dropped, namely that of *collinear* factorization. It will be investigated what happens if one allows for transverse momentum dependent parton distributions (TMDs). The spin density matrix of a noncollinear quark inside an unpolarized hadron can be nontrivial. In other words, the transverse polarization of a noncollinear quark inside an unpolarized hadron in principle can have a preferred direction and the TMD describing that situation is called h_1^\perp ¹⁰. As pointed out in Ref.¹ nonzero h_1^\perp leads to a deviation from Lam-Tung relation. It offers a parton model explanation of the DY data (i.e. with $\lambda = 1$ and $\mu = 0$): $\kappa = \frac{\kappa}{2} \propto h_1^\perp(\pi) h_1^\perp(N)$. In this way a good fit to data was obtained by assuming Gaussian transverse momentum dependence. The reason for this choice of transverse momentum dependence is that in order to be consistent with the factorization of the cross section in terms of TMDs, the transverse momentum of partons should not introduce another large scale. Therefore, explaining the Lam-Tung relation within this framework necessarily implies that $\kappa = \frac{\kappa}{2} \rightarrow 0$ for large Q_T . This offers a possible way to distinguish between the hadronic effect and the QCD vacuum effect.

It may be good to mention that not only a fit of h_1^\perp to data has been made (under certain assumptions), also several model calculations of h_1^\perp

and some of its resulting asymmetries have been performed^{11,12,13}, based on the recent insight that T-odd TMDs like h_1^\perp arise from the gauge link.

In order to see the parton model expectation $\kappa = \frac{\nu}{2} \rightarrow 0$ at large Q_T in the data, one has to keep in mind that the pQCD contributions (that grow as Q_T increases) will have to be subtracted. For κ perturbative corrections arise at order α_s^2 , but for ν already at order α_s . To be specific, at large Q_T hard gluon radiation (to first order in α_s) gives rise to¹⁴

$$\nu(Q_T) = \frac{Q_T^2}{Q^2 + \frac{3}{2}Q_T^2}. \quad (7)$$

Due to this growing large- Q_T perturbative contribution the fall-off of the h_1^\perp contribution will not be visible directly from the behavior of ν at large Q_T . Therefore, in order to use ν as function of Q_T to differentiate between effects, it is necessary to subtract the calculable pQCD contributions. In Fig. 3 an illustration of this point is given. The dashed curve corresponds

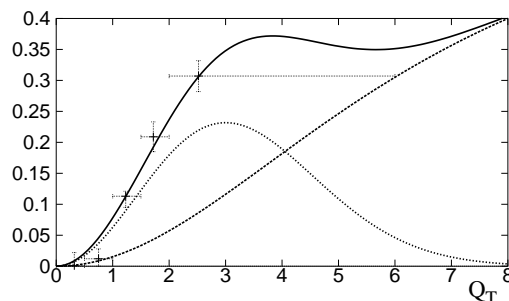


Figure 3. *Impression* of possible contributions to ν as function of Q_T compared to DY data of NA10 (for $Q = 8$ GeV). Dashed curve: contribution from perturbative one-gluon radiation. Dotted curve: contribution from a nonzero h_1^\perp . Solid curve: their sum.

to the contribution of Eq. (7) at $Q = 8$ GeV. The dotted line is a possible, parton model level, contribution from h_1^\perp with Gaussian transverse momentum dependence. Together these contributions yield the solid curve (although strictly speaking it is not the case that one can simply add them, since one is a noncollinear parton model contribution expected to be valid for small Q_T and the other is an order- α_s result within collinear factorization expected to be valid at large Q_T). The data are from the NA10 Collaboration for a pion beam energy of 194 GeV/c⁵.

The Q^2 dependence of the h_1^\perp contribution is not known to date. Only the effect of resummation of soft gluon radiation on the h_1^\perp contribution to

ν (and κ) has been studied to some extent and was found to be quite important¹⁵. It gives rise to a considerable Sudakov suppression with increasing Q : in going from $Q = 10$ to 90 GeV, the contribution decreases by an order of magnitude and approximately follows a $1/Q$ behavior (although it is neither a dynamical nor a kinematical higher twist effect). Interestingly, the contribution from hard gluon radiation (7) decreases more rapidly: as $1/Q^2$ at fixed Q_T . But it seems safe to conclude that using the Q^2 dependence of ν (or κ) to differentiate between effects is not feasible at present.

By assumption, nonzero h_1^\perp gives rise to a factorized product of spin density matrices $\rho^{(q,\bar{q})} = \rho^{(q)} \otimes \rho^{(\bar{q})}$ with⁷

$$\rho^{(q)} = \frac{1}{2} \left\{ \mathbf{1} + \frac{h_1^\perp}{f_1} \frac{x_1}{M_1} (\mathbf{e}_3 \times \mathbf{p}_1) \cdot \boldsymbol{\sigma} \right\} \equiv \frac{1}{2} \{ \mathbf{1} + F_j \boldsymbol{\sigma}_j \}, \quad (8)$$

$$\rho^{(\bar{q})} = \frac{1}{2} \left\{ \mathbf{1} - \frac{\bar{h}_1^\perp}{f_1} \frac{x_2}{M_2} (\mathbf{e}_3 \times \mathbf{p}_2) \cdot \boldsymbol{\sigma} \right\} \equiv \frac{1}{2} \{ \mathbf{1} + G_j \boldsymbol{\sigma}_j \}. \quad (9)$$

Therefore, $H_{ij} = F_i G_j$ with $H_{33} = 0$. Unfortunately it is hard to observe the difference between $H_{33} = 0$ and $H_{33} \neq 0$. But the factorization $H_{ij} = F_i G_j$ should show itself via consistency among various processes, which is based on the fact that the same function h_1^\perp appears in different processes. Regarding this universality, complications have recently been addressed¹⁶ that go beyond the sign change¹⁷ that occurs between semi-inclusive DIS ($e p \rightarrow e' \pi X$) and DY: $(h_1^\perp)_{\text{SIDIS}} = -(h_1^\perp)_{\text{DY}}$. Nevertheless, the different numerical factors with which h_1^\perp arises in different processes are calculable (functions of N_c only) and can be taken into account.

4. Hadronic effect versus vacuum effect

Summarizing the features of the two approaches in a table:

Table 1. Comparison of the hadronic and the vacuum effect

	$h_1^\perp \neq 0$	QCD vacuum effect
$\rho^{(q,\bar{q})}$	$\rho^{(q)} \otimes \rho^{(\bar{q})}$	possibly entangled
Q dependence	$\kappa \stackrel{?}{\sim} 1/Q$?
$Q_T \rightarrow \infty$	$\kappa \rightarrow 0$	need not disappear ($\kappa \rightarrow \kappa_0$)
flavor dependence	yes	flavor blind
x dependence	yes	yes, but flavor blind

As indicated in the table, the hadronic effect will generally be flavor depen-

dent and have an x dependence that is flavor dependent, since there is no reason to assume that h_1^\perp for the u quark should be the same as (or simply related to) that for the d quark. This is different from the QCD vacuum effect, which in this sense is flavor blind; it does not matter whether the spin correlation is between $u\bar{u}$ or $d\bar{d}$ (except for presumably small mass corrections). There will be an x dependence, since that determines the energy of the annihilation process, but this again should be flavor blind. It should be emphasized that flavor blindness in general does not imply hadron blindness or even process blindness. So the best next step would be to perform experiments with different beams (π^+, p, \bar{p}, \dots , where π^+ and \bar{p} offer the advantage of having valence anti-quarks) and in different kinematical regimes. For instance, the measurement of $\langle \cos 2\phi \rangle$ can be done at RHIC in $pp \rightarrow \mu^+\mu^-X$, or in $p\bar{p} \rightarrow \mu^+\mu^-X$ at Fermilab or GSI/FAIR.

The use of polarized beams can also help (e.g. at RHIC or GSI). In the DY process with one transversely polarized hadron, the differential cross section can namely depend on the azimuthal angle ϕ_S of the transverse hadron spin (\mathbf{S}_T) compared to the lepton plane:

$$\frac{d\sigma(pp^\uparrow \rightarrow \ell\bar{\ell}X)}{d\Omega d\phi_S} \propto 1 + \cos^2\theta + \sin^2\theta \left[\frac{\nu}{2} \cos 2\phi - \rho |\mathbf{S}_T| \sin(\phi + \phi_S) \right] + \dots$$

Within the framework of TMDs the analyzing power ρ is proportional to the product $h_1^\perp h_1^\perp$, which involves the transversity function h_1 . A nonzero function h_1^\perp will provide a relation between ν and ρ , which in case of one (dominant) flavor (usually called u -quark dominance) and Gaussian transverse momentum dependences, is approximately given by

$$\rho \approx \frac{1}{2} \sqrt{\frac{\nu}{\nu_{\max}}} \frac{h_1}{f_1}, \quad (10)$$

where ν_{\max} is the maximum value attained by $\nu(Q_T)$. This relation depends on the magnitude of h_1 compared to f_1 (see Refs.^{18,19} for explicit examples) and this may be extracted from double transverse spin asymmetries in DY (potentially at RHIC or GSI) or from SIDIS data (from e.g. HERMES or COMPASS) by exploiting the interference fragmentation functions (which can be obtained from e^+e^- data, e.g. at BELLE).

Also semi-inclusive DIS can be used. The $\langle \cos 2\phi \rangle$ in $ep \rightarrow e'\pi X$ would be $\propto h_1^\perp H_1^\perp$, where H_1^\perp is the Collins fragmentation function (also obtainable from BELLE). This particular SIDIS observable has been studied using model calculations²⁰. All this illustrates how the consistency among processes may be used to test the h_1^\perp hypothesis.

5. Conclusions

A transverse spin correlation in quark-antiquark annihilation ($q^\uparrow \bar{q}^\uparrow \rightarrow \gamma^*$) will lead to a $\cos(2\phi)$ asymmetry in the DY lepton-pair angular distribution. Such a spin correlation can arise from the chromomagnetic background field in the QCD vacuum or from noncollinear partons. If a flavor dependence is observed in future data, it would favor a hadronic effect. On the other hand, persistence of the asymmetry at large values of Q_T and Q (after subtraction of pQCD corrections if needed) would favor a vacuum effect. Several future and ongoing experiments will be able to provide crucial information on these dependences.

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