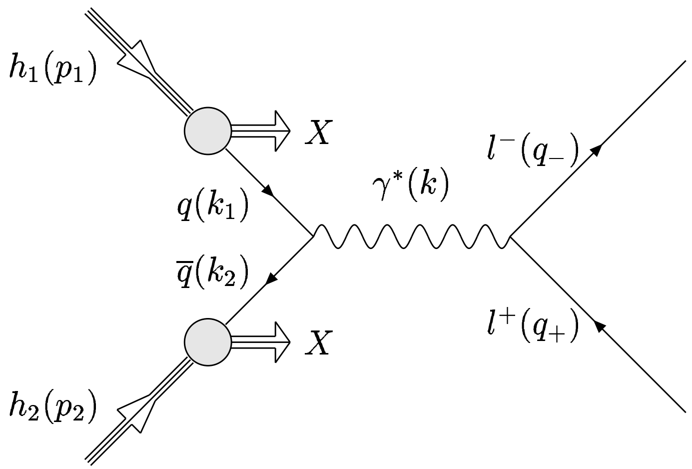
Anomalous Drell-Yan asymmetry from hadronic or QCD vacuum effects

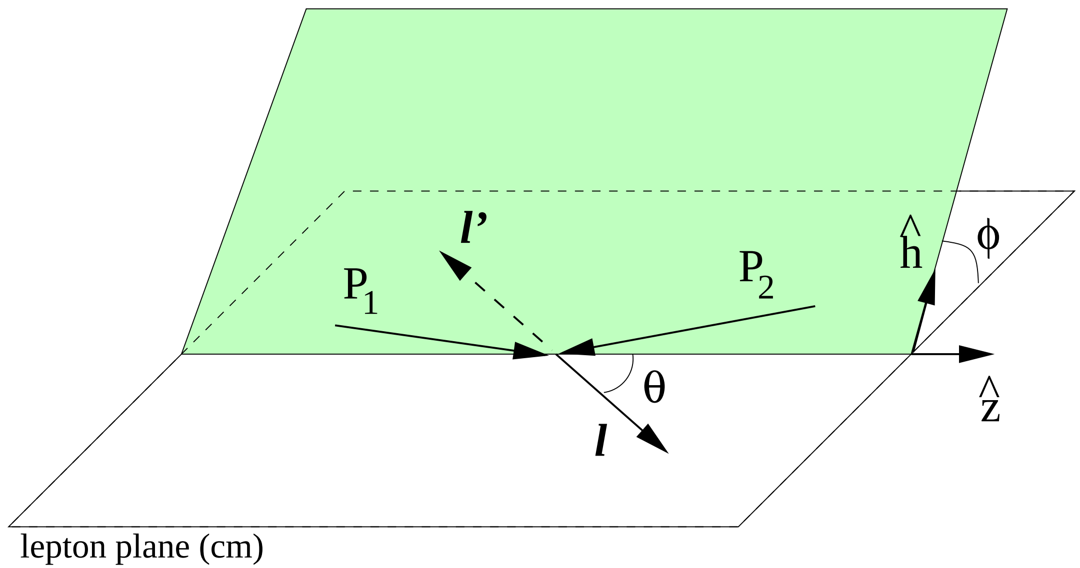
Daniël Boer
Free University, Amsterdam

Outline

- Anomalously large $\langle \cos(2\phi) \rangle$ asymmetry in Drell-Yan
- A QCD vacuum effect?
- A hadronic effect?
- Similarities and differences
- Conclusions

Azimuthal asymmetries in Drell-Yan in theory

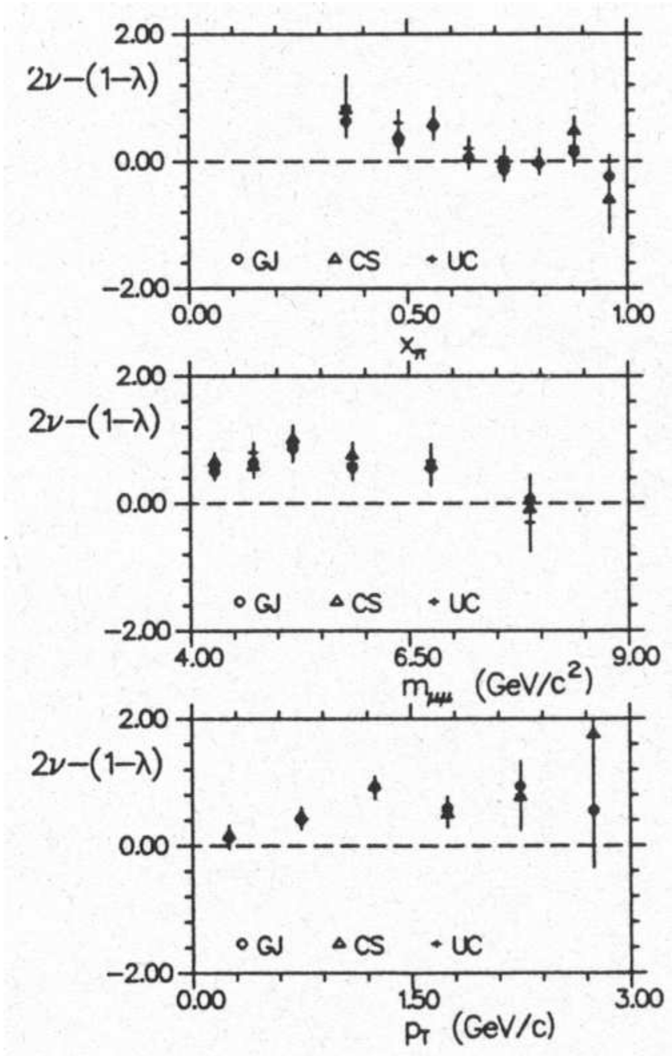




$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega} \propto \left(1 + \lambda \cos^2\theta + \mu \sin 2\theta \, \cos\phi + \frac{\nu}{2} \sin^2\theta \cos 2\phi\right)$$

Parton Model	$\mathcal{O}(\alpha_s^0)$	$\lambda = 1, \; \mu = \nu = 0$	
LO pQCD	$\mathcal{O}(\alpha_s^1)$	$1 - \lambda - 2\nu = 0$	Lam-Tung relation
NLO	$\mathcal{O}(\alpha_s^2)$	$1 - \lambda - 2\nu \neq 0$	small and positive

Azimuthal asymmetries in Drell-Yan in experiment



Data from NA10 Collab. ('86/'88) & E615 Collab. ('89)

Data for $\pi^- N \to \mu^+ \mu^- X$, with $N = D, W$

with π^--beams of 140-286 GeV

lepton pair invariant mass $Q \sim 4 - 12$ GeV

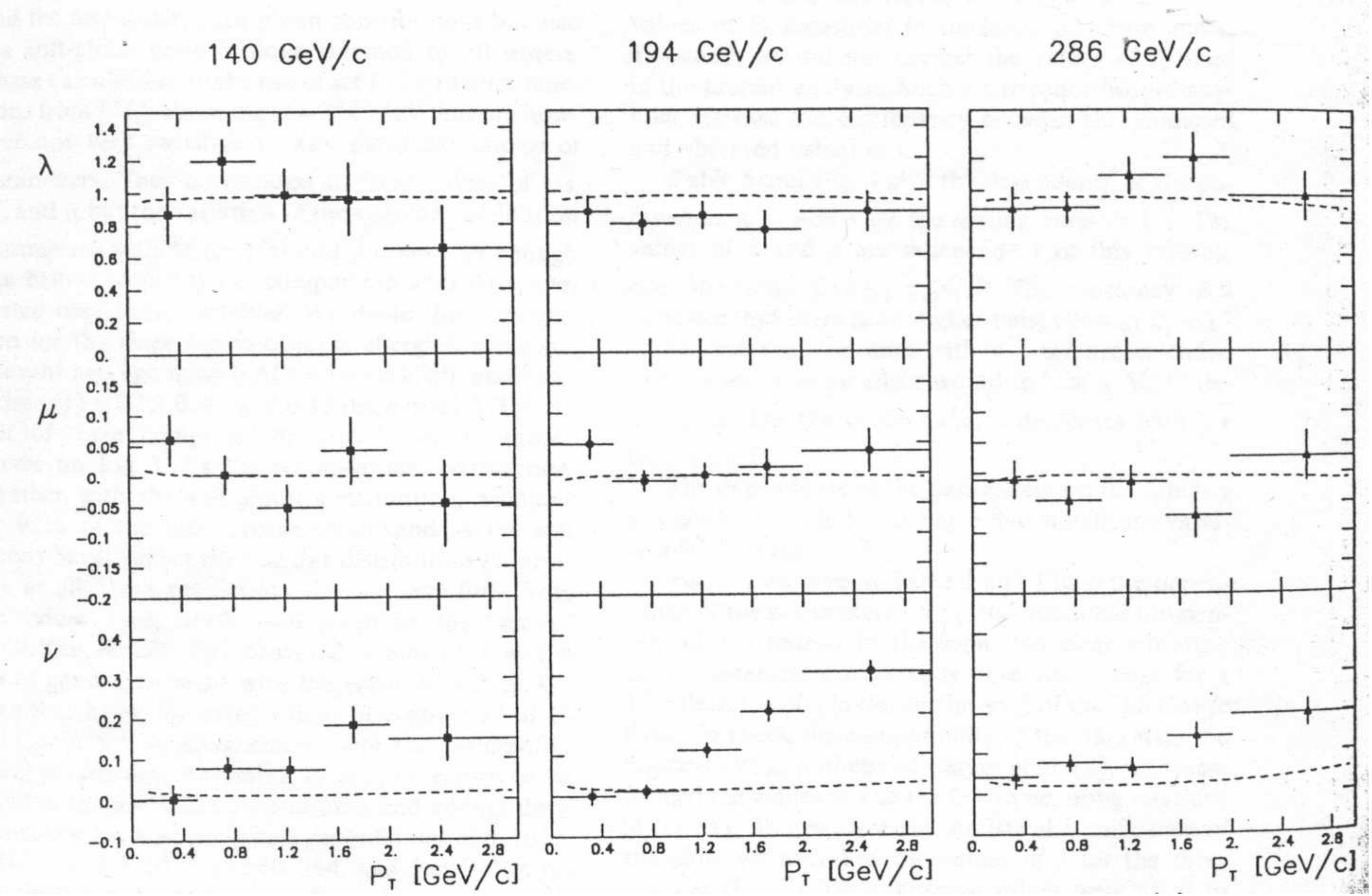
NA10: $-(1 - \lambda - 2\nu) \approx 0.6$ at $|\boldsymbol{k}_T| \sim 2 - 3$ GeV

E615: see figure

Large deviation from Lam-Tung relation

Order of magnitude larger & opposite sign
w.r.t. $\mathcal{O}(\alpha_s^2)$ pQCD result

NA10 data, ZPC 37 ('88) 545



Explanations of large deviation from Lam-Tung relation

Unlikely explanations:

- NNLO corrections
- Higher twist effect ($Q \sim 4 - 12$ GeV and $\mu \approx 0$, as opposed to expected $\mu > \nu$)
- Nuclear effect (although $\sigma(\boldsymbol{k}_T)_W/\sigma(\boldsymbol{k}_T)_D$ is an increasing function of $\boldsymbol{k}_T$, $\nu(\boldsymbol{k}_T)$ shows no apparent nuclear dependence)

Possible explanations to be discussed:

- QCD vacuum effect — Brandenburg, Nachtmann & Mirkes, ZPC 60 ('93) 697
- Hadronic effect — D.B., PRD 60 ('99) 014012

Recent comparative study — D.B., Brandenburg, Nachtmann & Utermann, EPJC 40 ('05) 55

Explanation as a QCD vacuum effect

Usually the DY process at $Q \sim 4 - 12$ GeV is described by collinear factorization

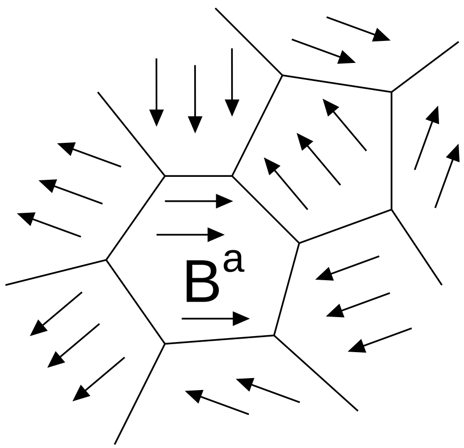
Collinear quarks inside unpolarized hadrons are unpolarized themselves

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

The QCD vacuum may alter this
The gluon condensate leads to a chromomagnetic field strength

$$\langle g^2 \boldsymbol{B}^a(x) \cdot \boldsymbol{B}^a(x) \rangle \approx (700\,\mathrm{MeV})^4$$

Savvidy; Shifman, Vainshtein, Zakharov; ...



Fluctuating domain structure of the vacuum with correlation length $a \approx 0.35$ fm

Explanation as a QCD vacuum effect

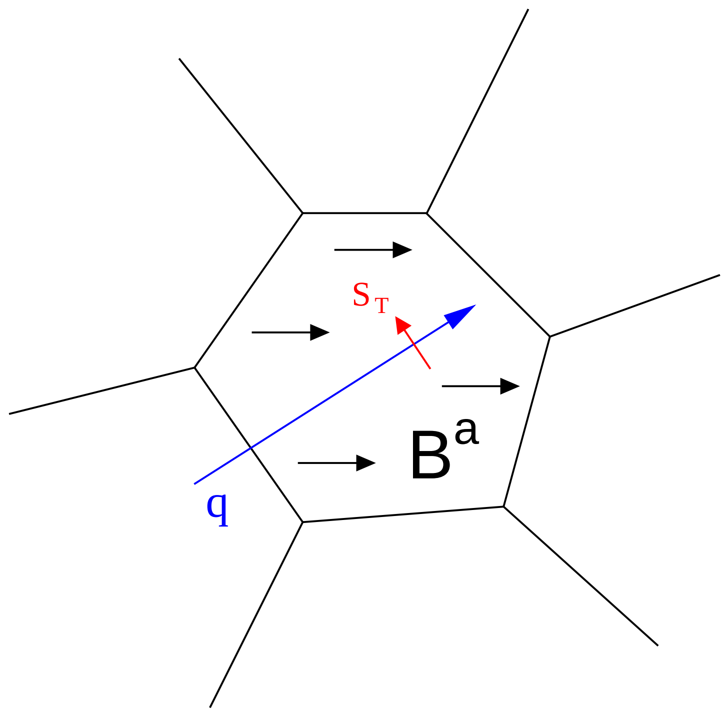
Time for traversing such a vacuum domain: $t \approx a$

Transverse polarization is built up due to the Sokolov-Ternov effect:

$$t \propto \frac{m_q^5}{|g\boldsymbol{B}_T|^3 \gamma^2} \Longrightarrow t \ll a$$

Nachtmann & Reiter, ZPC 24 ('84) 283

Botz, Haberl & Nachtmann, ZPC 67 ('95) 143

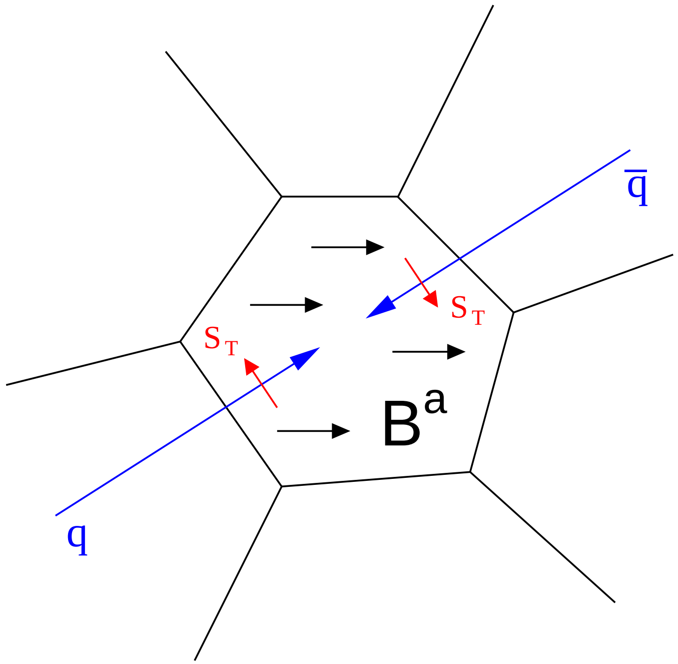


For an isolated hadron the radiated gluons/photons are just fluctuations of the cloud of virtual particles; they are included in the wave function

On average no quark polarization, but ...

Explanation as a QCD vacuum effect

The QCD vacuum can induce a spin correlation between an annihilating $q\,\bar{q}$



The spin density matrix becomes:

$$\rho^{(q,\bar{q})} \quad = \quad \frac{1}{4}\{\mathbf{1}\otimes\mathbf{1} + F_j\,\boldsymbol{\sigma}_j\otimes\mathbf{1} + G_j\,\mathbf{1}\otimes\boldsymbol{\sigma}_j + H_{ij}\,\boldsymbol{\sigma}_i\otimes\boldsymbol{\sigma}_j\}$$

If $H_{ij} = F_i G_j$, then the spin density matrix factorizes

$$\rho^{(q,\bar{q})} \quad = \quad \frac{1}{2}\{\mathbf{1} + F_j\,\boldsymbol{\sigma}_j\}\otimes\frac{1}{2}\{\mathbf{1} + G_j\,\boldsymbol{\sigma}_j\}$$

Explanation as a QCD vacuum effect

Brandenburg, Nachtmann & Mirkes (ZPC 60 ('93) 697) demonstrated that

$$H_{ii} \neq 0 \quad \Longrightarrow \quad \langle \cos(2\phi) \rangle \neq 0$$

More specifically,

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

A simple dependence of $(H_{22} - H_{11})/(1 + H_{33})$ on $|\boldsymbol{k}_T|$ could fit the data very well

$$\kappa = \kappa_0 \frac{|\boldsymbol{k}_T|^4}{|\boldsymbol{k}_T|^4 + m_T^4}, \qquad \kappa_0 = 0.17\,, \quad m_T = 1.5 \text{ GeV}$$

Note that for large $|\boldsymbol{k}_T|$: $\kappa \to \kappa_0$, a constant value

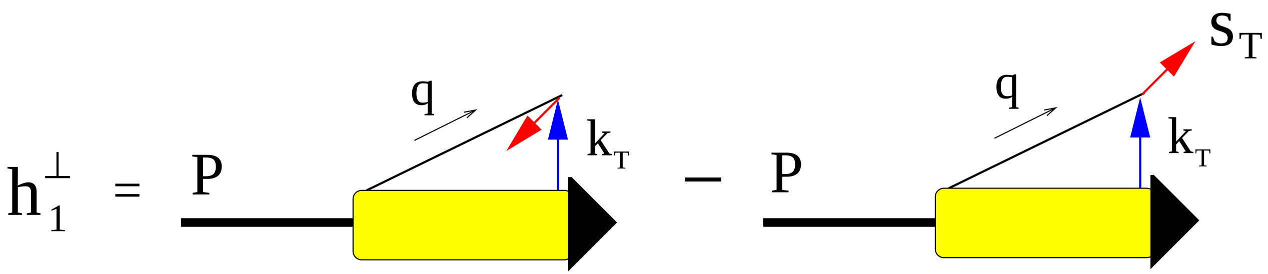
In other words, the vacuum effect could persist out to large values of $|\boldsymbol{k}_T|$

Explanation as a hadronic effect

Assume that factorization of soft and hard energy scales

implies factorization of the spin density matrices

But drop assumption of collinear factorization, i.e. allow for TMDs



$$h_1^\perp \neq 0 \quad \Longrightarrow \quad \text{deviation from Lam-Tung relation}$$

$h_1^\perp \neq 0$ offers a parton model explanation of NA10 data ($\lambda = 1,\ \mu = 0$):

$$\kappa = \frac{\nu}{2} \propto h_1^\perp(\pi)\, h_1^\perp(N)$$

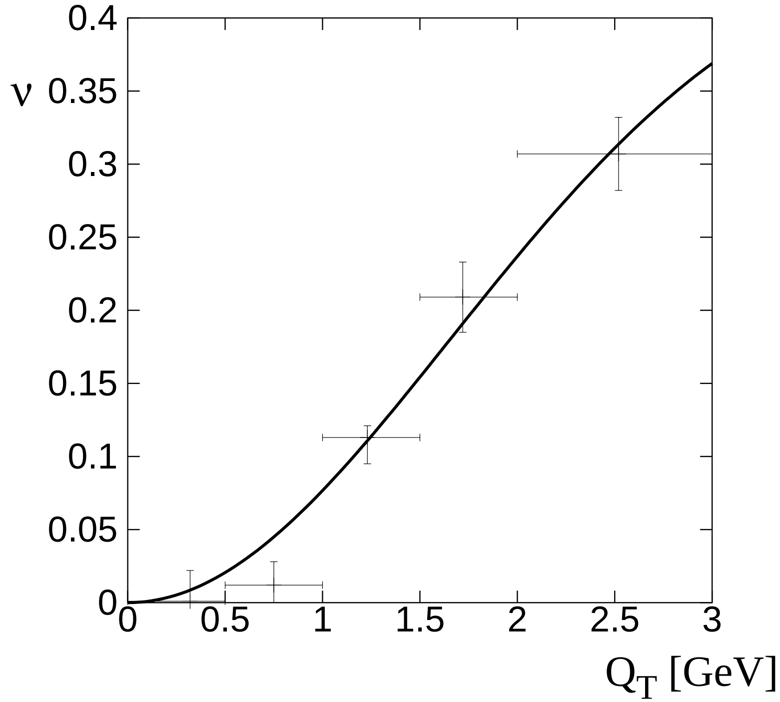
Explaining the unpolarized DY data

Fit $h_1^\perp$ to data by assuming Gaussian TM dependence

D.B., PRD 60 ('99) 014012

$\kappa = \frac{\nu}{2} \rightarrow 0$ for large $|\boldsymbol{k}_T|$ $(= Q_T)$

Consistency of factorization in terms of TMDs



Not only fit, but also model calculations of $h_1^\perp$ and asymmetries have been performed

Goldstein & Gamberg, hep-ph/0209085; D.B., Brodsky & Hwang, PRD 67 ('03) 054003

Lu & Ma, PRD 70 ('04) 094044 & hep-ph/0504184

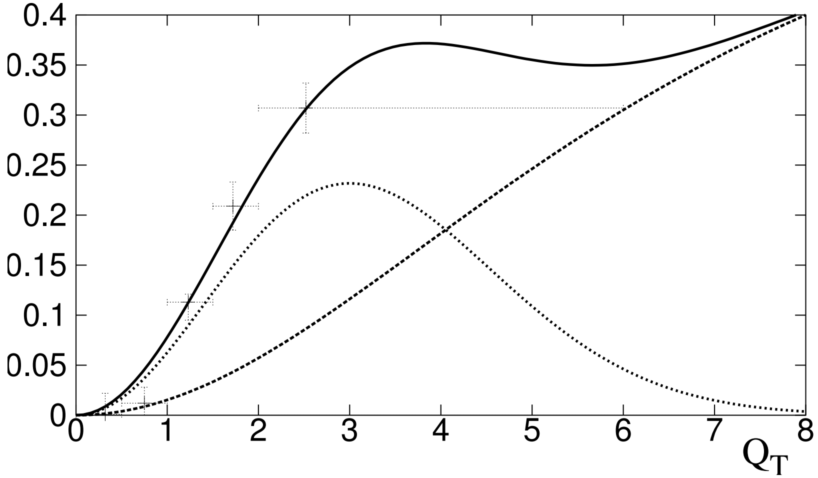
TM dependence beyond the parton model

At large Q_T hard gluon radiation (to first order in α_s) gives rise to

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

Collins, PRL 42 ('79) 291

Impression of small and large Q_T contributions (at $Q = 8$ GeV) to ν compared to DY data of NA10 ('88)



Therefore, in order to use the behavior of ν at large Q_T to differentiate between effects,

it is necessary to subtract the calculable pQCD contributions

At higher orders in α_s this is also necessary for κ (Mirkes & Ohnemus, PRD 51 (1995) 4891)

Q^2 dependence beyond the parton model

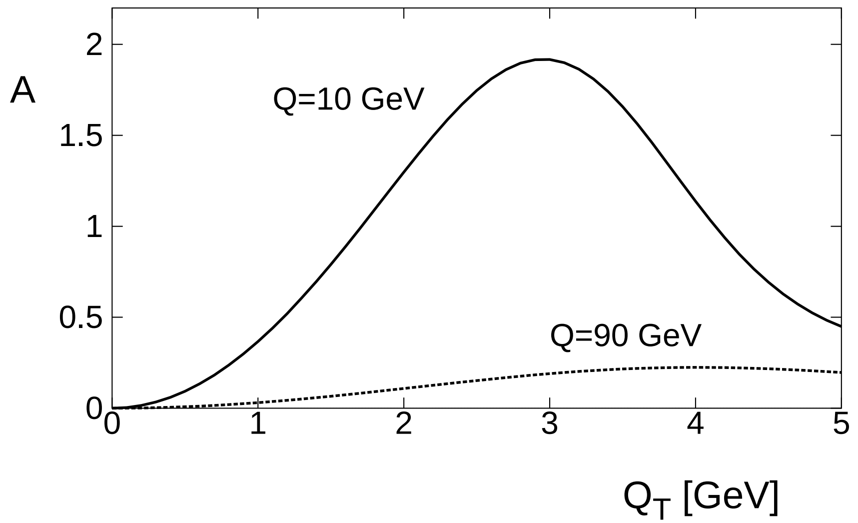
The Q^2 dependence of the vacuum effect is not known

At fixed Q_T the contribution from hard gluon radiation decreases as $1/Q^2$

The effect of resumming soft gluon radiation on the $h_1^\perp$ contribution to ν (and κ):

Considerable Sudakov suppression with increasing Q: $\sim 1/Q$

D.B., NPB 603 ('01) 195



Using the Q^2 dependence of ν (or κ) to differentiate between effects is not feasible (yet)

Factorization and universality

Nonzero $h_1^\perp$ gives rise to a factorized product of spin density matrices

$$
\begin{aligned}
\rho^{(q,\bar{q})} &= \rho^{(q)} \otimes \rho^{(\bar{q})} \\
\rho^{(q)} &= \frac{1}{2}\left\{\mathbf{1} + \frac{h_1^\perp}{f_1}\frac{x_1}{M_1}(\boldsymbol{e}_3 \times \boldsymbol{p}_1)\cdot\boldsymbol{\sigma}\right\} \equiv \frac{1}{2}\{\mathbf{1} + F_j\,\boldsymbol{\sigma}_j\} \\
\rho^{(\bar{q})} &= \frac{1}{2}\left\{\mathbf{1} - \frac{\bar{h}_1^\perp}{\bar{f}_1}\frac{x_2}{M_2}(\boldsymbol{e}_3 \times \boldsymbol{p}_2)\cdot\boldsymbol{\sigma}\right\} \equiv \frac{1}{2}\{\mathbf{1} + G_j\,\boldsymbol{\sigma}_j\}
\end{aligned}
$$

Therefore, $H_{ij} = F_i G_j$, but in addition, this implies $H_{33} = 0$

Unfortunately it is hard to observe the difference between $H_{33} = 0$ and $H_{33} \neq 0$

Factorization shows itself via consistency among various processes (universality)

Complications have recently been addressed, beyond Collins' $(h_1^\perp)_{\mathrm{DIS}} = -(h_1^\perp)_{\mathrm{DY}}$

Bacchetta, Bomhof, Mulders, Pijlman, hep-ph/0505268

Hadronic effect versus vacuum effect

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

Different experiments ($\pi^\pm, p, \bar{p}, \ldots$ beams) are needed in different kinematical regimes

Polarized beams can also help (SSA $\sim h_1 h_1^\perp$)

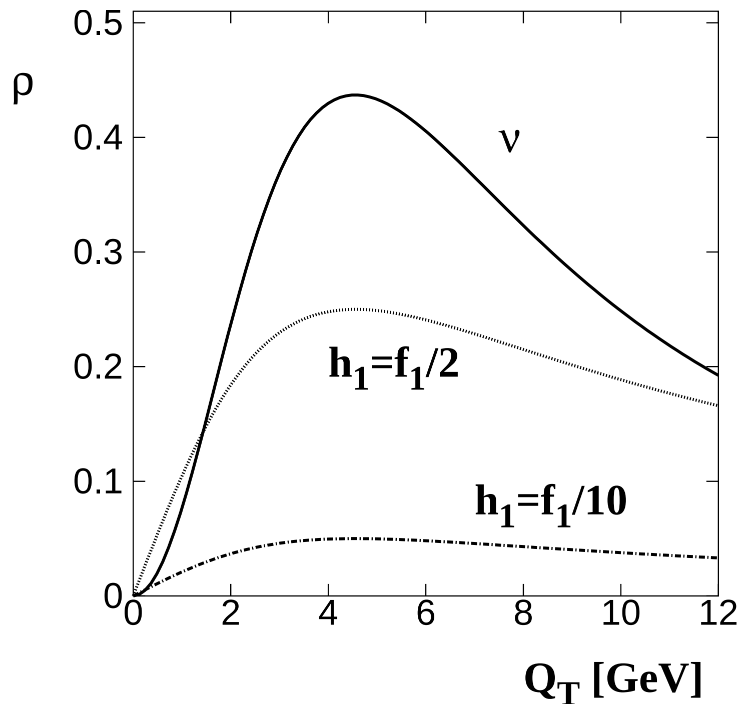
The polarized Drell-Yan process

In the case of one transversely polarized hadron:

$$\frac{d\sigma}{d\Omega\, d\phi_S} \propto 1 + \cos^2\theta + \sin^2\theta \left[\frac{\nu}{2}\,\cos 2\phi - \rho\,|\boldsymbol{S}_T|\,\sin(\phi + \phi_S)\right] + \ldots$$

Assuming u-quark dominance and Gaussian TM dependence for $h_1^\perp$:

$$\rho = \frac{1}{2}\sqrt{\frac{\nu}{\nu_{\text{max}}}}\,\frac{h_1^u}{f_1^u}$$



It offers a probe of transversity

D.B., NPB(PS) 79 ('99) 638

Data to test $h_1^\perp$ hypothesis

Possible future DY data

RHIC: can measure ν and $\rho \Longrightarrow$ information on $h_1^\perp$ and h_1

Also provides information on flavor dependence ($p\,p$ versus $\pi\,p$)

Fermilab: ν in $p\,\bar{p} \to \mu^+\mu^- X$ (advantage of $\bar{p}$: valence anti-quarks, like π)

GSI: future PANDA (ν) and PAX (ρ) experiments $p\,\bar{p} \to l^+l^- X$

But at considerably lower energies ($\sqrt{s} \sim 7 - 14$ GeV), so HT becomes important

Semi-inclusive DIS

The $\langle \cos 2\phi \rangle$ in $e\,p \to e'\,\pi\,X$ would be $\propto h_1^\perp H_1^\perp$

Gamberg, Goldstein & Oganessyan, PRD 67 ('03) 071504; PRD 68 ('03) 051501

Amrath, Bacchetta, Metz, PRD 71 (2005) 114018 [review of model calculations of $H_1^\perp$]

Conclusions

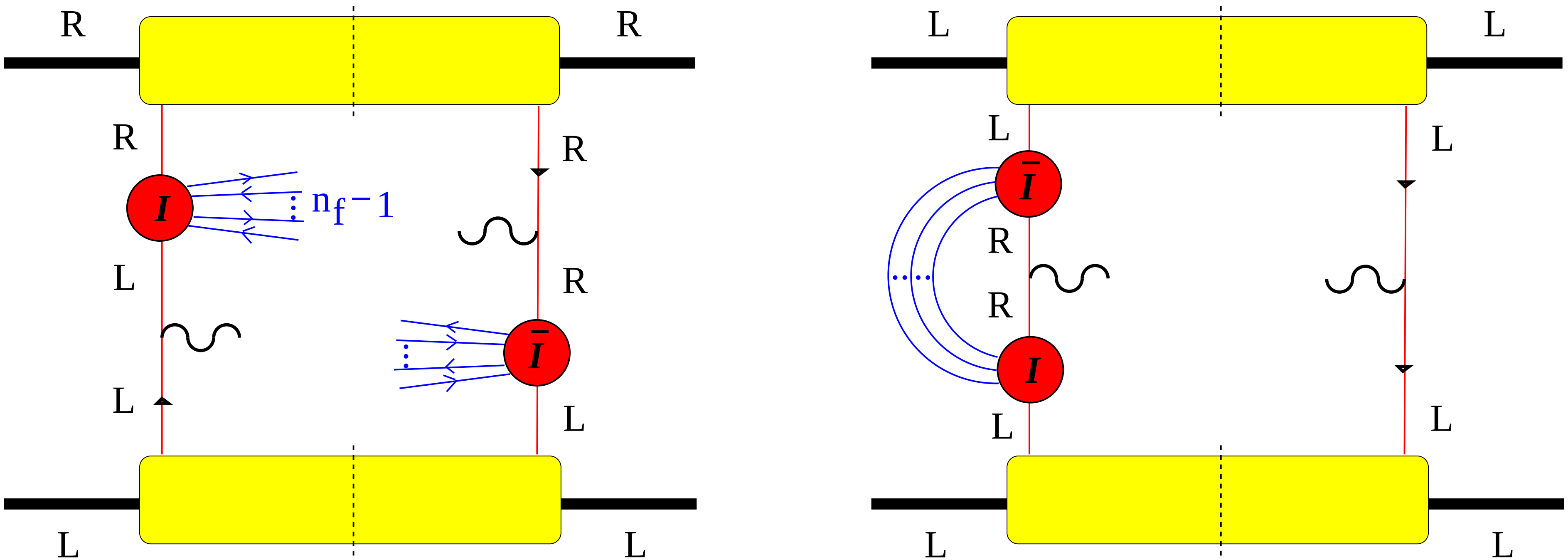
- $q^{\uparrow}\bar{q}^{\uparrow} \to \gamma^*$ leads to $\langle \cos(2\phi) \rangle$ asymmetry in DY lepton-pair angular distribution
- Such a spin correlation can arise from QCD vacuum or noncollinear partons
- Flavor dependence would favor a hadronic effect
- Persistence of the asymmetry at large $|\boldsymbol{k}_T|$ and Q favors a vacuum effect

Hopefully the future will tell whether the anomalous Drell-Yan asymmetry comes from factorizing hadronic effects or possibly nonfactorizing QCD vacuum effects

Instanton model

"Instanton induced azimuthal spin asymmetry in DIS", Ostrovsky & Shuryak, PRD 71 ('05) 014037
"The Pauli form factor of the quark induced by instantons", Kochelev, PLB 565 ('03) 131

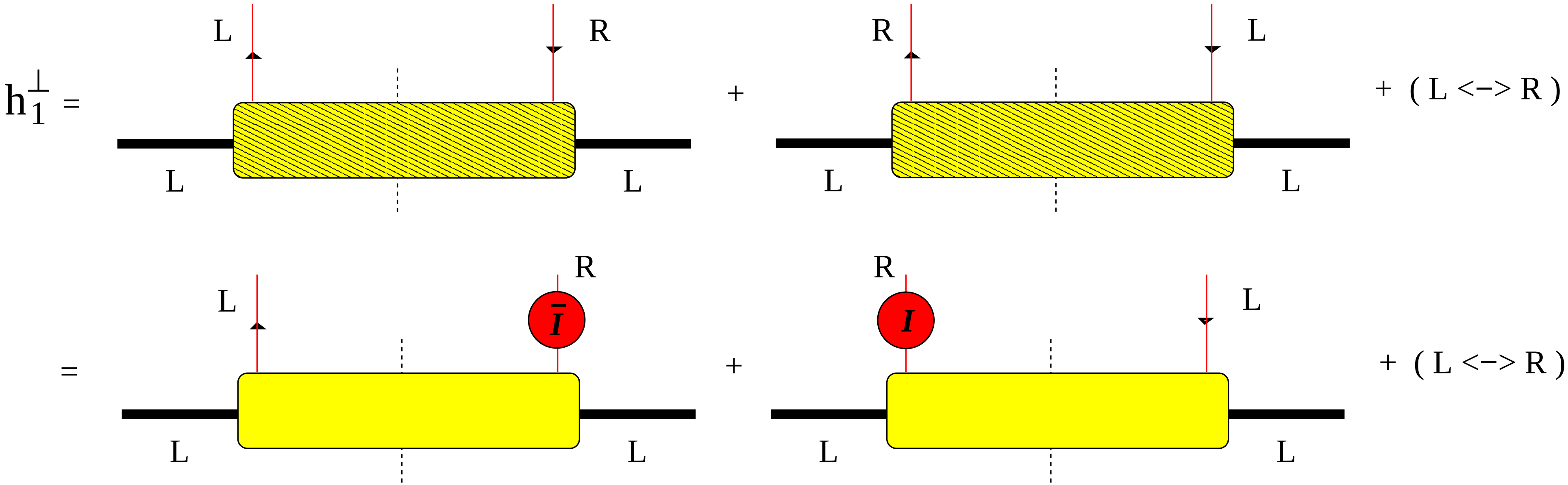
The general $n_f = 3$ case (and $n_g \neq 0$) is non-factorizing, e.g.

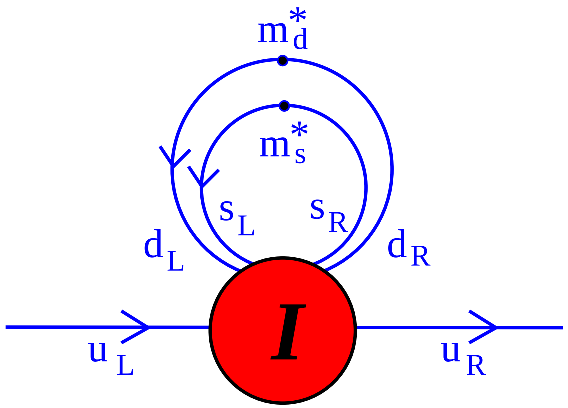


But perhaps suppressed (like higher twist)

Instanton model

The effective $n_f = 1$ case is factorizing:





$$m_q^* = m_q - \frac{2\pi^2}{3}\rho^2\langle 0|\bar{q}q|0\rangle$$

m_q^* is not small, thanks to spontaneous χSB