DOUBLE TRANSVERSE SPIN ASYMMETRIES AT

NEXT-TO-LEADING ORDER IN QCD

Asmita Mukherjee
University of Leiden, Netherlands

- Transversity
- How can transversity be measured
- Problems with NLO calculation involving transverse polarization
- New technique
- Applicaions
- Summary and outlook

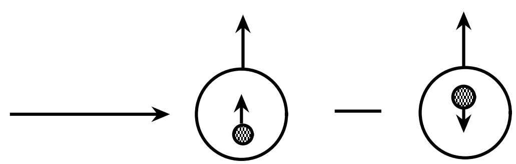
SPIN'04

In collaboration with M. Stratmann (Regensburg) and W. Vogelsang (Brookhaven and Riken BNL).

What is Transversity ?

• Parton language : nucleon moving with (infinite) momentum along $\hat{z}$ direction but polarized in the transverse direction.

Transversity $\delta q_a(x, Q^2) \rightarrow$ the number of partons of flavor a and momentum fraction x with spin parallel to the spin of the nucleon minus the number antiparallel.



$$\delta f(x,\mu) = f_{\uparrow\uparrow}(x,\mu) - f_{\uparrow\downarrow}(x,\mu)$$

• Required together with the unpolarized distribution $q_a(x, Q^2)$ and helicity distribution $\Delta q_a(x, Q^2)$ to give a complete description of quark spin in the nucleon at leading twist

• First mentioned by Ralston and Soper $'79$ for Drell-Yan muon pair production by transversely polarized protons.

Transversity : Continued

- Transversity different from helicity distribution because quark motion is relativistic in the nucleon

Transversity $\rightarrow$ quark and nucleon helicity flip : difficult to measure.

- Chiral odd ; some other process must flip quark chirality a second time.

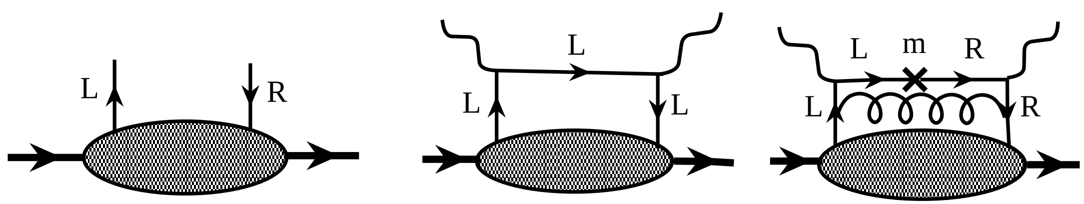
- $q(x, Q^2)$: known

$\Delta q(x, Q^2)$: known (more or less)

$\delta q(x, Q^2)$: unknown.

- δq decouples from DIS

Mass insertion flips chirality : suppressed by $\frac{1}{\sqrt{Q^2}}$



How to Measure Transversity

(1) Single transverse spin asymmetries in pp or ep scattering; azimuthal asymmetries..

$\checkmark$ Large

$\times$ Transversity convoluted with other (unknown) distribution/fragmentation functions

$\checkmark$ Experimental data already available

We won't discuss this here.....

(2) Double transverse spin asymmetries

Candidate processes $p^{\uparrow}p^{\uparrow} \rightarrow l^{+}l^{-}X, p^{\uparrow}p^{\uparrow} \rightarrow \gamma X, p^{\uparrow}p^{\uparrow} \rightarrow jetX$...

• Chirality flipped twice at two soft distributions
A_{TT} defined as :

$$A_{TT} = \frac{(\sigma_{++} + \sigma_{--}) - (\sigma_{+-} + \sigma_{-+})}{(\sigma_{++} + \sigma_{--}) + (\sigma_{+-} + \sigma_{-+})}$$

$+$ and $-$ $\rightarrow$ transverse spin directions of the beam proton.

Double Transverse Spin Asymmetry

✓ A_{TT} depends only on transversity (quadratically); not on any other unknown distributions
Cleanest possible extraction of transversity

× Small, because gluon initiated subprocesses contribute to the denominator but not to the numerator

Jaffe, Saito 96; Soffer, Stratmann, Vogelsang 02

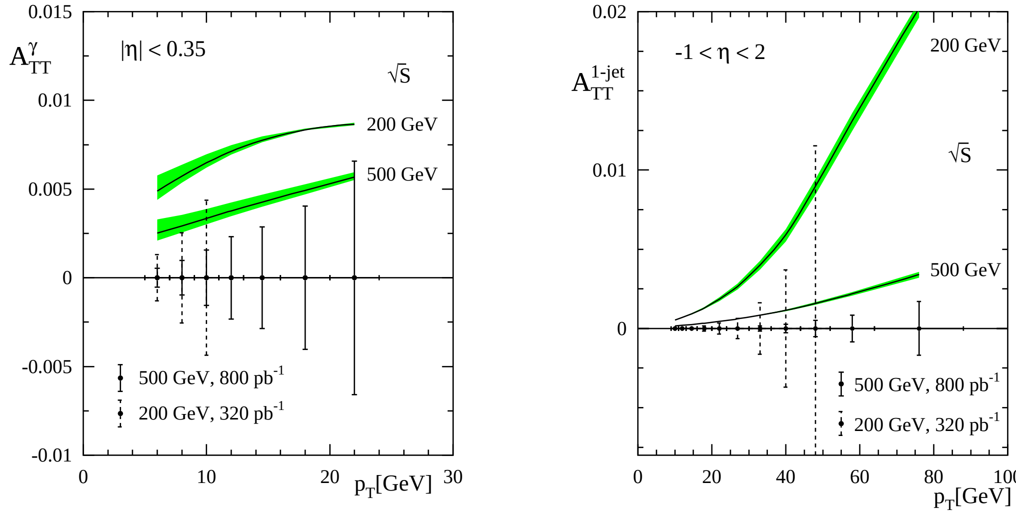
✓ Only exception : Drell-Yan lepton pair production
At LO : $q\bar{q}$ annihilation; no gluon contribution to unpol. cross section

Martin, Schäfer, Stratmann, Vogelsang 98

• Also : A_{TT} in $p^{\uparrow}p^{\uparrow} \rightarrow J/\psi X \rightarrow l^{+}l^{-}X$ at the PAX experiment at GSI-HESR

Anselmino *et al*, Efremov *et al* 04

A_{TT} for other processes :



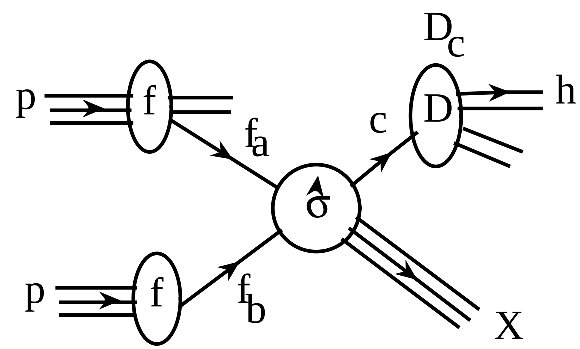
Soffer, Stratmann, Vogelsang 02

- LO estimate by saturating Soffer's inequality at a low input scale; at higher scales transversity is obtained by solving the evolution eqn.
- Hard to detect : good control over systematic and statistical errors necessary
- Higher order correction a must : reduction of scale dependency ..
- Further motivation : technical challenge for NLO calculation of cross sections involving transversely polarized particles in the initial state

Hard Scattering Cross Section

- Use factorization and universality of pdfs

Libby, Sterman; Ellis et al; Amati et al; Collins et al;..



$$d\sigma = \sum_{a,b,c} f_a(x_a, \mu_f) \otimes f_b(x_b, \mu_f) \otimes d\hat{\sigma}(x_a, x_b, z_c, \mu_f, \mu'_f) \otimes D_c^h(z_c, \mu'_f)$$

- In order that the factorized framework works, minimum requirement $\rightarrow$ at least one hard (=large) scale present, usually p_T

$$\mu_f \approx \mu'_f \approx \mu_r = O(p_T)$$

If $p_T \geq 2$ GeV (say); $\alpha_s(\mu_r) << 1 \rightarrow$ pert. expansion should work
Multiparton correlations $\rightarrow$ hopefully small

Problem with Transverse Polarization Beyond LO

- Spin vectors introduce extra spacial directions : nontrivial Φ dependence
- Assuming both initial spin vectors in $\pm x$ direction in cm frame of the initial hadrons; for a parity consrving theory with vector couplings

$$\frac{d^3\delta\sigma}{dp_T\, d\eta\, d\Phi} \equiv \cos(2\Phi) \left\langle \frac{d^2\delta\sigma}{dp_T\, d\eta} \right\rangle$$

- Φ cannot be integrated out !
- Difficult to use standard tools for doing phase space integrations at NLO
- **Severe problem if the customary dimensional regularization is used for dealing with collinear and infrared singularities.**
- Only Drell-Yan : kinematically most simple process at NLO without using dimensional regularization

Vogelsang, Weber 93, Contogouris et al 94, Kamal 96, Martin et al 98,99

- Need : A general technique to perform calculations at NLO with transverse polarization

Projection Technique for Azimuthal Dependence

Integrate with $cos 2\Phi$ weight :

$$\left\langle \frac{d^2\delta\sigma}{dp_T d\eta} \right\rangle = \frac{1}{\pi} \int_0^{2\pi} d\Phi \cos(2\Phi) \frac{d^3\delta\sigma}{dp_T d\eta d\Phi}$$

Consider prompt photon production as an example
LO $\rightarrow q\bar{q} \rightarrow \gamma g$

Polarization for initial quark projected out by

$$u(p_a, s_a)\, \bar{u}(p_a, s_a) = \frac{1}{2} \not{p}_a \left[1 + \gamma_5 \not{s}_a\right]$$

Note : Covariant expression below give $cos 2\Phi$ in the c. m. frame of initial hadrons

$$\mathcal{F}(p_\gamma, s_a, s_b) = \frac{s}{\pi t u} \left[2\,(p_\gamma \cdot s_a)\,(p_\gamma \cdot s_b) + \frac{tu}{s}\,(s_a \cdot s_b) \right]$$

AM, Stratmann, Vogelsang 03

Projection Technique (Continued)

At LO for $q\bar{q} \to \gamma g$ we have

$$\frac{d\delta^2 \hat{\sigma}^{(0)}_{q\bar{q}\to\gamma g}}{dt d\Phi} = \frac{1}{32\pi^2 s^2} \, \delta|M(q\bar{q} \to \gamma g)|^2 \ ,$$

$$\delta|M(q\bar{q} \to \gamma g)|^2 = (e e_q g)^2 \, \frac{4C_F}{N_C} \, \frac{s}{tu} \left[2\,(p_\gamma \cdot s_a)\,(p_\gamma \cdot s_b) \ + \ \frac{tu}{s}\,(s_a \cdot s_b) \right]$$

- Multiply $\delta|M|^2$ by $\mathcal{F}(p_\gamma, s_a, s_b)$
- Do $d\Omega_\gamma$ integration covariantly
- Dependence on spin vectors : $(p_\gamma \cdot s_a)^2 (p_\gamma \cdot s_b)^2$, $(p_\gamma \cdot s_a)(p_\gamma \cdot s_b)(s_a \cdot s_b)$, and $(s_a \cdot s_b)^2$
- Expand tensors $p_\gamma^\mu p_\gamma^\nu p_\gamma^\rho p_\gamma^\sigma$ and $p_\gamma^\mu p_\gamma^\nu$ into all possible tensors made up of the metric tensor and the incoming partonic momenta

Projection Technique (Continued)

$$\int d\Omega_\gamma \, (p_\gamma \cdot s_a)^2 (p_\gamma \cdot s_b)^2 = \int d\Omega_\gamma \, \frac{t^2u^2}{8s^2} \left(2(s_a \cdot s_b)^2 + s_a^2 s_b^2\right) \; = \; \int d\Omega_\gamma \, \frac{3t^2u^2}{8s^2} \; ,$$

$$\int d\Omega_\gamma \, (p_\gamma \cdot s_a)(p_\gamma \cdot s_b)(s_a \cdot s_b) = -\int d\Omega_\gamma \, \frac{tu}{2s} (s_a \cdot s_b)^2 \; = \; -\int d\Omega_\gamma \, \frac{tu}{2s} \; ,$$

- $s_i \cdot p_a = s_i \cdot p_b = 0$ ($i = a, b$) and $s_a^2 = s_b^2 = -1$
- Now integrate phase space over p_γ including the (now trivial) azimuthal part
- Particularly suitable at NLO
- At NLO we have $ab \to \gamma cd$; one has to do

$$\int d\Omega_\gamma \int d\Omega_c \, \mathcal{F}(p_\gamma, s_a, s_b) \, \delta |M(ab \to \gamma cd)|^2$$

- Momentum of particle d fixed by momentum conservation
- Dimensional regularization : $d = 4 - 2\epsilon$ dimension

Projection Technique : Continued

- Scalar products of s_i $(i = a, b)$ with p_c : $\propto (s_a \cdot p_c)(s_b \cdot p_c)$ and $\propto (s_i \cdot p_c)$
$\longrightarrow$ removed by expanding the ensuing tensor and vector integrals in terms of the available tensors

- These are made of the metric tensor, p_a, p_b, and p_γ

- We are left with terms containing $(p_\gamma \cdot s_i)$: they are of the form $(p_\gamma \cdot s_a)^2 (p_\gamma \cdot s_b)^2$ and $(p_\gamma \cdot s_a)(p_\gamma \cdot s_b)$.

- Use the same relations as in LO in d dimensions

- Recall : $s_a \cdot s_b = -1$. We can now integrate over all phase space using known techniques from unpolarized and longitudinally polarized cases

- Check : reproduces known NLO result for Drell-Yan transversity cross section

Some Applications

- Prompt photon production

Two processes contribute at NLO :

$$
\begin{aligned}
q\bar{q} &\rightarrow \gamma X; X = g(LO); X = q\bar{q} + gg + q'\bar{q}'(NLO); \\
qq &\rightarrow \gamma X; X = qq
\end{aligned}
$$

(i) Virtual corrections to LO $(q\bar{q} \rightarrow \gamma g)$

(ii) $2 \rightarrow 3$ processes

- Singularities in the intermediate steps

(a) UV singlularities in loops ; removed by renormalization of the strong coupling constant at scale $\mu_R(\overline{MS}$ scheme).

(b) IR sigularities canceled after adding loops and $2 \rightarrow 3$,

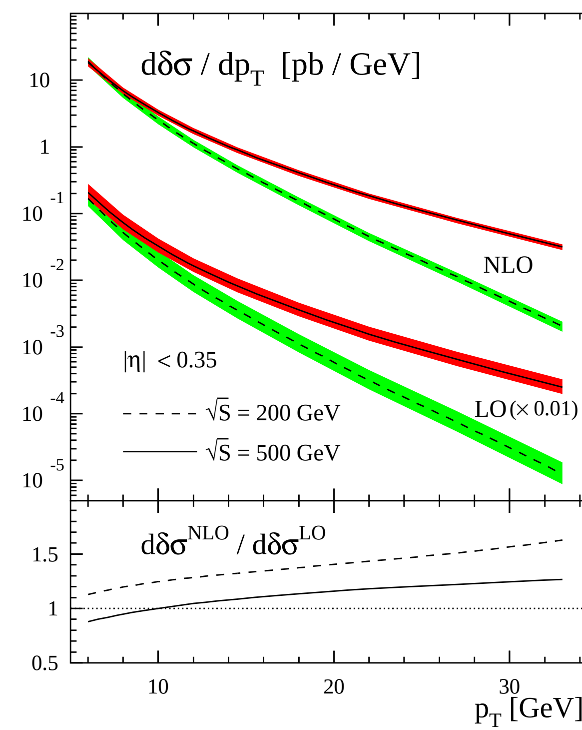
(c) collinear singularities : parton in initial state split into two collinear partons

Only $q \rightarrow qg$ collinear splitting for transversity : $(q\bar{q} \rightarrow \gamma gg)$

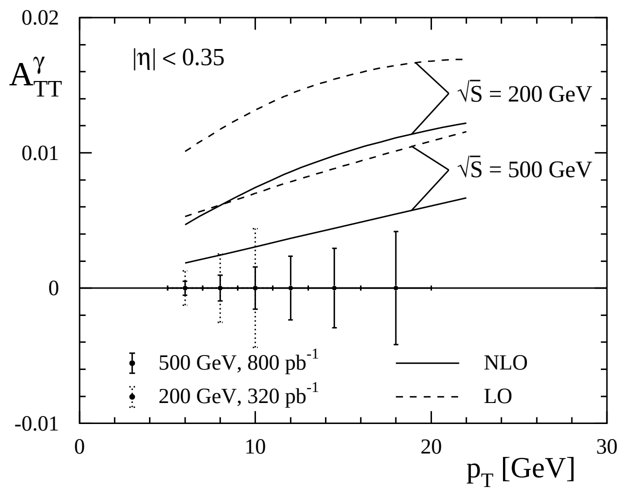
Factored into the distribution and fragmentation functions

Numerical Results

- Prompt photon : experimental cuts necessary to isolate the photon signal from hadronic background
- PHENIX detector at RHIC : pseudorapidity $|\eta| \leq 0.35$; $-\pi/4 < \Phi < \pi/4$ and $3\pi/4 < \Phi < 5\pi/4$
- Substantial reduction of scale dependency at NLO



Numerical Results : A_{TT}



- Saturate Soffer's inequality at a low input scale $\mu_0 \simeq 0.6\,\mathrm{GeV}$ using GRV and GRSV, for higher scale transversity density is obtained by solving the evolution eq.
- All scales set to p_T
- Statistical error : $\delta A^{\gamma}_{\mathrm{TT}} \simeq \dfrac{1}{P^2\sqrt{\mathcal{L}\sigma_{\mathrm{bin}}}}$

Further Applications

- Further application of projection technique: $p^{\uparrow}p^{\uparrow} \rightarrow \pi X$ (almost finished); $p^{\uparrow}p^{\uparrow} \rightarrow jetX$ ...

Summary and Conclusions

- Introduced new technique to perform calculation of cross sections involving transverse polarization beyond leading order in QCD using standard dimensional regularization

- Presented first calculation of cross sections in transversely polarized pp collision using this technique at NLO

- Substantial reduction of scale dependency

- Upper limit of A_{TT} ; any experimental observation higher than our prediction $\rightarrow$ new 'spin surprise'

Isolation Cone

- Experimental cuts necessary to isolate the photon signal from hadronic background

- Reduces the fragmentation contributions, because photons produced by fragmentation are always accompanied by hadronic energy

- Define a cone around the photon by $\sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} \leq R$, where typically $R \approx 0.4 \ldots 0.7$

- Demand that hadronic transverse energy in the cone smaller than $\tau\, p_T$, where τ is a parameter of order 0.1

- Further, for any $r \leq R$ the hadronic energy be smaller than roughly $\tau (r/R)^2 p_T$ inside a cone of opening r.

Isolation Cone

- It is possible to introduce the isolation cut in an approximate, but accurate, analytical way by introducing certain 'subtraction cross sections'

- Assumpton : Isolation cone is rather narrow

- Cross section includes

$$\mathcal{I}^{\rm final}(z) = \begin{cases} P_{\gamma q}(z)\ \ln\left(\frac{\mu_F^2}{s}\right) & \text{incl.} \\ P_{\gamma q}(z)\ \ln\left(\frac{\mu_F^2}{s}\right) + \Theta(1-z[1+\tau])\left[P_{\gamma q}(z)\ \ln\left(\frac{(1-z)^2 p_T^2 R^2}{\mu_F^2}\right) + z\right] & \text{std.} \\ P_{\gamma q}(z)\ \ln\left(\frac{(1-z)^3 p_T^2 R^2}{s\,\tau\,z}\right) & \text{smooth} \end{cases}$$

- $P_{\gamma/q}$ is the quark-to-photon splitting function