Azimuthal asymmetries from hadronic versus QCD vacuum effects

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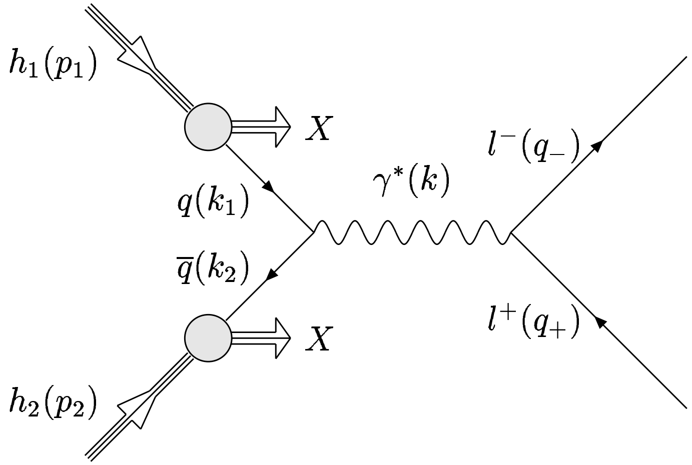
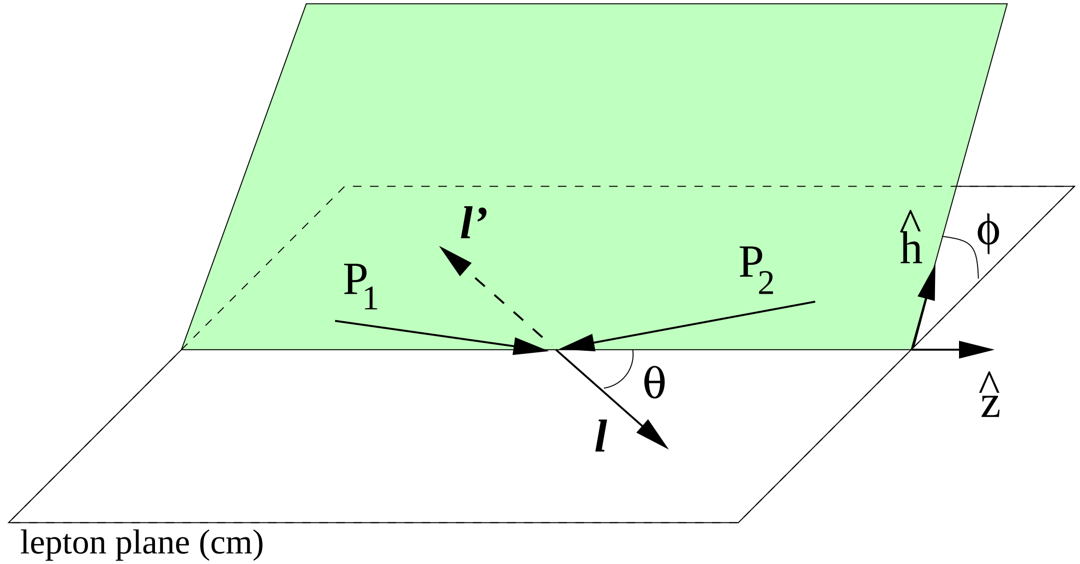
Outline

- Anomalously large $\langle \cos(2\phi) \rangle$ asymmetry in Drell-Yan
- A QCD vacuum effect?
- A hadronic effect?
- Similarities and differences
- An instanton picture
- Handedness correlations in e^+e^- annihilation
- Conclusions

Azimuthal asymmetries in Drell-Yan in theory

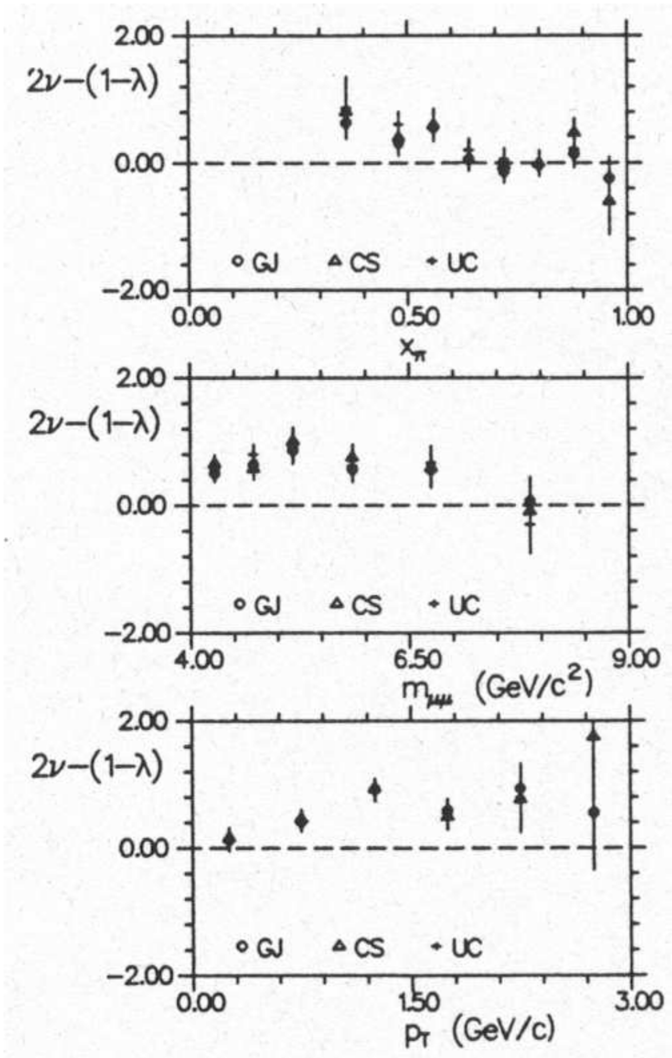




$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega} \propto \left(1 + \lambda \cos^2\theta + \mu \sin^2\theta \, \cos\phi + \frac{\nu}{2}\sin^2\theta \cos 2\phi\right)$$

Parton Model	$\mathcal{O}(\alpha_s^0)$	$\lambda = 1, \ \mu = \nu = 0$	
LO pQCD	$\mathcal{O}(\alpha_s)$	$1 - \lambda - 2\nu = 0$	Lam-Tung relation
NLO	$\mathcal{O}(\alpha_s^2)$	$(1 - \lambda - 2\nu) \lesssim 0.02$ for $\lvert \boldsymbol{k}_T \rvert \leq 3$ GeV	

Azimuthal asymmetries in Drell-Yan in experiment



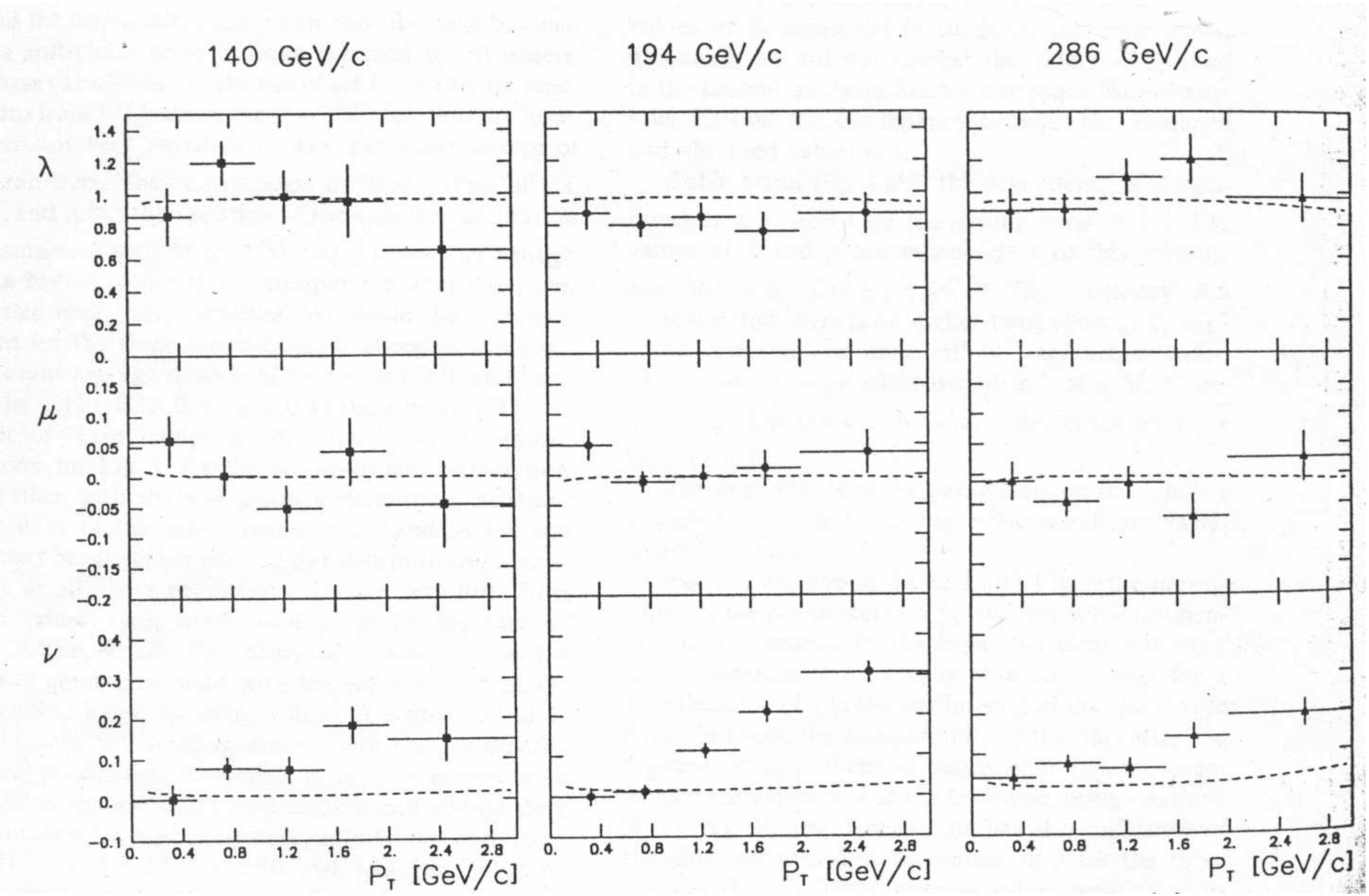
Data from NA10 Collab. ('86/'88) & E615 Collab. ('89)

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

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 $\mu \approx 0$)
- Nuclear effect (although $\sigma(\boldsymbol{k}_T)_W/\sigma(\boldsymbol{k}_T)_D$ is an increasing function of $\boldsymbol{p}_T$, $\nu(\boldsymbol{k}_T)$ 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 ('05)

Explanation as a QCD vacuum effect

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

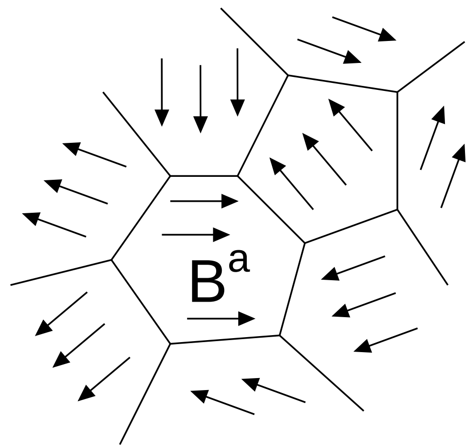
Collinear quarks inside unpolarized hadrons are unpolarized themselves

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

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

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

Savvidy; Shifman, Vainshtein, Zakharov; ...



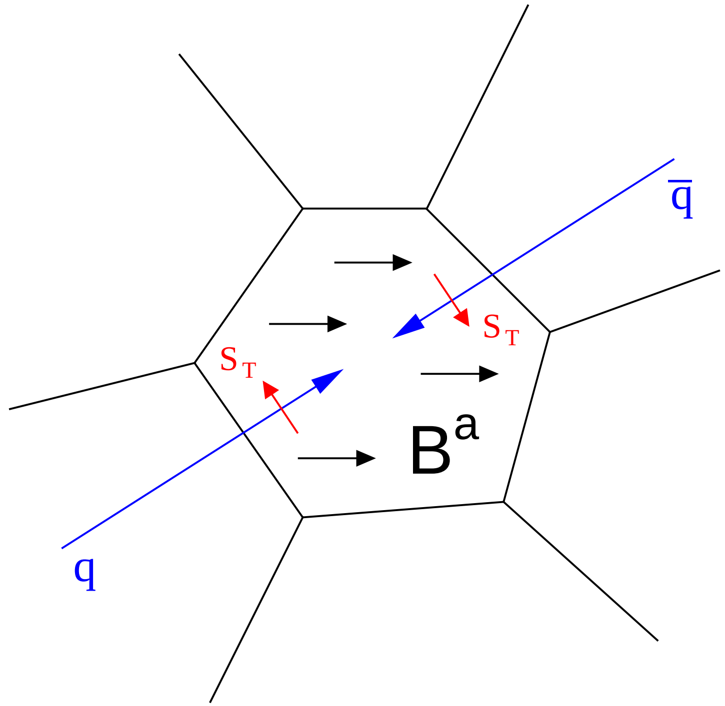
Fluctuating domain structure of the vacuum with correlation length $a \approx 0.35$ fm

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

On average no quark polarization, but:

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

Explanation as a QCD vacuum effect

There will be a polarization correlation if the q and $\bar{q}$ annihilate in the same domain

The spin density matrix becomes

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

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

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

Otherwise it could be called entangled

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

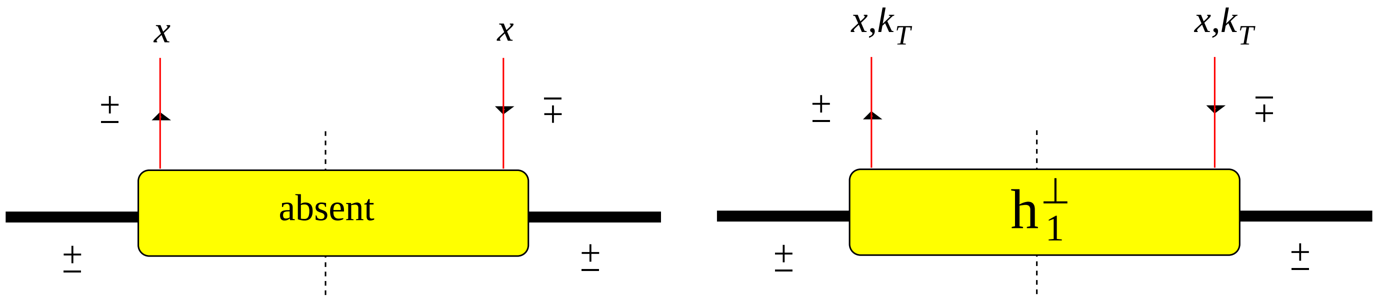
Transverse momenta also become correlated by the deflection due to $\boldsymbol{B}$, but this is not the dominant effect in this observable

Explanation as a hadronic effect

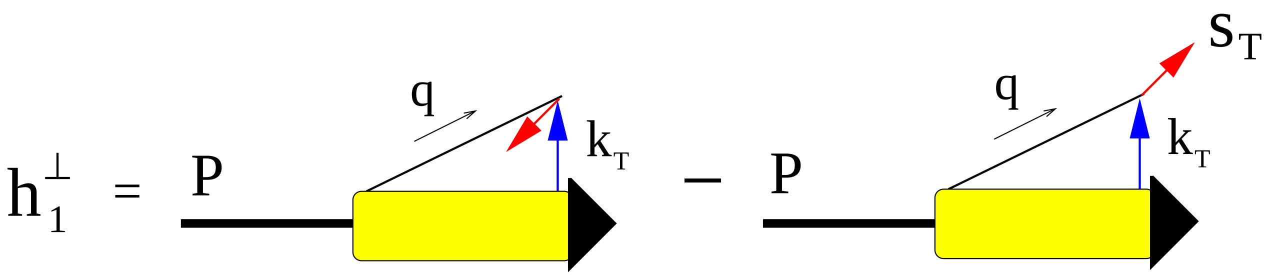
Assume that factorization of soft and hard energy scales

$\Longrightarrow$ factorization of the spin density matrices

But drop assumption of collinear factorization



Transverse polarization of a noncollinear quark inside an unpolarized hadron in principle can have a preferred direction



D.B. & Mulders, PRD 57 ('98) 5780

Explaining the unpolarized DY data

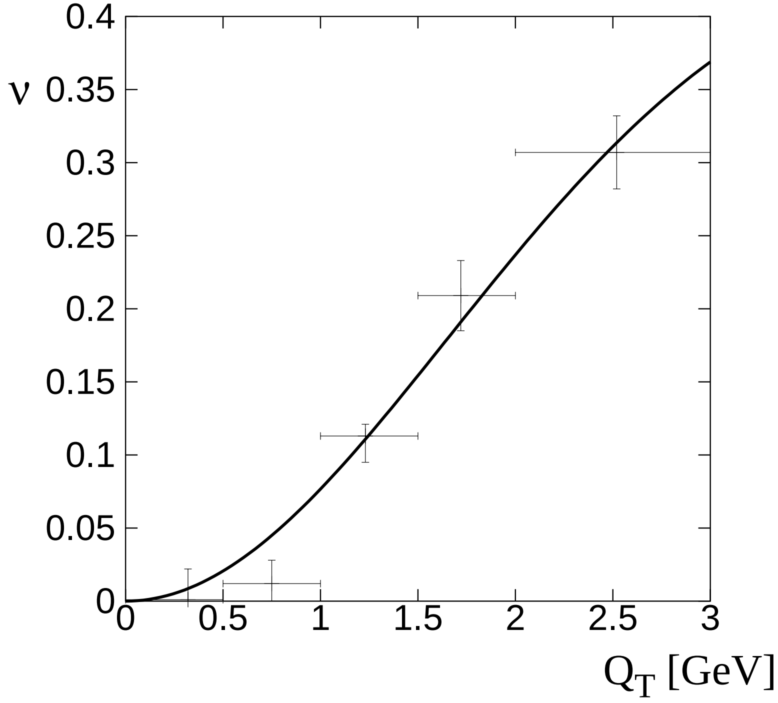
$h_1^\perp \neq 0 \quad \Longrightarrow \quad$ deviation from Lam-Tung relation

Offers a tree level ($\lambda = 1$, $\mu = 0$) explanation of NA10 data:

$$\nu \propto h_1^\perp(\pi)\, h_1^\perp(N)$$

Fit $h_1^\perp$ to data

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



Hadronic effect versus vacuum effect

Nonzero $h_1^\perp$ gives rise to

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

This implies $H_{ij} = F_i G_j$ and $H_{33} = 0$

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

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
Lü & Ma, PRD 70 ('04) 094044

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	$\kappa \sim 1/Q$	?
$\|\boldsymbol{k}_T\| \to \infty$	$\kappa \to 0$	need not disappear ($\kappa \to \kappa_0$)
flavor dependence	yes	flavor blind
x dependence	yes	yes, but flavor blind

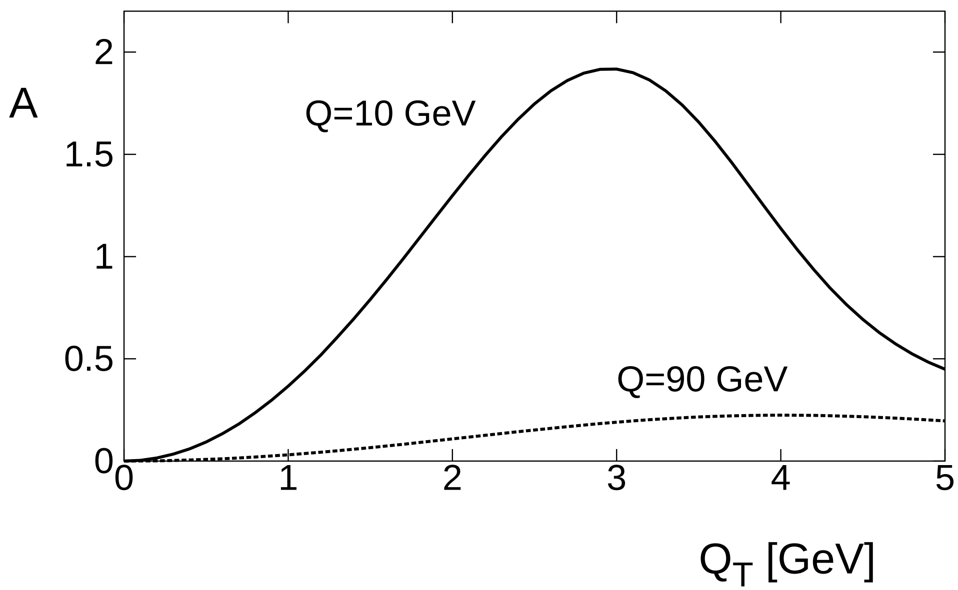
Different experiments ($\pi^\pm, p, \bar{p}, \ldots$ beams) are needed at different kinematical regimes

Polarized beams can also help

Sudakov suppression

Assuming Gaussian k_T dependence for $h_1^\perp$, the $\cos(2\phi)$ asymmetry is proportional to

$$\mathcal{A}(Q_T) \equiv M^2 \frac{\int_0^\infty db\, b^3\, J_2(bQ_T)\, \exp\left(-S(b_*) - S_{NP}(b)\right)}{\int_0^\infty db\, b\, J_0(bQ_T)\, \exp\left(-S(b_*) - S_{NP}(b)\right)} \qquad Q_T = |\boldsymbol{k}_T|$$



Resummation of soft gluon emissions

Generic Sudakov factor $\longrightarrow$ figure

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

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

Hadronic effect versus vacuum effect

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Polarized beams can also help

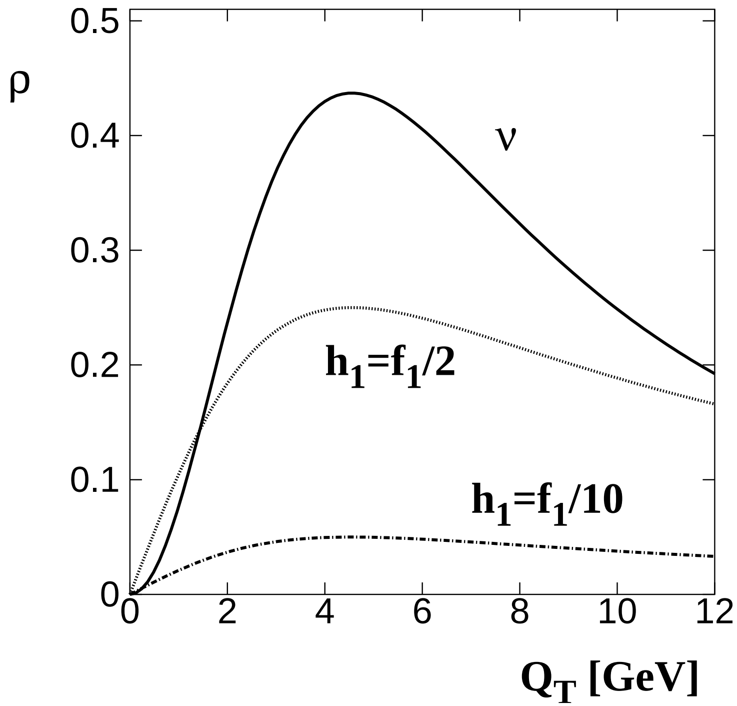
The polarized Drell-Yan process

In the case of one transversely polarized hadron (choosing $\lambda = 1$ and $\mu = 0$):

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

Assuming u-quark dominance and Gaussian k_T 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

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

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

But at considerably lower energies ($\sqrt{s} \sim 7 - 14$ GeV)

Semi-inclusive DIS

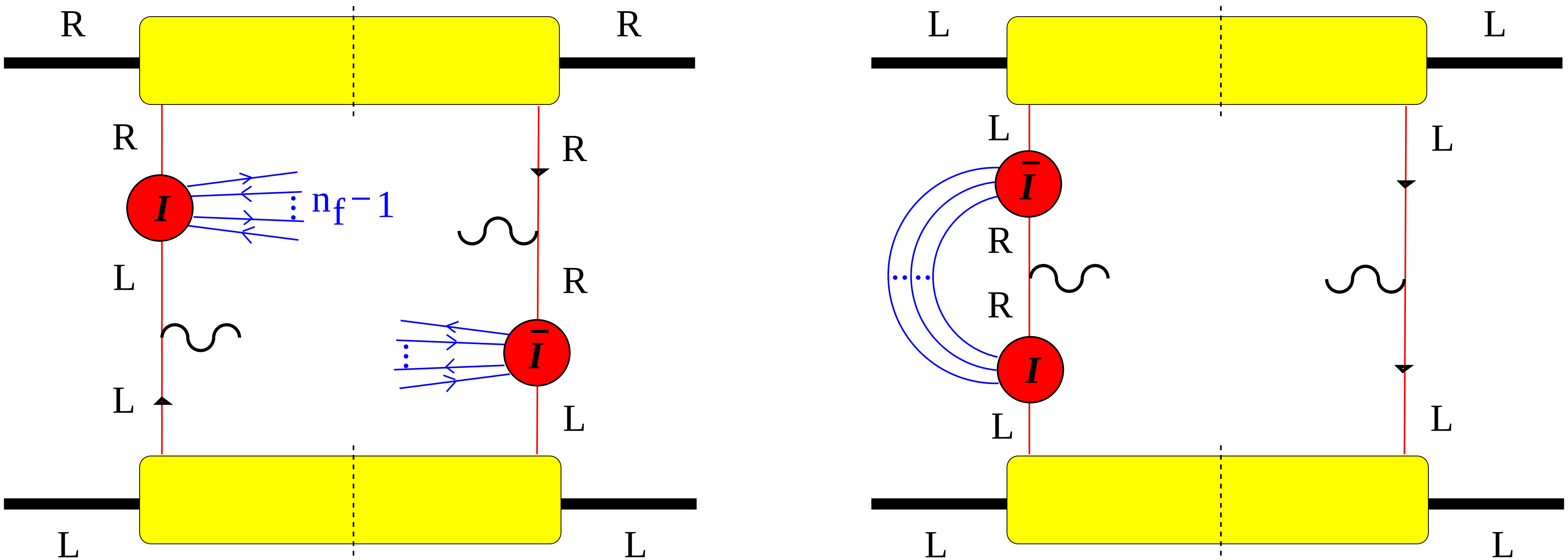
The $\langle \cos 2\phi \rangle$ in $e\,p \rightarrow e'\,\pi\,X$ would be $\propto h_1^\perp H_1^\perp$

$H_1^\perp$ is the fragmentation function analogue of $h_1^\perp$ (also unknown and unrelated in magnitude)

Instanton model

A calculation similar to "Instanton induced azimuthal spin asymmetry in DIS", by Ostrovsky & Shuryak, PRD 71 ('05) 014037, can be done

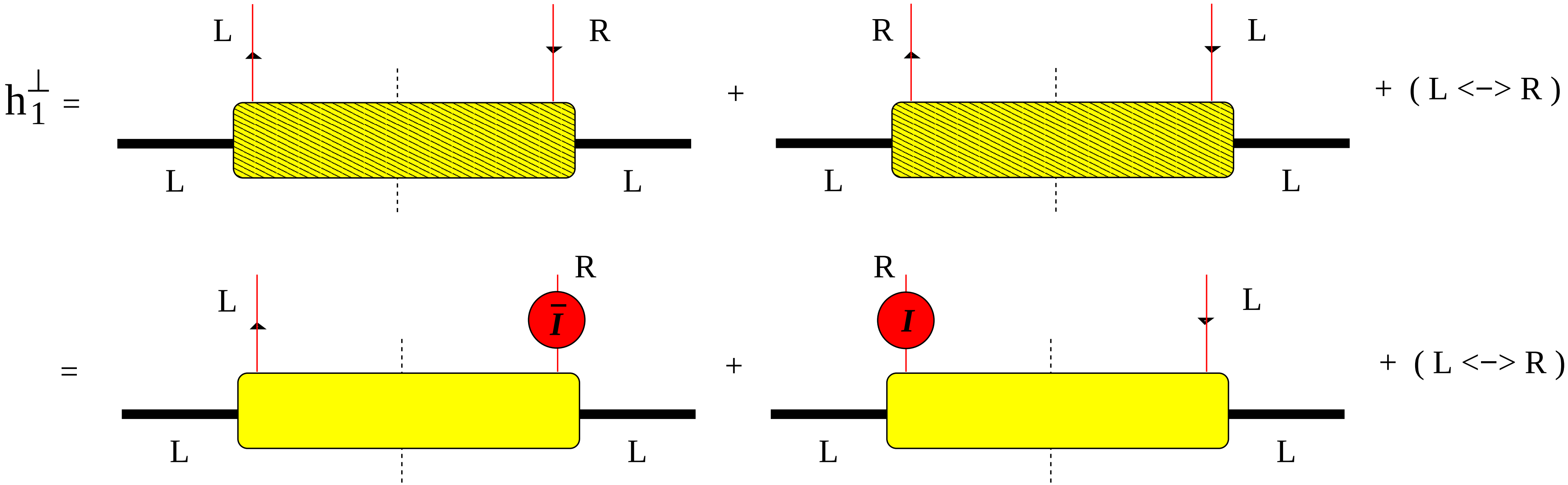
The general $n_f = 3$ case (and $n_g \neq 0$) is non-factorizing, e.g.

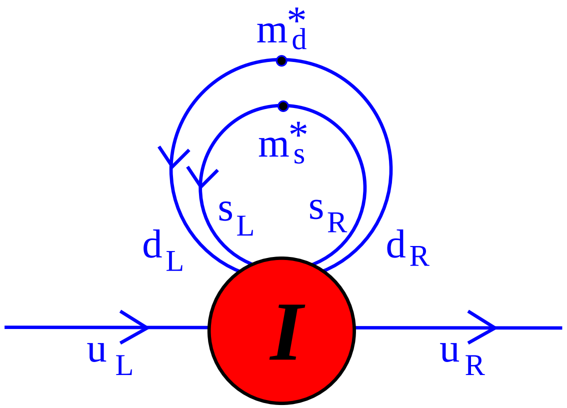


But perhaps suppressed

Instanton model

The effective $n_f = 1$ case is factorizing:





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

Longitudinal jet handedness

Longitudinal jet handedness studied as a means to probe helicity of fragmenting quarks
Nachtmann '77; Efremov, Mankiewicz & Tornqvist, '92; Ryskin '93

A longitudinally polarized, fragmenting quark creates a chromomagnetic field that deflects secondary $q\bar{q}$ pairs in a preferred direction

This leads to a handedness of h^+ and h^- momenta w.r.t. jet axis:

$$X \equiv (\hat{k}_+ \times \hat{k}_-) \cdot \hat{t} = \sin(\phi)$$

The pair is called left-handed if $X > 0$

$$H \equiv \frac{N(X > 0) - N(X < 0)}{N(X > 0) + N(X < 0)} = \alpha P$$

P is the longitudinal quark polarization

SLD ('95): $H < 5\%$ (95 % CL)   DELPHI ('94): $H = (1.2 \pm 0.5)\%$

Application to e^+e^-

Consider the handedness correlation in $e^+ e^- \to 2\,\text{jets}\,X$:

$$C_{LL} \equiv \frac{N(X_1 X_2 < 0) - N(X_1 X_2 > 0)}{N(X_1 X_2 < 0) + N(X_1 X_2 > 0)}$$

Efremov, Potashnikova & Tkatchev, '94

Longitudinal jet handedness is a hadronization phenomenon and is not affected by the opposite side fragmentation

Charge conjugation, $\alpha^{\bar{q}} = -\alpha^q$, leads to $C_{LL} < 0$ expectation

DELPHI data hint at $C_{LL} > 0$

Efremov & Tkatchev, Acta Physica Polonica B 29 ('98) 1385

Influence of chromomagnetic vacuum field in e^+e^-

The nonzero vacuum chromomagnetic field creates a global effect, whereas longitudinal jet handedness is a local effect

Nonzero vacuum chromomagnetic field ($\boldsymbol{B}^a_\parallel$) creates a positive (C-odd)^2 correlation

Estimated to be $C_{LL} \approx +0.5\%$ on the Z pole

Efremov & Kharzeev, PLB 366 ('96) 311

A similar idea was put forward for C_{LL} defined using cumulative momenta

$$\vec{k}^{\pm} = \sum_{\text{jet}} \vec{k}_i^{\pm}$$

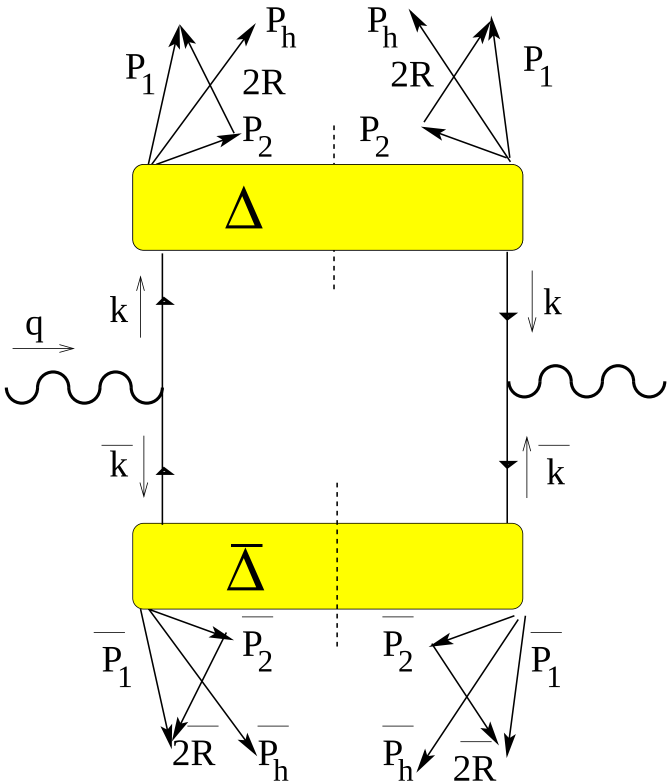
Czyż & Turnau, PRD 53 ('96) 1452

The quark and antiquark need not be polarized on average ($H = 0 \not\Rightarrow C_{LL} = 0$)
The experiment need not be done at the Z-pole

For SLD and DELPHI statistics was a limiting factor, as opposed to BELLE and BABAR, even off-resonance

Two-hadron fragmentation functions

Consider a factorized description in terms of 2-hadron fragmentation functions



$$\begin{aligned}
\Delta &= \Delta(k; P_h, R) \\
P_h &= P_1 + P_2 \\
R &= (P_1 - P_2)/2 \\
z &= z_1 + z_2 = P_h^- / k^- \\
R_T &= (z_1 P_2 - z_2 P_1)/z
\end{aligned}$$

A longitudinally polarized quark leads to a 2-hadron fragmentation function $G_1^\perp(z, M_h^2)$
An analyzer of quark helicity due to a $(\boldsymbol{k}_T \times \boldsymbol{R}_T)$ correlation

In fact, a direct link with longitudinal jet handedness can be made

$G_1^\perp$ definition details

$$\frac{\pi}{2z}\int dk^+ \Delta(k;P_h,R)\Big|_{k^-=P_h^-/z,\mathbf{k}_T} = D_1\, \not{n}_-$$

$$-G_1^\perp \frac{\epsilon_{\mu\nu\rho\sigma}\,\gamma^\mu\, n_-^\nu\, k_T^\rho\, R_T^\sigma}{M_1 M_2}\gamma_5 + H_1^{\sphericalangle}\frac{\sigma_{\mu\nu}\, R_T^\mu\, n_-^\nu}{M_1+M_2} + H_1^\perp \frac{\sigma_{\mu\nu}\, k_T^\mu\, n_-^\nu}{M_1+M_2}$$

Bianconi et al., PRD 62 ('00) 034008

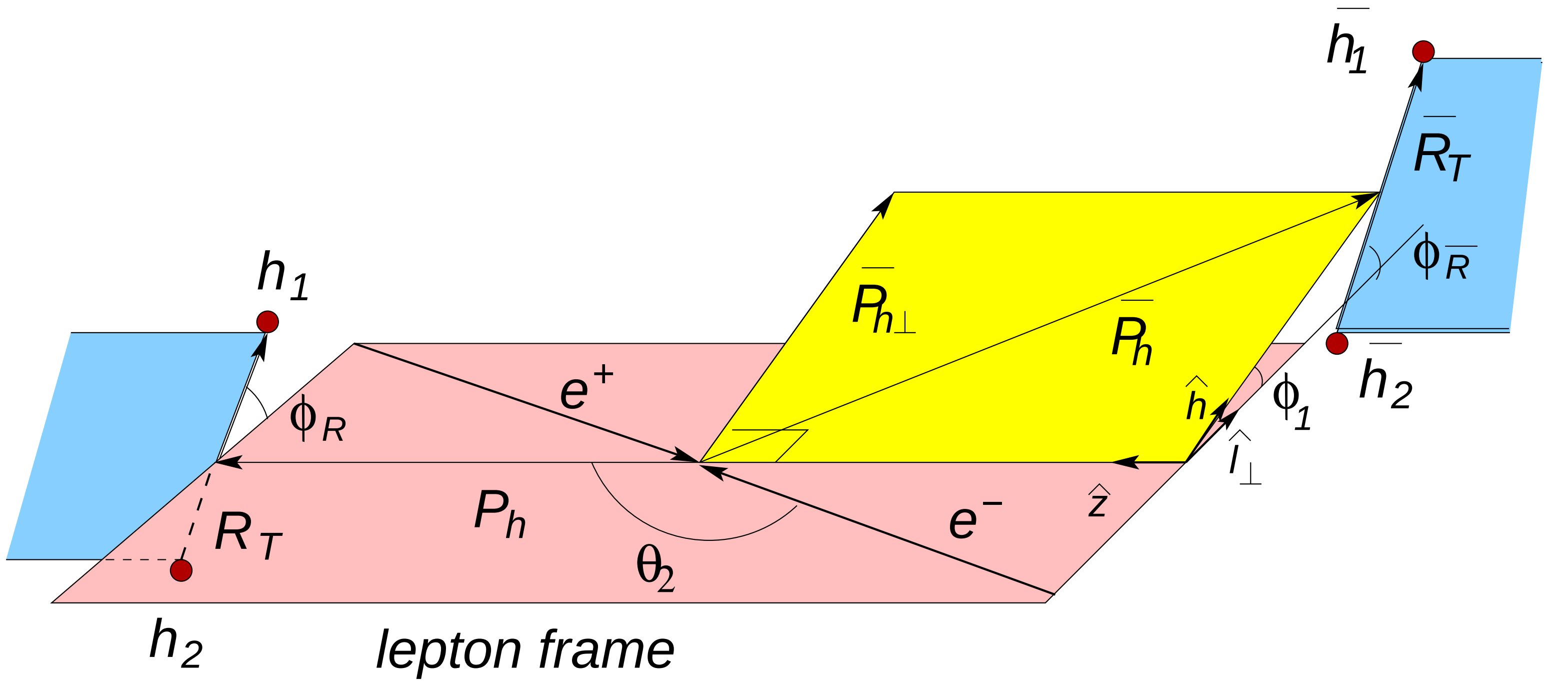
Each function is a function of the quark flavor a and the variables $z, \xi, \boldsymbol{k}_T^2, \boldsymbol{R}_T^2, \boldsymbol{k}_T\cdot\boldsymbol{R}_T$, where $\xi = P_1^-/(P_1^- + P_2^-)$

$$D_1(z, M_h^2) \equiv \int d\xi \int_0^{2\pi} d\phi_R \int d\boldsymbol{k}_T\; D_1(z,\xi,\boldsymbol{k}_T^2,\boldsymbol{R}_T^2,\boldsymbol{k}_T\cdot\boldsymbol{R}_T)$$

$$G_1^\perp(z, M_h^2) \equiv \int d\xi \int_0^{2\pi} d\phi_R \int d\boldsymbol{k}_T\; \boldsymbol{k}_T\cdot\boldsymbol{R}_T\; G_1^\perp(z,\xi,\boldsymbol{k}_T^2,\boldsymbol{R}_T^2,\boldsymbol{k}_T\cdot\boldsymbol{R}_T)$$

It is crucial that one is not dealing with collinear factorization

Azimuthal asymmetry from handedness correlations



$$\langle \cos(2(\phi_R - \phi_{\overline{R}})) \rangle \propto \frac{\sum_{a,\overline{a}} e_a^2 \; z^2 \overline{z}^2 \; G_1^{\perp\, a}(z, M_h^2) \; \overline{G}_1^{\perp\, a}(\overline{z}, \overline{M}_h^2)}{\sum_{a,\overline{a}} e_a^2 \; z^2 \, \overline{z}^2 \; D_1^a(z, M_h^2) \; \overline{D}_1^a(\overline{z}, \overline{M}_h^2)}$$

D.B., Jakob, Radici, PRD 67 ('03) 094003

$G_1^{\perp}$ asymmetry

$$\langle \cos(2(\phi_R - \phi_{\overline{R}}))\rangle \propto \frac{\sum_{a,\overline{a}}\, e_a^2\, z^2 \overline{z}^2\, G_1^{\perp\,a}(z, M_h^2)\, \overline{G}_1^{\perp\,a}(\overline{z}, \overline{M}_h^2)}{\sum_{a,\overline{a}}\, e_a^2\, z^2\, \overline{z}^2\, D_1^a(z, M_h^2)\, \overline{D}_1^a(\overline{z}, \overline{M}_h^2)}$$

The partonic process requires nonzero parton transverse momentum, but the measurement does not require determination of $\overline{P}_h^{\perp}$

Note that indeed the quark and antiquark need not be polarized on average for this correlation to be nonzero; it need not be measured on the Z pole

Expectation for B-factories: no average jet handedness in each jet separately

Longitudinal jet handedness

In the process $e\,\vec{p} \to e'\,(h_1 h_2)\,X$ there is an azimuthal asymmetry $\propto g_1 G_1^\perp$ as expected from longitudinal jet handedness

$$\frac{d\sigma(e\vec{p} \to e' h_1 h_2 X)_{OL}}{d\Omega\, dx\, dz\, d\xi\, d\boldsymbol{P}_{h\perp}\, d\boldsymbol{R}_T} \propto -\lambda\, |\boldsymbol{R}_T|\; A(y)\; \sin(\phi_h - \phi_R)\; \mathcal{F}\left[\hat{h}\cdot\boldsymbol{k}_T\, \frac{g_1\, G_1^\perp}{M_1 M_2}\right]$$

Bianconi et al., PRD 62 ('00) 034008

Nowadays g_1 is known to good accuracy, one can extract $G_1^\perp$ from $e\,\vec{p} \to e'\,(h_1 h_2)\,X$ and predict the longitudinal jet handedness correlation in $e^+e^- \to (h_1 h_2)(\bar{h}_1 \bar{h}_2) X$

Any experimental deviation from factorization may be related to a CP-violating effect of the QCD vacuum

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
- RHIC can provide valuable information on these dependences

- Longitudinal spin correlations lead to an azimuthal asymmetry in $e^+ e^- \to 2\,\text{jets}\,X$
- Such a handedness correlation can arise from QCD vacuum or jet handedness
- Proposal: study $\langle\cos(2(\phi_R - \phi_{\overline{R}}))\rangle$ at BELLE/BABAR and relate it to SIDIS

- Azimuthal asymmetries allow to study the issue of factorizing hadronic effects versus nonfactorizing QCD vacuum effects