Challenges of spin physics

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This talk will be about the physics of:

polarization in high energy collisions

The interesting challenges lie in the hadronic part of this story

Goal of spin physics: To understand the spin structure of hadrons in terms of quarks and gluons

Outline:

A short overview of the types of available spin physics data
Next, the theoretical description of this kind of data and the open problems related to that

Polarized structure functions

The cross section for the inclusive DIS process $e\,p \to e'\,X$ is proportional to the contraction of the lepton tensor with the hadron tensor $W_{\mu\nu}$

$$W_{\mu\nu}(P,q) \quad = \quad \frac{1}{4\pi}\int d^4x e^{iq\cdot x}\langle P|[J_\mu(x),J_\nu(0)]|P\rangle$$

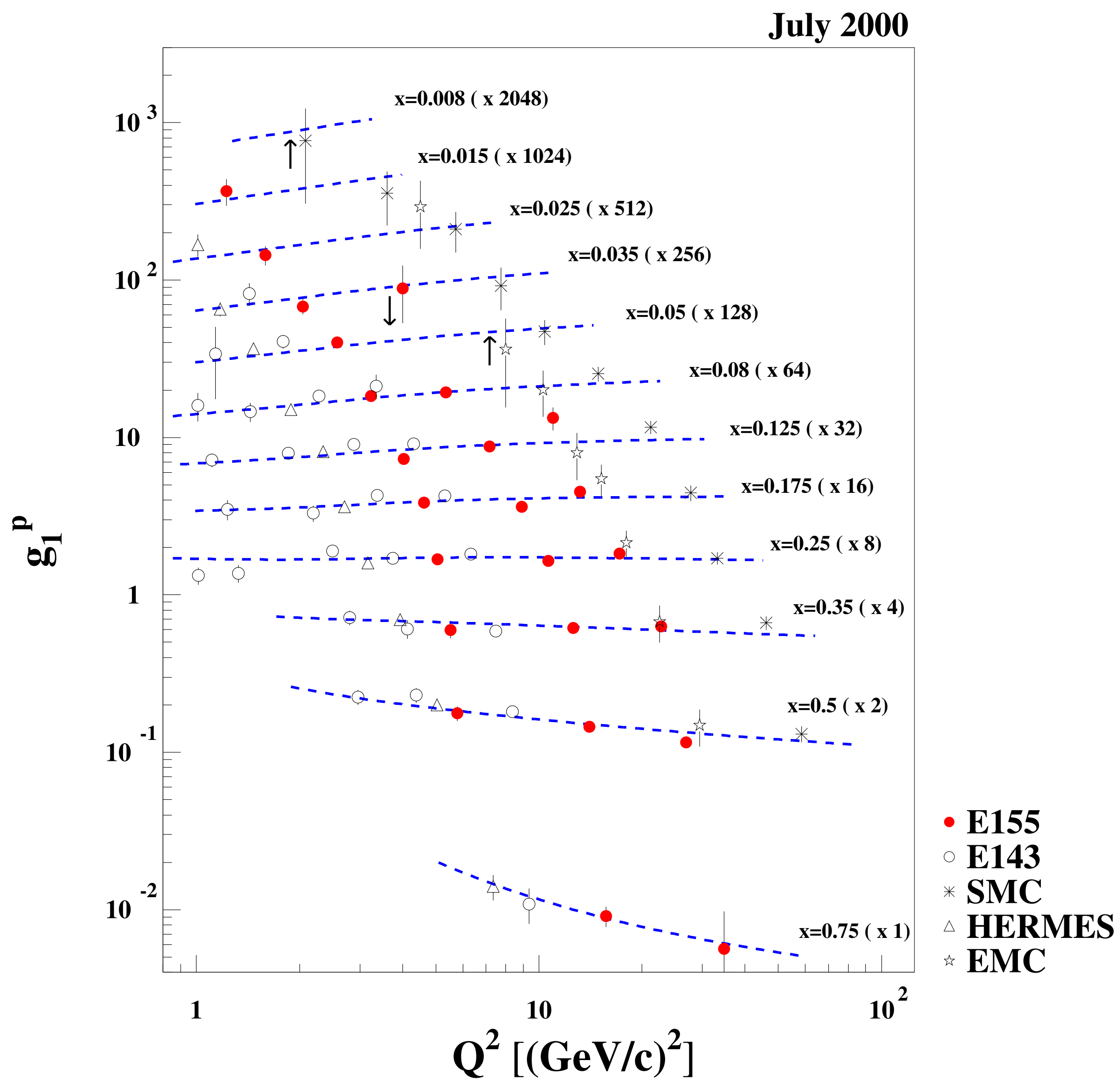
which for a polarized spin-$1/2$ hadron (and E.M. currents) is parameterized in terms of the structure functions g_1, g_2

$$W_A^{\mu\nu} = \frac{i\epsilon^{\mu\nu\rho\sigma}q_\rho}{P\cdot q}\left[S_\sigma g_1(x_{_B},Q^2) + \left(S_\sigma - \frac{S\cdot q}{P\cdot q}P_\sigma\right) g_2(x_{_B},Q^2)\right]$$

where $x_{_B} = Q^2/2P\cdot q$ and $Q^2 = -q^2$

$\{g_1, g_2\}$ are obtained from $A_{P_e P_p} = \{A_{LL}, A_{LT}\}$ asymmetries in $\vec{e}\,\vec{p} \to e'\,X$, $\vec{e}\,p^\uparrow \to e'\,X$

Polarized structure functions



Taken from the E155 Collaboration webpage

Distribution functions

Definition of structure functions is independent of the constituents of the hadron

The OPE or the pQCD improved parton model allows one to go to the quark-gluon level, i.e. the polarized structure functions are expressed in terms of parton distribution functions (tree level):

$$g_1(x_B) = \sum_{a,\bar{a}} \frac{e_a^2}{2} g_1^a(x_B) \qquad \text{and} \qquad g_1(x_B)+g_2(x_B) = \sum_{a,\bar{a}} \frac{e_a^2}{2} g_T^a(x_B)$$

$$\frac{d\sigma(\vec{e}\vec{p} \to e' X)}{dx_B\, dy} = \frac{4\pi\alpha^2 s}{Q^4} \sum_{a,\bar{a}} e_a^2 \left\{ \left(\tfrac{y^2}{2}+1-y\right) x_B f_1^a(x_B) \right.$$

$$\left. + y(1-\tfrac{y}{2})\, \lambda_e\, \lambda_p\, x_B g_1^a(x_B) - 2y\sqrt{1-y}\, \lambda_e\, |\boldsymbol{S}_T| \cos(\phi_S^e)\, \frac{M}{Q}\, x_B^2\, g_T^a(x_B) \right\}$$

g_1^a is the density of longitudinally polarized quarks inside a longitudinally polarized proton

g_T^a is not a parton *density* and enters a power suppressed azimuthal spin asymmetry A_{LT} in the cross section

Spin asymmetries in hadron production

The direction of produced hadrons can be correlated with the polarization of one or more particles in the collision

Large single spin asymmetries are observed in $p + p^\uparrow \to \pi + X$
Here $\vec{p}_\pi \perp \vec{S}_T$ (a left-right asymmetry)

$$A_N = \frac{\sigma(p\, p^\uparrow \to \pi\, X) - \sigma(p\, p^\downarrow \to \pi\, X)}{\sigma(p\, p^\uparrow \to \pi\, X) + \sigma(p\, p^\downarrow \to \pi\, X)}$$

Also asymmetries in $p + p \to \Lambda^\uparrow + X$ and in $p + p^\uparrow \to \Lambda^\uparrow + X$

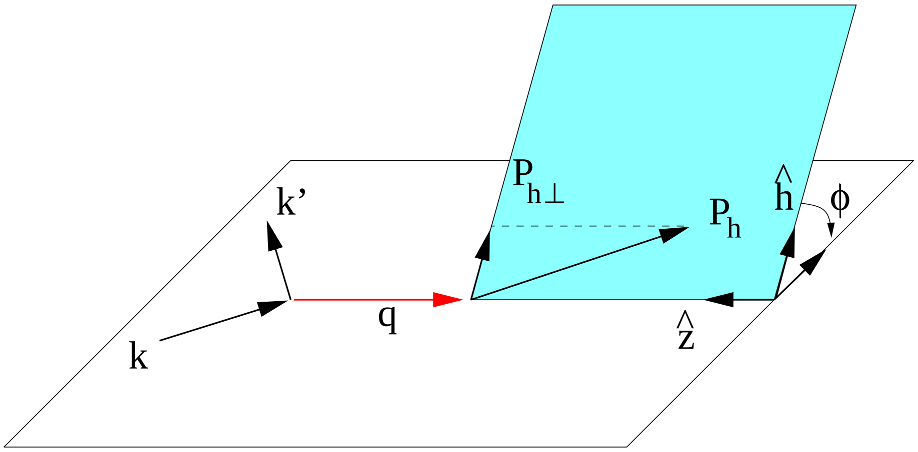
Especially single transverse spin asymmetries are not understood
It is not clear how to go to the quark-gluon level

Suggested mechanisms:
$\boldsymbol{k}_T$-dependent distributions; higher twist; semi-classical models

The Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory is expected to deliver high $\sqrt{s}$ and p_T data
($\sqrt{s}$ of 200 and 500 GeV)

Azimuthal spin asymmetries

More recently, azimuthal spin asymmetries in semi-inclusive DIS ($e + p \to e' + \pi + X$) have been reported



HERMES Collaboration: nonzero A_{UL}
CLAS Collaboration (Jefferson Lab): nonzero A_{LU}

These "DIS" data are at low Q^2 $\quad \langle Q^2 \rangle \sim 1 - 3$ GeV^2

Soon also data from HERMES expected on A_{UT}

Also, HERMES and CLAS have observed nonzero A_{LU} in Deeply Virtual Compton Scattering ($e + p \to e' + \gamma + p$) $\sim$ GPDs

An order of magnitude larger than the semi-inclusive DIS ones

Sketchy overview of challenges (I)

C1: To describe the complete spin structure of hadrons
In terms of specific operator matrix elements

C1a: Not only the leading twist functions of x, Q^2
But also as function of $\boldsymbol{k}_T$; ξ, t; ...
Structure functions; parton distributions; GPDs
Orbital angular momentum; Spin sum rule

C1b: Evolution equations; higher twist

C2: To describe measurable processes in terms of the above objects

C2a: Factorization theorems

C2b: pQCD evolution, including process dependent parts

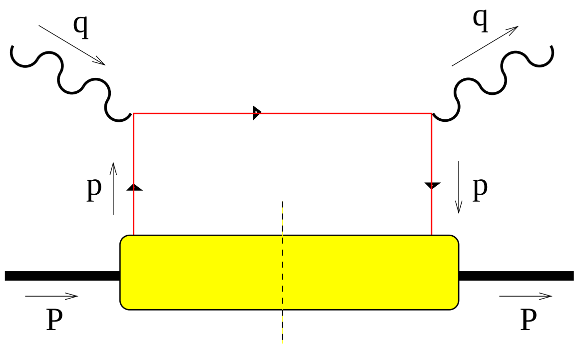
(More later)

Spin structure of the proton

As a first objective one wants to obtain a complete map of the spin structure of the proton (as function of x and Q^2)

At leading twist this entails: knowing g_1^a for all quark flavors and for gluons and h_1^a for all quark flavors
(There is no gluon analogue of transversity)

$g_1^q = \Delta q$ is fairly well-known, but less for the sea contributions ($\Delta s, \Delta\bar{q}$); the gluon contribution: $g_1^g = \Delta g$ is still hardly constrained and $h_1^q = \delta q$ is unknown (no data)

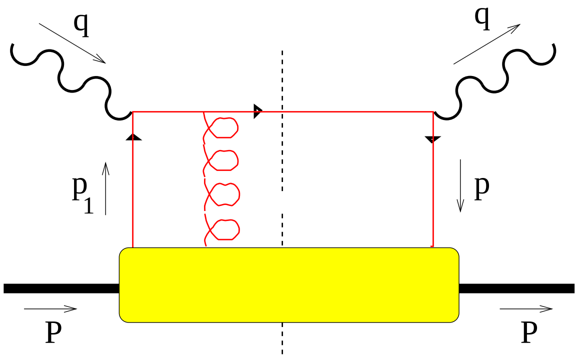


$$
\begin{aligned}
\Phi(x) &= \int \frac{d\lambda}{2\pi}\, e^{i\lambda x}\, \langle P, S|\overline{\psi}(0)\, \mathcal{L}[0,\lambda]\, \psi(\lambda)|P, S\rangle \\
&= \frac{1}{2}\left[f_1(x)\, \not{P} + g_1(x)\, \lambda\gamma_5\, \not{P} + h_1(x)\, \gamma_5\, \not{S}_T\, \not{P} \right] + \text{H.T.}
\end{aligned}
$$

Spin structure of the proton

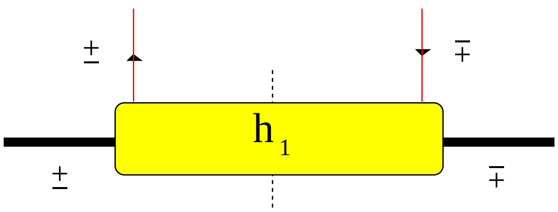
At subleading order in $1/Q$, $\Phi(x)$ must be expanded further

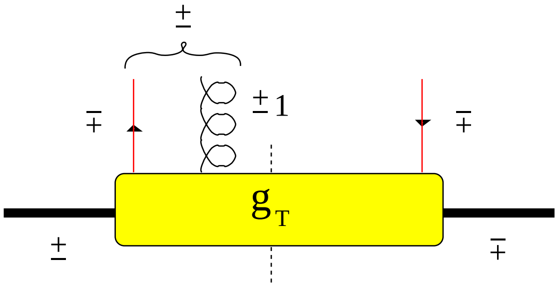
$$\Phi(x) = \frac{1}{2}\left[f_1(x)\,\not{P} + g_1(x)\,\lambda\gamma_5\,\not{P} + h_1(x)\,\gamma_5\,\not{S}_T\,\not{P}\,\right] + \frac{M}{2}g_T(x)\gamma_5\,\not{S}_T + \text{other higher twist}$$



Dynamical power corrections $1/Q^n$

h_1 and g_T both depend on S_T, but are not related





The transversity function h_1 does not appear in inclusive DIS (Or rather, it is heavily suppressed)

Spin structure of the proton

Evolution: of f_1, g_1, h_1 known to NLO; of g_T to LO

No sign yet of the role of gluons in the transverse spin of the proton

$$d_2 = 3 \int_0^1 x^2 \, g_2(x)|_{\text{twist-3}} \, dx$$

E155x data: $d_2^p = 0.0032 \pm 0.0017$ [hep-ex/0204028]

JLab goal: measure $g_2^n|_{\text{twist-3}}$

One also wants to understand the detailed spin structure of the neutron and of hyperons like Λ's

The latter in terms of fragmentation functions (for $G_1(z)$ some information is available, nothing for $H_1(z)$)

But even at leading twist one actually wants to learn about even more complicated functions, namely as function of the transverse momentum and so-called generalized parton distributions

Spin sum rule

Another leading twist goal: to complete the spin sum rule

Sum of the contributions to the proton spin add up to 1/2

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta g + L_z + \stackrel{?}{\ldots}$$

$\Delta\Sigma = \Delta u + \Delta d + \Delta s \qquad (\Delta q = g_1^q)$

Only x integrated information enters in the sum rule

$\Delta q = \int_0^1 dx\,[(q_+ - q_-) + (\bar{q}_+ - \bar{q}_-)]; \quad \Delta g = \int_0^1 dx\,[g_+ - g_-]$

Naive parton model: $\Delta\Sigma = 1$

Hyperon decay data & $\Delta s = 0 \longrightarrow \Delta\Sigma \sim 0.6$

Experiment: $\Delta\Sigma \sim 0.3, \quad \Delta s \sim -0.1 \qquad$ [Spin crisis]

One wants to find a way to get at the orbital angular momentum (OAM) of the quarks and gluons inside the proton

Orbital angular momentum

$$\begin{aligned}\frac{1}{2} &= \frac{1}{2}\Delta\Sigma + \Delta g + L_z \\ &= \frac{1}{2}\Delta\Sigma + L_q + J_g\end{aligned}$$

Problem: Is $L_z = L_q + L_g$ or $J_g = \Delta g + L_g$?

Appears not to be the case, unless one chooses a specific gauge or a specific frame (not Lorentz invariant)

Hard processes have a preferred direction: the probe momentum

Bashinsky, Jaffe, NPB 536 (1998) 303:
A gauge invariant, frame dependent decomposition of AM

$$1/2 = \Delta\Sigma/2 + L_q + \Delta g + L_g$$

This contains as definition of the polarized gluon distribution

$$\Delta g(x) = \frac{i}{4\pi x (P^+)^2} \langle\!\langle\, F^{+\alpha}(0)\, \mathcal{L}[0,\lambda]\, \tilde{F}_\alpha{}^{+}(\lambda n_-)\,\rangle\!\rangle$$

L_q, L_g: no known way of accessing experimentally

Orbital angular momentum

There is another gauge invariant decomposition:

$$1/2 = \Delta\Sigma/2 + L_q^z + J_g^z$$

where

$$\begin{aligned} \vec{J}_q &= \int d^3x \left[\psi^\dagger \frac{\vec{\Sigma}}{2} \psi + \psi^\dagger \vec{x} \times (-i\vec{D})\psi \right] \\ \vec{J}_g &= \int d^3x \left[\vec{x} \times (\vec{E} \times \vec{B}) \right] \end{aligned}$$

Ji, PRL 78 (1997) 610

Lead to proposal to measure the quark OAM in DVCS

Deeply Virtual Compton Scattering: $\gamma^* + p \to \gamma + p'$

where $t = \Delta^2 = (p' - p)^2$ is small

Hoodbhoy, Ji, Lu, PRD 59 (1999) 014013

Generalized parton distributions

Consider the generalization of $\text{Tr}(\Phi(x)\gamma^+) \sim q(x)$

$$\int \frac{d\lambda}{2\pi}\, e^{i\lambda x}\, \langle P'|\overline{\psi}(-\lambda/2)\,\gamma^+\mathcal{L}[-\lambda/2,\lambda/2]\,\psi(\lambda/2)|P\rangle =$$

$$H_q(x,\xi,t)\,\bar{u}(P')\gamma^+u(P) + E_q(x,\xi,t)\,\bar{u}(P')\frac{i\sigma^{+\nu}\Delta_\nu}{2M}u(P)$$

with $\xi = -\Delta^+/2$, $\Delta = P' - P$ and $t = \Delta^2$

H_q and E_q are called Generalized Parton Distributions

Forward limit: $H_q(x,0,0) = q(x)$, $\quad E_q(x,0,0) \equiv E_q(x)$

$$\begin{aligned} J_q(x) &= \frac{1}{2}x\,[q(x) + E_q(x)] \\ L_q(x) &= \frac{1}{2}\,[xq(x) + xE_q(x) - \Delta q(x)] \end{aligned}$$

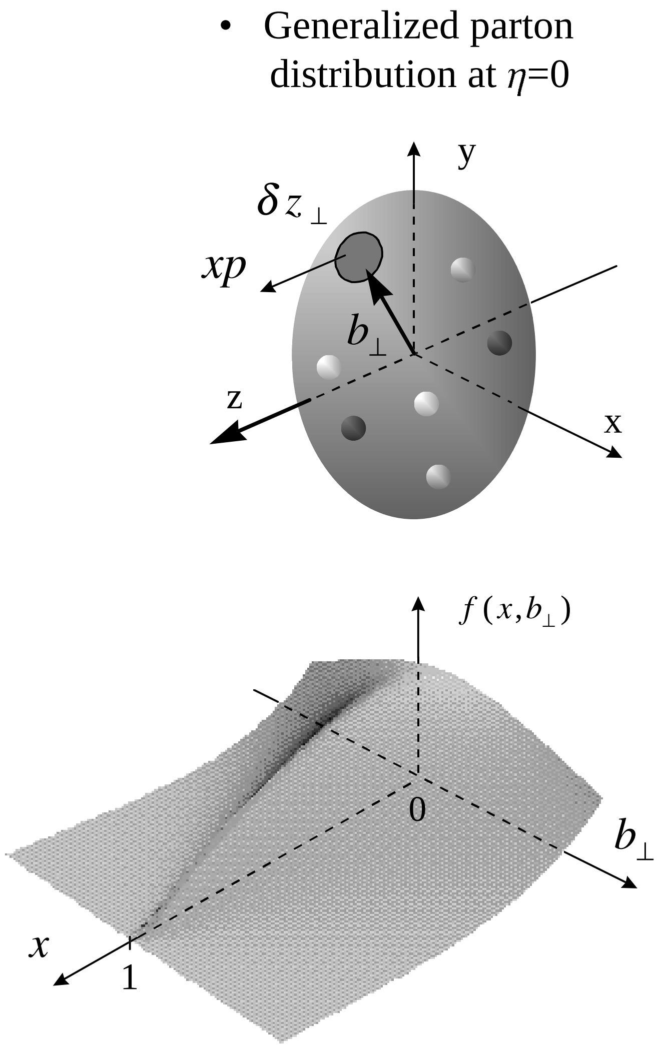
Hoodbhoy, Ji, Lu, PRD 59 (1999) 014013 (and J_g via evolution)

GPDs are also interesting in itself; they yield a more complete picture of momentum *and* spatial distributions of quarks and gluons

Burkardt, PRD 62 (2000) 071503; hep-ph/0207047; Belitsky & Müller, hep-ph/0206306; Diehl, hep-ph/0205208

In addition, there are several quark and gluon spin dependent GPD's

Probabilistic interpretation of GPD

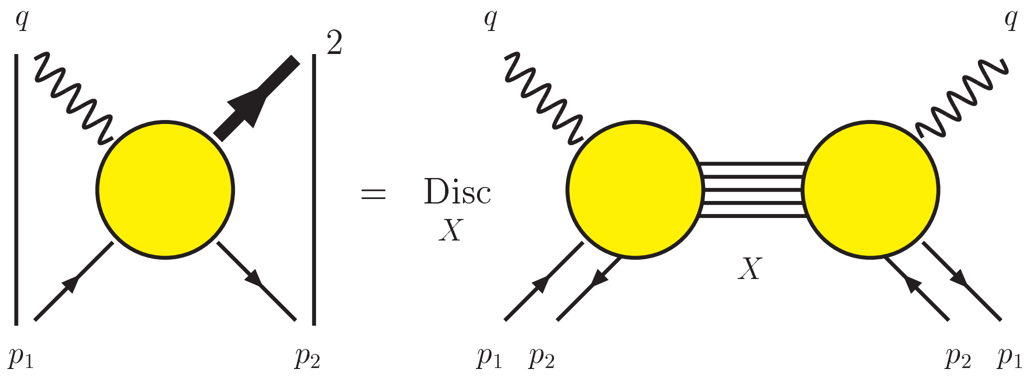


Taken from Belitsky & Müller, hep-ph/0206306

Polarized diffractive DIS

Diffractive structure functions (x, Q^2, x_P, t dependent) in terms of diffractive parton densities
Berera & Soper, PRD 50 (1994) 4328

Polarized diffractive DIS: Blümlein & Robaschik, PRD 65 (2002) 096002
8 polarized diffractive structure functions (2 if $t, M^2 \to 0$)



A. Mueller's optical theorem

Generalized Bjorken limit ($p_i \cdot q \to \infty, Q^2 \to \infty$ and x, x_P fixed) and sufficiently large rapidity gap ($\Delta y \sim \ln(1/x_P)$)

Diffractive $e\,p \to e'\,N'\,X$ viewed as:

DIS off a two-particle initial state $|p_1, S_1; -p_2, S_2\rangle$

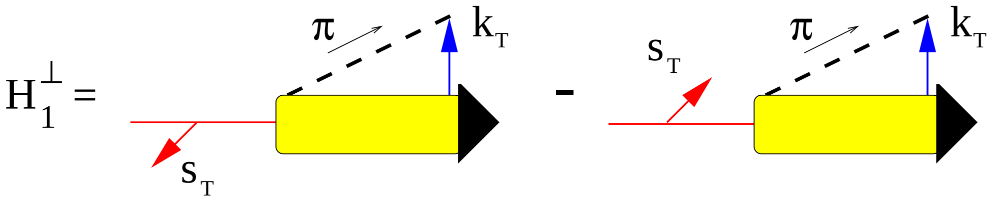
Transversity from spin asymmetries

h_1 perhaps also enters in the description of single spin asymmetries in $e\,p^\uparrow \to e'\pi\,X$ and $p\,p^\uparrow \to \pi\,X$

Exploit the fact that the transverse spin may be correlated to the direction of produced hadrons, i.e. to an unpolarized final state

'Collins effect': the transverse spin of quarks can be transformed into orbital angular momentum during the fragmentation process

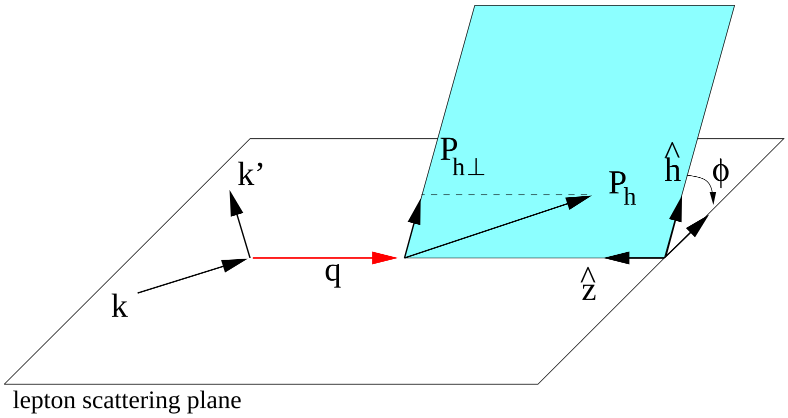
Produces particles with transverse momentum orthogonal to the spin direction of the fragmenting quark (allowed by all symmetries)



One needs to consider: transverse momentum dependent functions

Collins effect

Collins '93: asymmetry in semi-inclusive DIS $e + p^{\uparrow} \to e' + \pi + X$ where the spin of the proton is orthogonal to the direction of γ^*



Asymmetry depends on the angles of the transverse spin and the pion momentum $\boldsymbol{P}_\perp^\pi$ compared to the lepton scattering plane

$$A_T \propto \sin(\phi_C)\, |\boldsymbol{S}_T|\, h_1\, H_1^\perp$$

From the theoretical point of view Collins effect asymmetries are not like ordinary leading twist asymmetries

The dependence on the hard scale Q is highly non-trivial

Transverse momentum dependence

One needs to consider: transverse momentum dependent functions

$$\Phi(x) \to \Phi(x, \boldsymbol{p}_T)$$

Ralston & Soper, NPB 152 (1979) 109

Also for fragmentation (Collins & Soper, NPB 194 (1982) 445)
The unpolarized fragmentation correlation function $\Delta(z)$ is parameterized as

$$\Delta(z) = D_1(z)\,\frac{\gamma^+}{4}$$

but $\Delta(z, \boldsymbol{k}_T)$ as

$$\Delta(z, \boldsymbol{k}_T) = D_1(z, \boldsymbol{k}_T)\,\frac{\gamma^+}{4} + i H_1^\perp(z, \boldsymbol{k}_T)\,\frac{\not{k}_T \gamma^+}{4}$$

Collins, NPB 396 (1993) 161

Recent developments concern the so-called T-odd functions and the proper gauge invariant definition of these correlation functions using path-ordered exponentials
Brodsky, Hwang, Schmidt, PLB 530 (2002) 99; Collins, PLB 536 (2002) 43; Ji, Yuan, hep-ph/0206057; Belitsky, Ji, Yuan, hep-ph/0208038

Sudakov suppresion of Collins effect

So far all studies of the Collins effect have been done at tree level

Going beyond tree level is necessary, but complicated
Collinear factorization does not apply; it is a multiscale process (M, $|\boldsymbol{P}_\perp^\pi|$ and Q with $|\boldsymbol{P}_\perp^\pi|^2 \ll Q^2$)

$d\sigma/d^2\boldsymbol{P}_\perp^\pi$ beyond tree level: soft gluon corrections do not cancel;
Sudakov factors need to be taken into account
Crucial reference: Collins & Soper, NPB 193 (1981) 381 $[e^+e^-]$

Effect of Sudakov factors: lowering and broadening (in transverse momentum) of the asymmetry

This decrease can be quite substantial, estimated to be roughly $1/\sqrt{Q}$ per Collins function compared to tree level
D.B., NPB 603 (2001) 195

The LO Q^2 evolution in the large N_c limit is known for

$$H_1^{\perp(1)}(z) \sim \int d\boldsymbol{k}_T \boldsymbol{k}_T^2 H_1^\perp(z, \boldsymbol{k}_T^2)$$

Henneman, D.B., Mulders, NPB 620 (2002) 331; based on
Belitsky, PLB 405 (1997) 312 (full twist-3 evolution calculation)

Factorization and transverse momentum

Leading twist (LT) factorization theorem in Drell-Yan:

$$\frac{d\sigma}{d\Omega dx_1 dx_2} = \sum_{a,b} \int_{x_1}^{1} \frac{dx}{x} \int_{x_2}^{1} \frac{d\bar{x}}{\bar{x}} \, f_1^a(x) \, \frac{d\hat{\sigma}_{ab}}{d\Omega dx d\bar{x}} \, \overline{f}_1^b(\bar{x})$$

Transverse momentum distribution in DY or W/Z production

$$\frac{d\sigma}{dQ^2 dy dQ_T^2} \sim Y(x_1, x_2, Q, Q_T) + \int d^2b \, e^{-i\boldsymbol{b}\cdot\boldsymbol{Q}_T} \sum_j e_j^2$$

$$\sum_{a,b} \int_{x_1}^{1} \frac{dx}{x} \int_{x_2}^{1} \frac{d\bar{x}}{\bar{x}} \, f_1^a(x) \, \overline{f}_1^b(\bar{x}) e^{-S(b)} \, C_{ja}(x_1/x) \, C_{\bar{j}b}(x_2/\bar{x})$$

(Collins, Soper & Sterman, NPB 250 (1985) 199)

Here I left out the factorization/renormalization scale dependences

$Y(x_1, x_2, Q, Q_T)$ becomes important only when $Q_T \sim Q$

$e^{-S(\boldsymbol{b})}$ is a Sudakov form factor (exponentiation rather than cancellation of soft gluon contributions)

$$S(b, Q) = \int_{b_0^2/b^2}^{Q^2} \frac{d\mu^2}{\mu^2} \left[A(\alpha_s(\mu)) \, \ln \frac{Q^2}{\mu^2} + B(\alpha_s(\mu)) \right]$$

Factorization and transverse momentum

The previous factorization theorem is valid for Q^2 very large, such that the restriction $b^2 \ll 1/\Lambda^2$ is justified

If also $b^2 \gtrsim 1/\Lambda^2$ contributions are important, then one needs to include a nonperturbative Sudakov factor as well or even return to the more general factorization theorem, schematically written as:

$$\frac{d\sigma}{d\Omega dx_1 dx_2 d^2\boldsymbol{q}_T} = Y(x_1, x_2, Q, Q_T) +$$

$$\sum_{a,b} \int_{x_1}^{1} dx \int_{x_2}^{1} d\bar{x} \int d^2\boldsymbol{k}_T \, d^2\boldsymbol{p}_T \, f_1^a(x, \boldsymbol{k}_T) \frac{d\hat{\sigma}_{ab}}{d\Omega dx d\bar{x} d^2\boldsymbol{q}_T} \overline{f}_1^b(\bar{x}, \boldsymbol{p}_T)$$

$$\frac{d\hat{\sigma}}{d\Omega dx d\bar{x} d^2\boldsymbol{q}_T} = H(x, \bar{x}; Q) \int \frac{d^2\boldsymbol{b}}{(2\pi)^2} \, e^{-i\boldsymbol{b}\cdot(\boldsymbol{p}_T + \boldsymbol{k}_T - \boldsymbol{q}_T)} \, e^{-S(\boldsymbol{b})}$$

However, this form has not been proven for Drell-Yan, only for e^+e^- annihilation: Collins & Soper, NPB 193 (1981) 381

The nonperturbative Sudakov factor has not been determined experimentally for SIDIS or e^+e^- annihilation, despite the large amount of ZEUS/H1 and LEP data!

Factorization beyond leading twist

Next-to-leading twist (NLT): Qiu & Sterman, NPB 353 (1991) 137

$$\sigma(Q) = H^0 \otimes f_2 \otimes f_2 + \frac{1}{Q^n} H^1 \otimes f_2 \otimes f_{2+n} + \mathcal{O}\left(\frac{1}{Q^{n+1}}\right)$$

$n = 1, 2$ for the polarized and unpolarized case respectively

Beyond NLT: breakdown of factorization
Doria, Frenkel & Taylor, NPB 168 (1980) 93,
Basu, Ramalho & Sterman, NPB 244 (1984) 221, ...

Status of factorization proofs for Drell-Yan cross sections

	$\sigma(Q)$	$d\sigma/d\boldsymbol{q}_T(Q)$
LT	$\surd$	"$\surd$"
NLT	"$\surd$"	?
NNLT	$\times$	$\times$

Sketchy overview of challenges (II)

C1: To describe the complete spin structure of hadrons
In terms of specific operator matrix elements

C2: To describe measurable processes in terms of the above objects

C3: To try to understand the soft physics from QCD

- C3a: Models, lattice, sum rules, bounds
  Including spin effects in hadronization
- C3b: Nonfactorizable processes
  Spin asymmetries in forward scattering (Regge theory)

C4: To use the above knowledge (as a tool)
Beyond the Standard Model physics

Many spin physics issues not addressed: small x behavior, electroweak polarized structure functions, GDH sum rule, etc, etc

Spin Physics and Beyond the SM

An advantage of polarization is that SM contributions (or at least QCD contributions) may be filtered out

Some examples in polarized $p\,p$ scattering

Parity violation:

$\vec{p}\,p \to \text{jet}\,X$ (A_L^{jet}) and $\vec{p}\,\vec{p} \to \text{jet}\,X$ (A_{LL}^{PV}, $\bar{A}_{LL}^{PV}$)

$$A_{LL}^{PV} = \frac{\sigma_{--} - \sigma_{++}}{\sigma_{--} + \sigma_{++}} \quad \bar{A}_{LL}^{PV} = \frac{\sigma_{-+} - \sigma_{+-}}{\sigma_{-+} + \sigma_{+-}}$$

CP violation:

Since the quark coupling to the W has fixed helicity, transverse spin asymmetries (helicity flip) should be absent

For example, A_T^W and A_{TT}^W

RHIC probably has just insufficient energy/precision
How about a polarized LHC?

Summary of specific challenges

- Devise a gauge invariant sum rule $1/2 = \Delta\Sigma/2 + L_q + \Delta g + L_g$

  Find ways to measure the separate terms

  Do the same for fragmentation $(\Lambda, \rho, \ldots)$
- Relate difference of $h_1 - g_1$ to OAM?

  Devise new ways of measuring tensor charge $\int dx\, h_1(x)$
- Understand SSA in semi-inclusive hadron production
- Complete factorization proofs for cross sections differential in transverse momentum (DY, SIDIS)

  Deal with Sudakov factors in asymmetries
- Complete the picture of polarized GPDs and "conditional" PDs, like fracture functions and diffractive PDs

  Idem for (multi-) hadron fragmentation functions
- Obtain moments of the functions on the lattice
- Future uses of the functions (beyond SM)