When collinear factorization fails
An anomalous asymmetry in Drell-Yan

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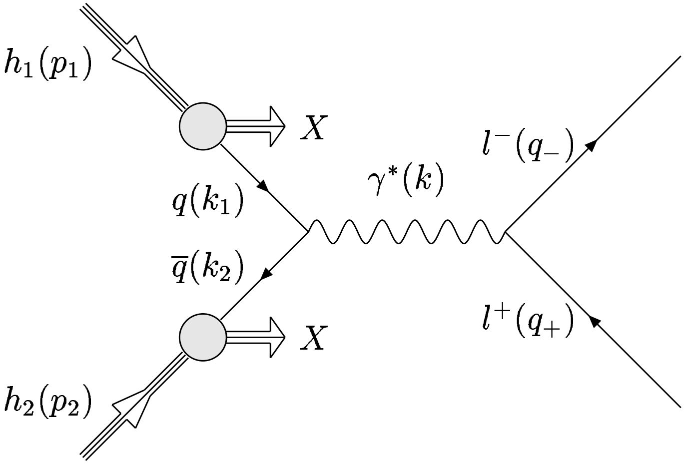
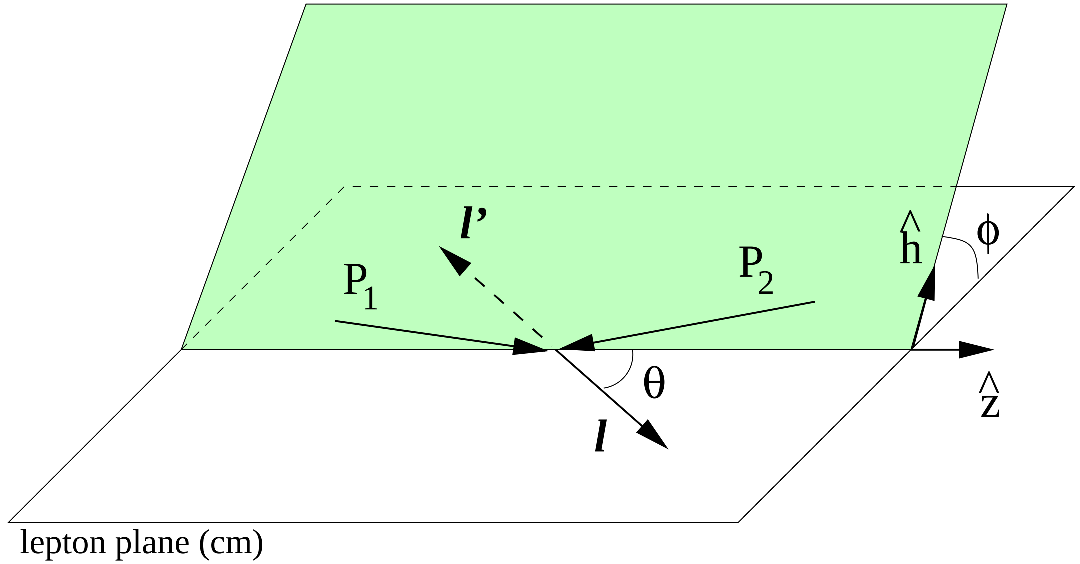
Outline

- Anomalous asymmetry in Drell-Yan
- Standard explanations seem to fail
- Alternative explanations: a QCD vacuum effect? a hadronic effect?
- An instanton model
- Recent experimental results
- A lattice QCD result
- Conclusions

Angular asymmetries in Drell-Yan in theory

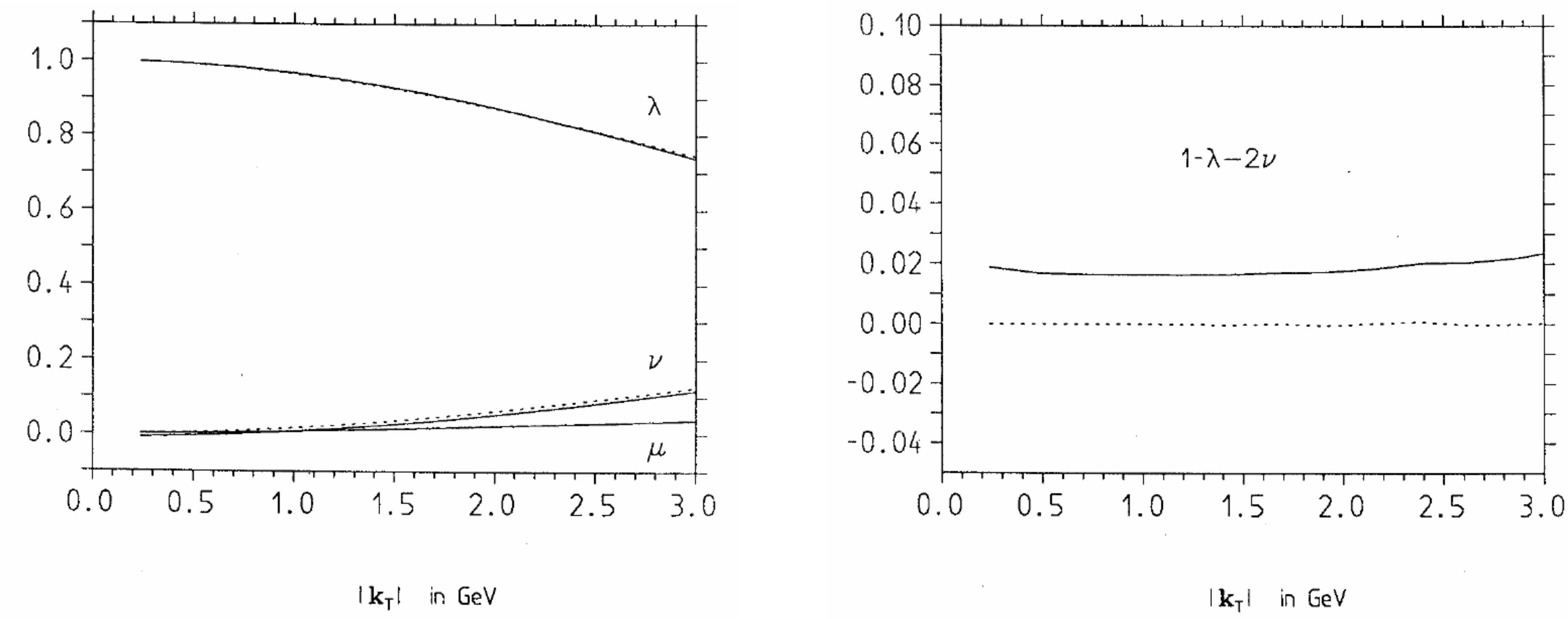




$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega} \propto \left(1 + \lambda\cos^2\theta + \mu\sin 2\theta\,\cos\phi + \frac{\nu}{2}\sin^2\theta\cos 2\phi\right)$$

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

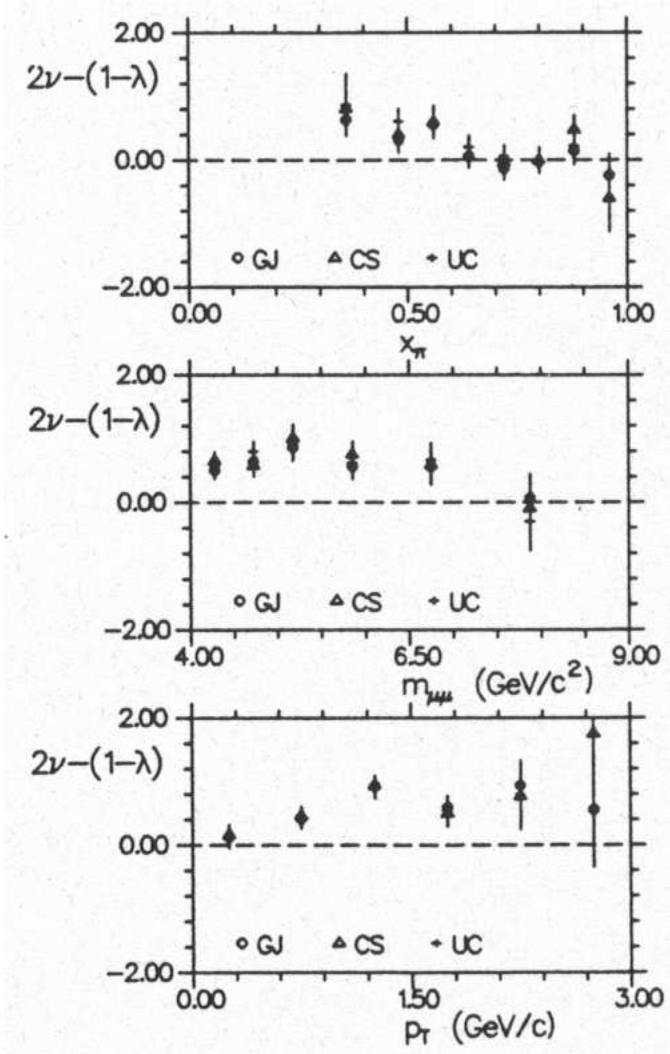
Angular asymmetries in Drell-Yan in theory



Dashed lines: $\mathcal{O}(\alpha_s)$; Solid lines: $\mathcal{O}(\alpha_s^2)$; $Q = 8$ GeV

Brandenburg, Nachtmann & Mirkes, ZPC 60 (1993) 697

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

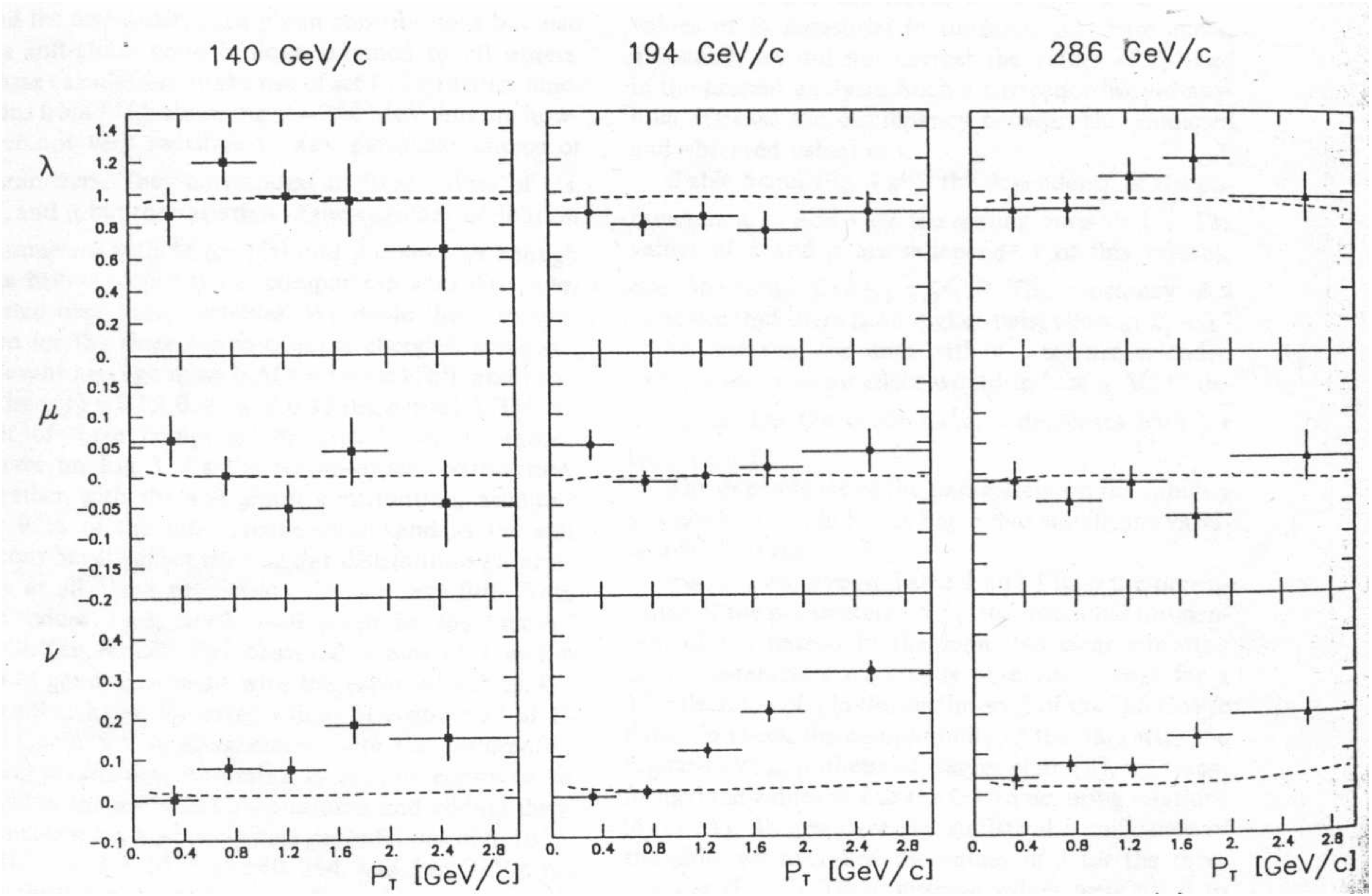
lepton pair invariant mass $Q \sim 4 - 12$ GeV

Figure: E615 data

Large deviation from Lam-Tung relation!

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

CERN-NA10 DY data



Standard explanations seem to fail

Perturbative QCD at NLO fails to describe the data

What about even higher order perturbative corrections?

- If NNLO corrections would be large, the perturbative expansion cannot be trusted

What about resummation?

- The Lam-Tung relation is unaffected at LLA: $\alpha_s^k \ln^{2k-1}(Q^2/Q_T^2)/Q_T^2$

  D.B. & Vogelsang, PRD74 (2006) 014004

Dismiss it as purely soft physics (completely nonperturbative)?

- Higher twist effects (data does not follow HT expectations)
- Nuclear effect (deuterium - tungsten comparison rules this out)

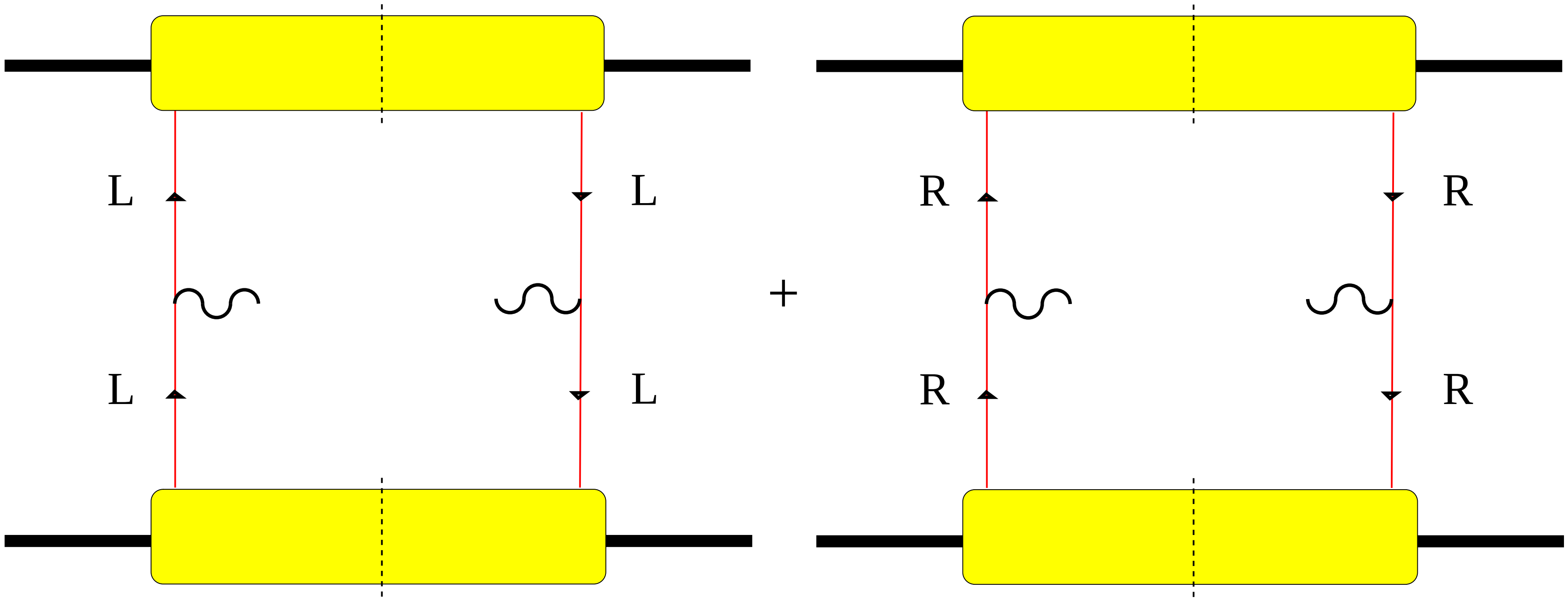
The DY process at $Q \sim 4 - 12$ GeV usually *is* described by collinear factorization

The ϕ-integrated cross section does not pose a problem

Collinear factorization

Collinear quarks ($p_{\text{quark}} = xP_{\text{hadron}}$) inside unpolarized hadrons are unpolarized too

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



Angular asymmetries require nontrivial spin density

In general, the spin density matrix could be of the form:

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

Spin density matrix does not necessarily factorize: $H_{ij} \stackrel{?}{=} F_i G_j$

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

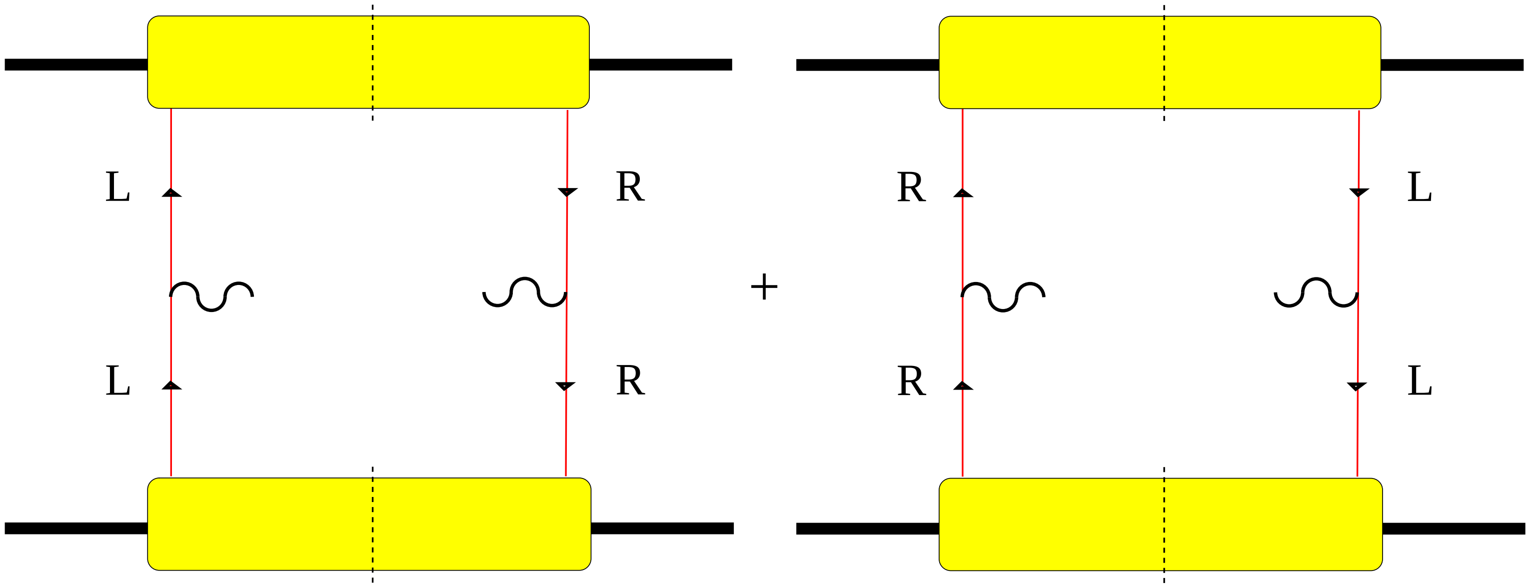
More specifically,

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

Brandenburg, Nachtmann & Mirkes, ZPC 60 (1993) 697

Angular asymmetry requires helicity flip

The $\cos 2\phi$ asymmetry arises from an interference between $+1$ and -1 photon helicities



This requires transversely polarized quark-antiquark annihilation

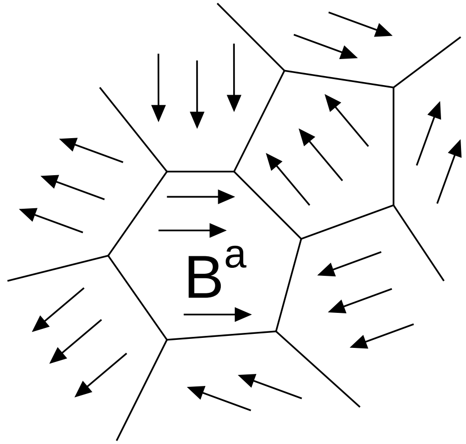
The question is: how can this transverse polarization arise?

Could it be a QCD vacuum effect?

The gluon condensate leads to an average 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

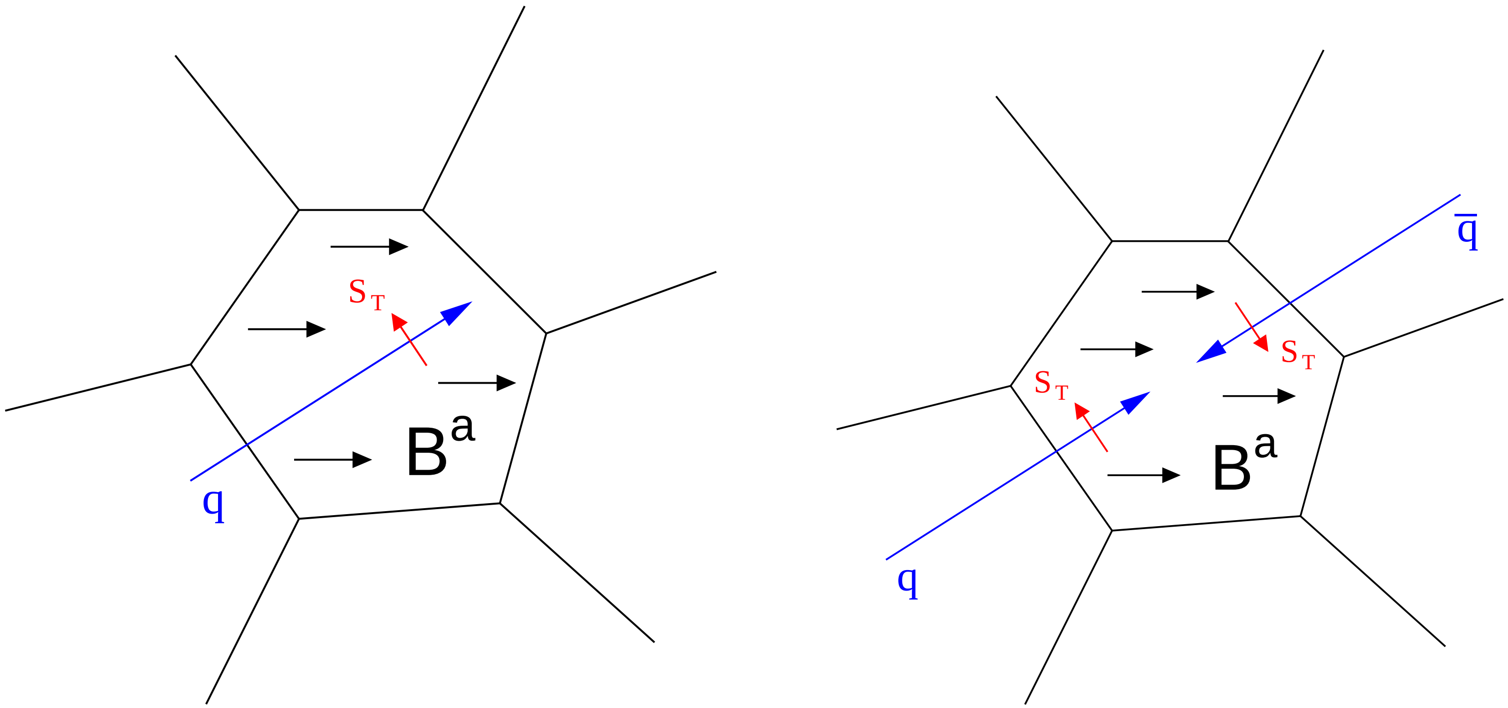
Time for traversing such a vacuum domain: $t \approx a$

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

Anomalous asymmetry from a QCD vacuum effect



On average no quark polarization, but a spin correlation between an annihilating $q\,\bar{q}$

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

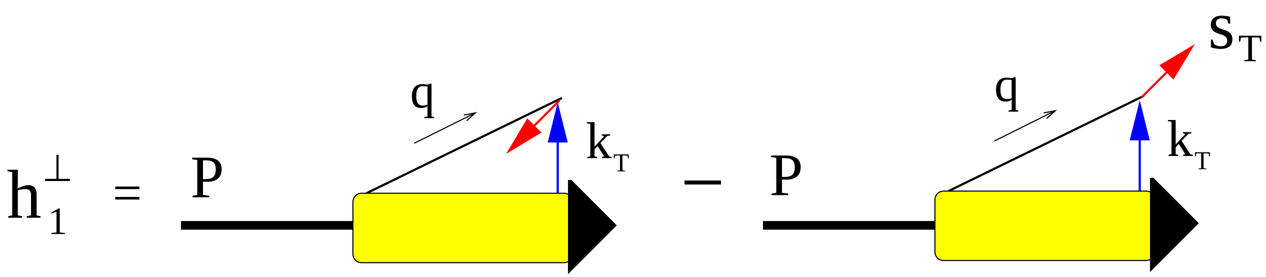
Beyond collinear factorization

A less exotic option is to drop the assumption of *collinear* factorization, i.e. to allow for k_T dependence in the quark distribution

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

A kind of intrinsic handedness allowed by parity & time reversal invariance

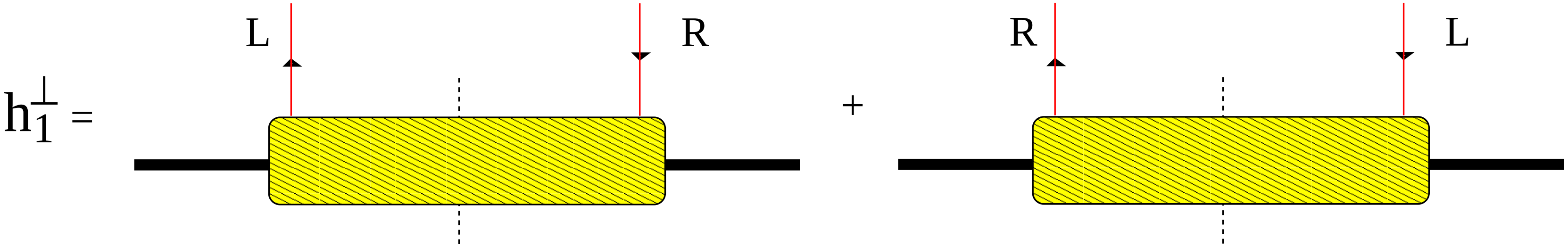
$$S_T^q \sim P_{\text{hadron}} \times p_{\text{quark}}$$



A formal nonlocal operator matrix element definition can be given

D.B. & Mulders, PRD 57 (1998) 5780

Anomalous asymmetry could be a hadronic effect



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

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

Simple model for k_T dependence of $h_1^\perp$ allows for a good description of the data

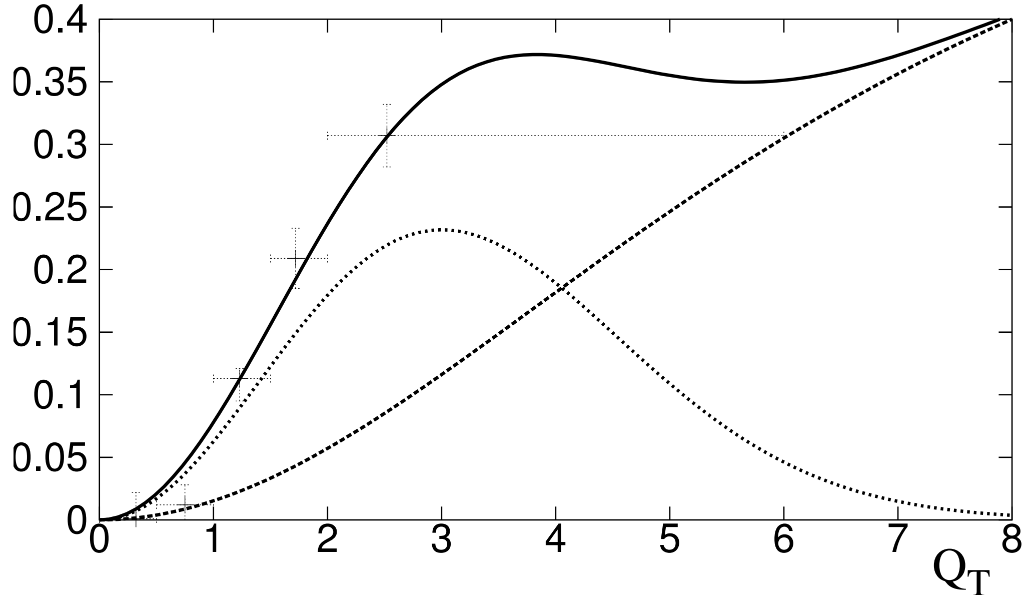
D.B., PRD 60 (1999) 014012

Explaining the unpolarized DY data

Small and large Q_T contributions to ν compared to one NA10 data set:

$Q = 8$ GeV

Beam energy 194 GeV



Perturbative gluon radiation (to first order in α_s) gives rise to

$$\nu(Q_T) = \frac{Q_T^2}{Q^2 + \frac{3}{2}Q_T^2} \qquad \text{(but } \kappa = 0\text{)}$$

Collins, PRL 42 ('79) 291

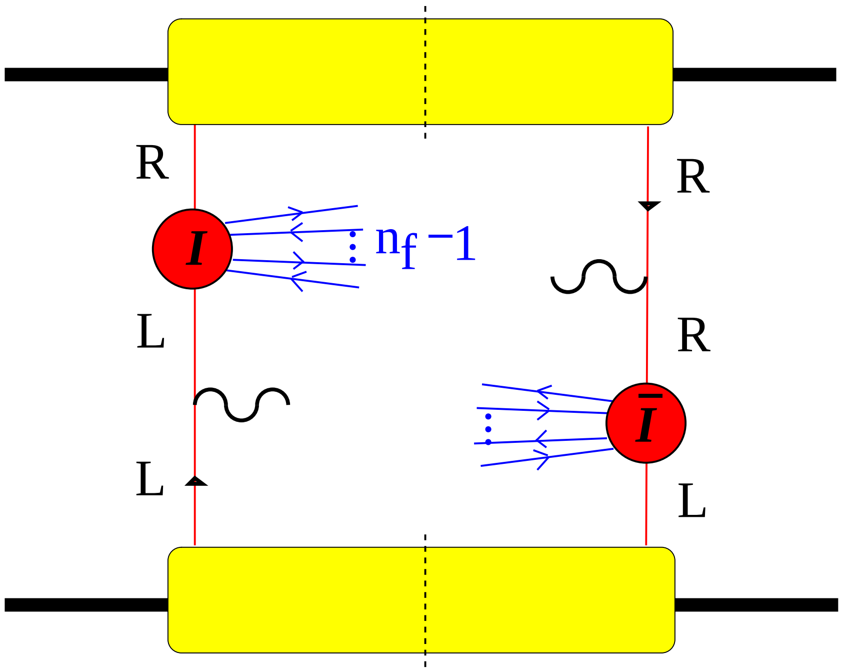
Hadronic effect versus vacuum effect

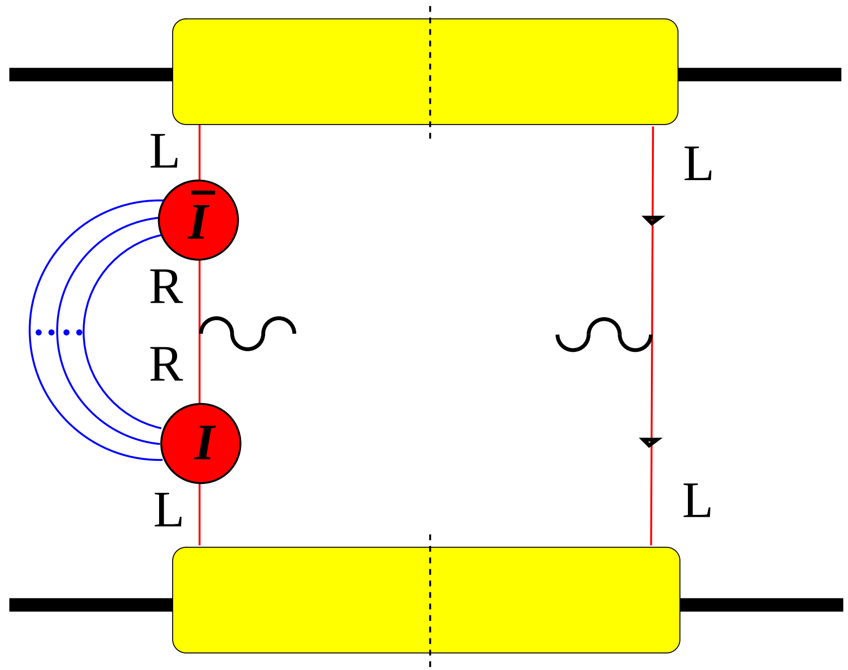
	$h_1^\perp \neq 0$	QCD vacuum effect
$\rho^{(q,\bar{q})}$	$\rho^{(q)} \otimes \rho^{(\bar{q})}$	possibly entangled
Q dependence	$\kappa \sim 1/Q$	?
large Q_T limit	$\kappa \longrightarrow 0$	need not disappear ($\kappa \longrightarrow \kappa_0$)
flavor dependence	yes	flavor blind
x dependence	yes	yes,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

D.B., Brandenburg, Nachtmann & Utermann, EPJC 40 (2005) 55

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

Instanton contributions to DY cross section

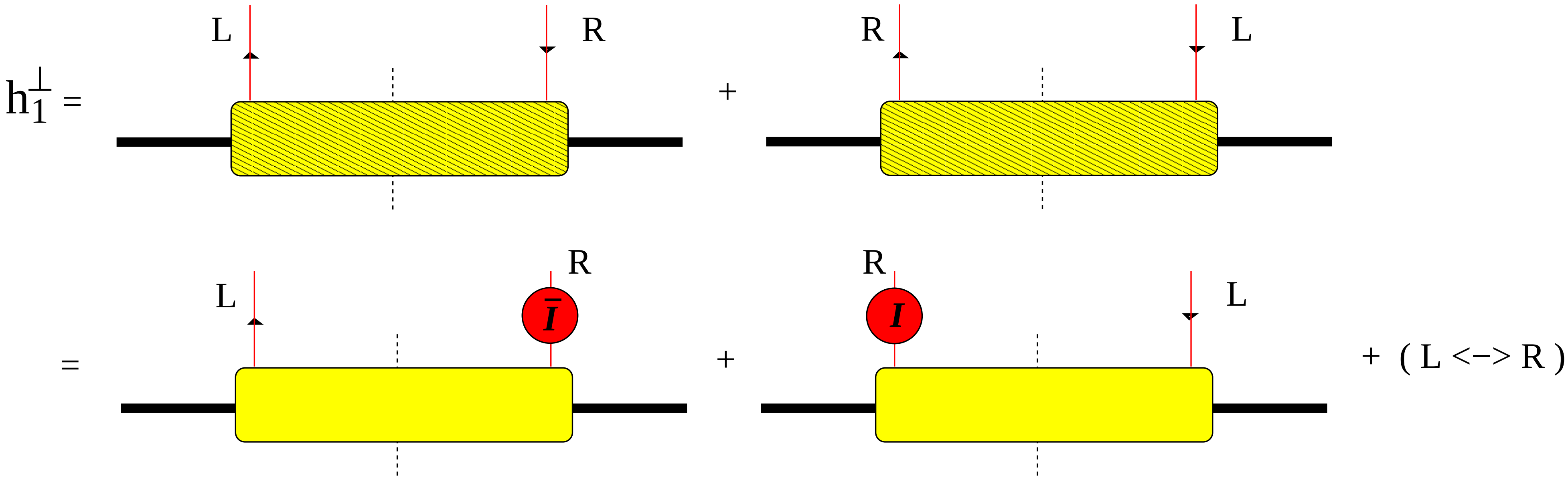


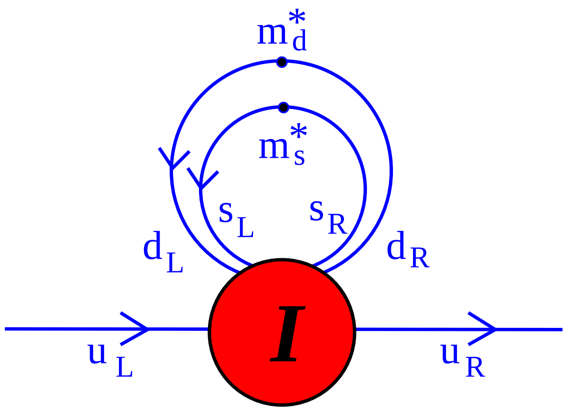


Reliably calculable for large Q^2 - leads to significant violations of Lam-Tung relation

Brandenburg, Ringwald & Utermann, NPB754 (2006) 107

Effective instanton model for $h_1^\perp$



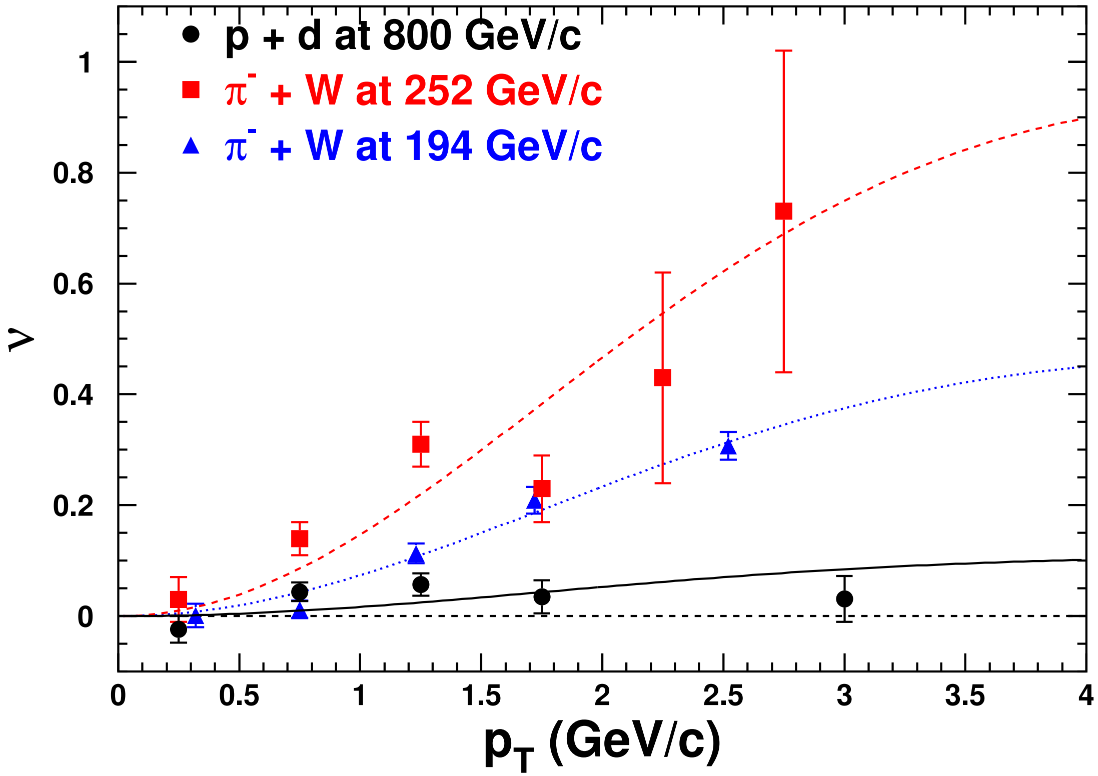


$$m_q^* = m_q - \frac{2\pi^2}{3}\rho^2\langle 0|\bar{q}q|0\rangle$$

m_q^* is not small, thanks to spontaneous χSB

Recent experimental results

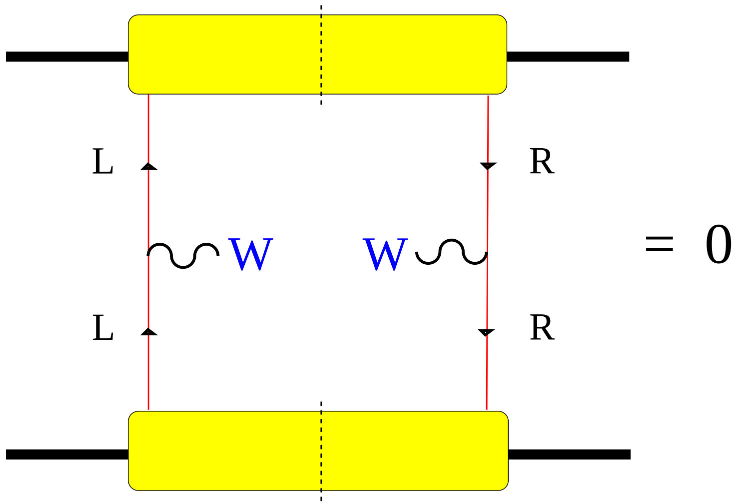
New $p\,d$ DY data from Fermilab

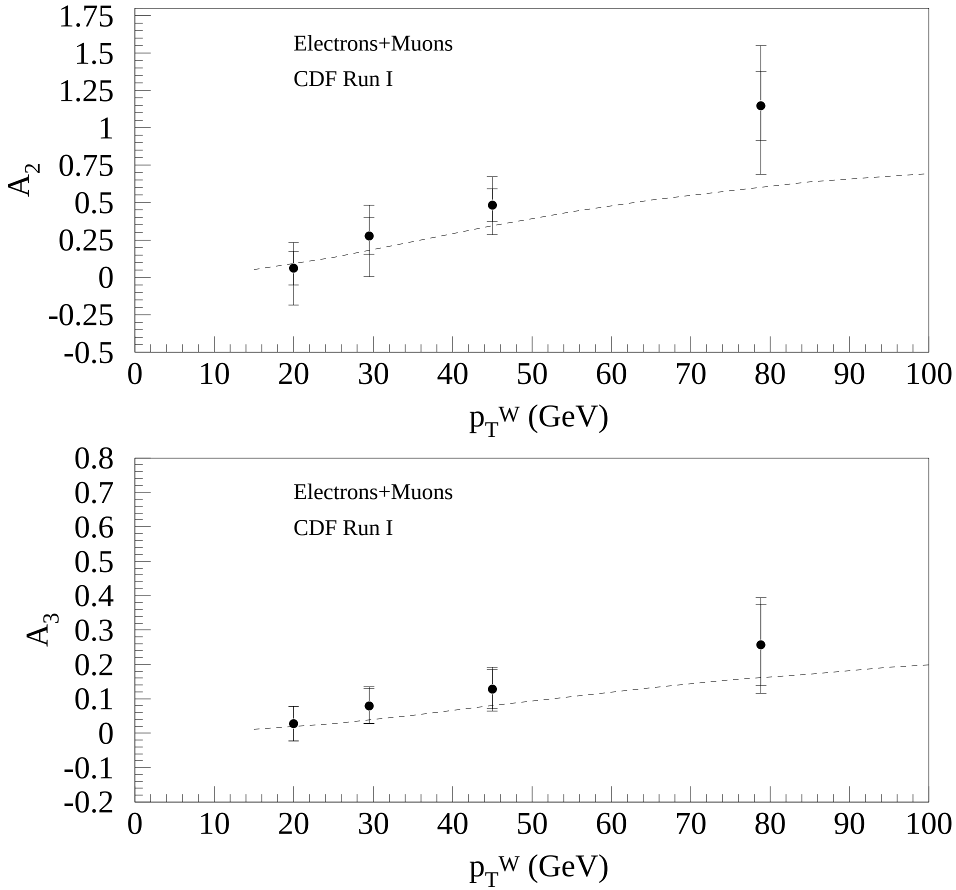


FNAL-E866/NuSea Collaboration, L.Y. Zhu *et al.*, PRL 99 (2007) 082301

Natural to expect $\nu(p\,p) \ll \nu(\bar{p}\,p) \approx \nu(\pi\,p)$, due to valence antiquarks in $\bar{p}$ and π

No deviation from Lam-Tung in W production





W couples only to lefthanded quarks

$\bar{p}\,p \rightarrow W\,X \rightarrow \ell\,\nu_\ell\,X$ data consistent with NLO pQCD prediction

No need/room for extra contributions

CDF Collab., D. Acosta *et al.*, PRD 73 (2006) 052002

Future experimental tests

Future DY data

RHIC: $p\,p$ collisions

Fermilab: $\bar{p}\,p \to Z\,X$

CERN: $\pi\,p$ COMPASS experiment

GSI: $\bar{p}\,p$ collisions

Factorized approach in terms of k_T-dependent functions can be tested through the consistency among the predictions for other processes (e.g. $e\,p$ scattering)

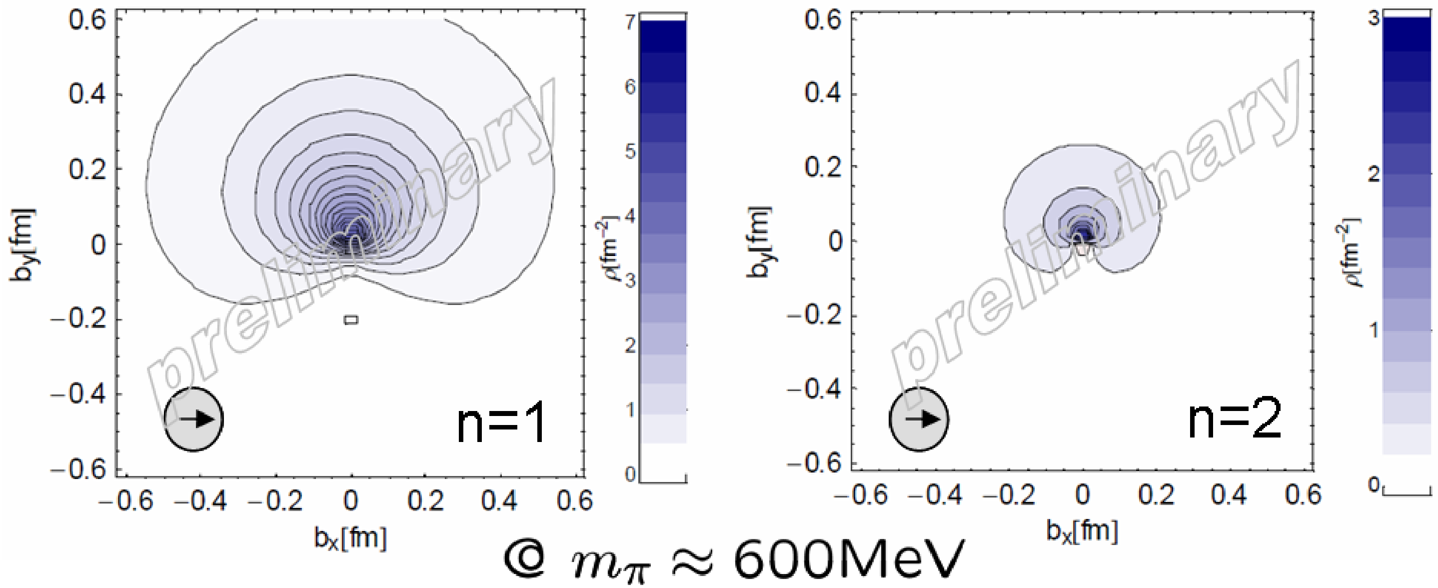
Also, polarized hadron experiments will be helpful (RHIC/GSI)
k_T dependence can lead to additional spin-depedent angular asymmetries

Lattice QCD

$h_1^\perp$ may be related to an asymmetric spatial (impact parameter) distribution of transversely polarized quarks inside an unpolarized hadron

Burkardt, NPA 635 (2004) 185

Hägler recently showed at DIS 2007 the first lattice results relevant for this distribution inside the pion:



There is a clear $b_T \times s_T$ correlation inside a pion

Conclusions

- A large violation of the Lam-Tung relation has been observed in experiment
- The violation strongly disagrees with NLO pQCD
- $q^{\uparrow}\bar{q}^{\uparrow}$ annihilation leads to a $\cos 2\phi$ asymmetry
- Such transverse spin correlation can arise from QCD vacuum or noncollinear partons
- Flavor dependence would favor a hadronic effect
- Persistence of the asymmetry at large Q_T and Q favors a vacuum effect
- Recent $p\,d$ DY data and $\bar{p}\,p \to W\,X$ data do follow standard expectations
- Lattice shows a $b_T \times s_T$ correlation which may support a $k_T \times s_T$ correlation
- Collinear factorization is an approximation that may fail in multiscale processes