Nucleon Spin Structure:
A Brief Overview

(A. Metz, Temple University, Philadelphia)

Focus on: QCD Spin Structure, Parton Distributions

Experiments: BNL, CERN, DESY, FNAL, JLab, KEK

Disclaimer: no comprehensive introduction for following talks,
several topics not covered at all

Outline

1. Longitudinal Spin Structure
   - Quark helicity distributions
   - Gluon helicity distribution

2. Transverse Spin Structure
   - Transversity distribution
   - Transverse single spin asymmetries
   - TMDs and 3-D image of the nucleon in $(x, \vec{k}_T)$-space
   - Sign reversal of the Sivers function

3. GPDs and Spin Sum Rule of the Nucleon
   - GPDs and 3-D image of the nucleon in $(x, \vec{b}_T)$-space
   - Ji's spin sum rule of the nucleon
   - Alternative decompositions of the nucleon spin

(Leading Twist) Parton Distributions of the Nucleon

	Quarks				Gluons			
PDFs	f_1^q	$g_1^q \, (\Delta q)$	$h_1^q \, (\Delta_T q)$		g	Δg		
TMDs	f_1^q	$f_{1T}^{\perp q}$	g_{1L}^q	g_{1T}^q	f_1^g	$f_{1T}^{\perp g}$	g_{1L}^g	g_{1T}^g
	h_{1T}^q	$h_{1L}^{\perp q}$	$h_{1T}^{\perp q}$	$h_1^{\perp q}$	h_{1T}^g	$h_{1L}^{\perp g}$	$h_{1T}^{\perp g}$	$h_1^{\perp g}$
GPDs	H^q	E^q	$\tilde{H}^q$	$\tilde{E}^q$	H^g	E^g	$\tilde{H}^g$	$\tilde{E}^g$
	H_T^q	E_T^q	$\tilde{H}_T^q$	$\tilde{E}_T^q$	H_T^g	E_T^g	$\tilde{H}_T^g$	$\tilde{E}_T^g$

$\longrightarrow$ Almost all parton distributions (indicated in red) related to spin !

$\longrightarrow$ Each parton distribution contains unique physics !

Forward Parton Distributions: Field-Theoretic Definition

- Unpolarized PDF: unpolarized quarks in unpolarized nucleon

$$f_1^q(x) = \frac{1}{2} \int \frac{dz^-}{2\pi} e^{ik\cdot z} \langle P; S | \bar{\psi}^q(0) \gamma^+ \mathcal{W}_{PDF} \psi^q(z) | P; S \rangle \Big|_{z^+=z_T=0}$$

- Helicity PDF: long. polarized quarks in long. polarized nucleon

$$\lambda \langle \, | \bar{\psi}^q \gamma^+ \gamma_5 \psi^q | \, \rangle \sim \lambda \Lambda \, g_1^q(x) \quad \longrightarrow \quad \text{spin-spin correlation}$$

- Transversity PDF: transv. polarized quarks in transv. polarized nucleon

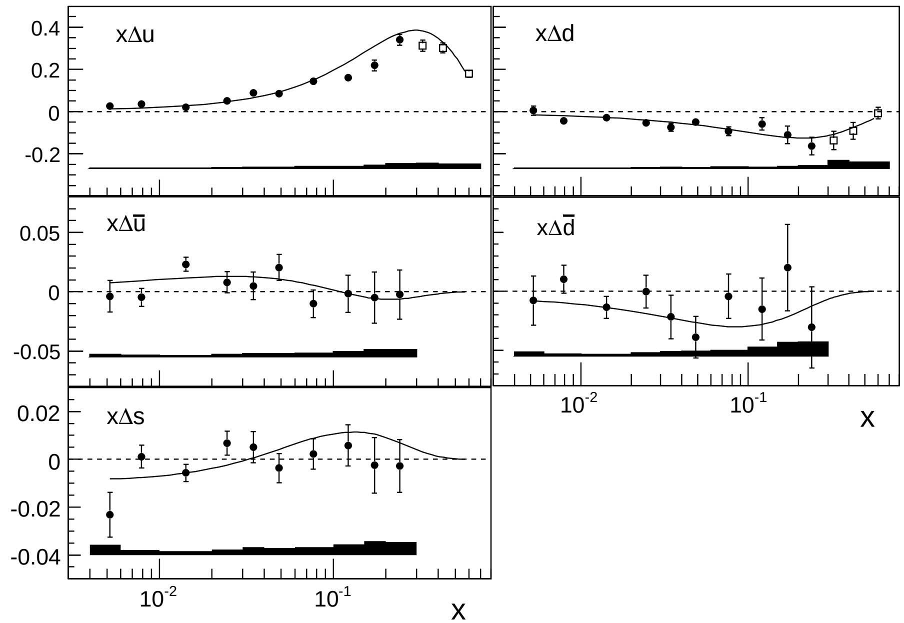
$$s_T^i \langle \, | \bar{\psi}^q \, i\sigma^{i+} \gamma_5 \psi^q | \, \rangle \sim \vec{s}_T \cdot \vec{S}_T \, h_1^q(x) \quad \longrightarrow \quad \text{spin-spin correlation}$$

  - transversity decouples from inclusive DIS (chiral-odd)
  - hard to measure !

Quark Helicity Distributions

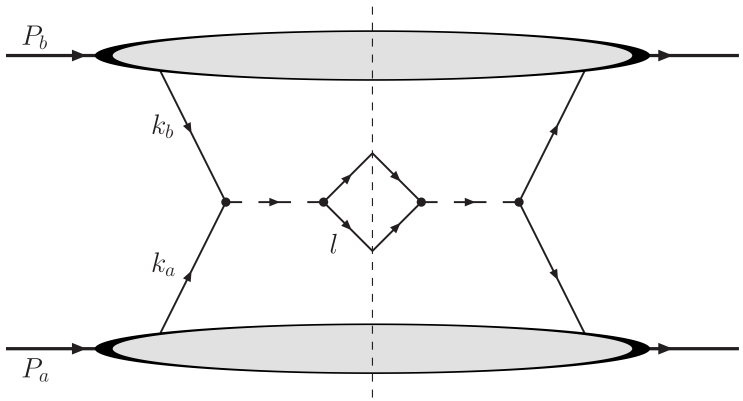
- Results from inclusive DIS ($\vec{l}\,\vec{N} \to l\,X$) and semi-inclusive DIS ($\vec{l}\,\vec{N} \to l\,H\,X$) (COMPASS, HERMES, JLab)

COMPASS, 2010 $\quad Q^2 = 3.0\,\mathrm{GeV}^2$



  - by now, consistent picture: e.g., very similar to HERMES results (in overlap region)
  - Δu, Δd nonzero, and clearly peak in valence region
  - all other distributions compatible with zero ($\Delta\bar{u} - \Delta\bar{d}$ seems slightly positive)
  - also comparison with DSSV-analysis, which includes pp-data, gives consistent picture

- First RHIC results from W-production in pp-collisions $(\vec{p}\,p \to l^{\pm}\,X)$



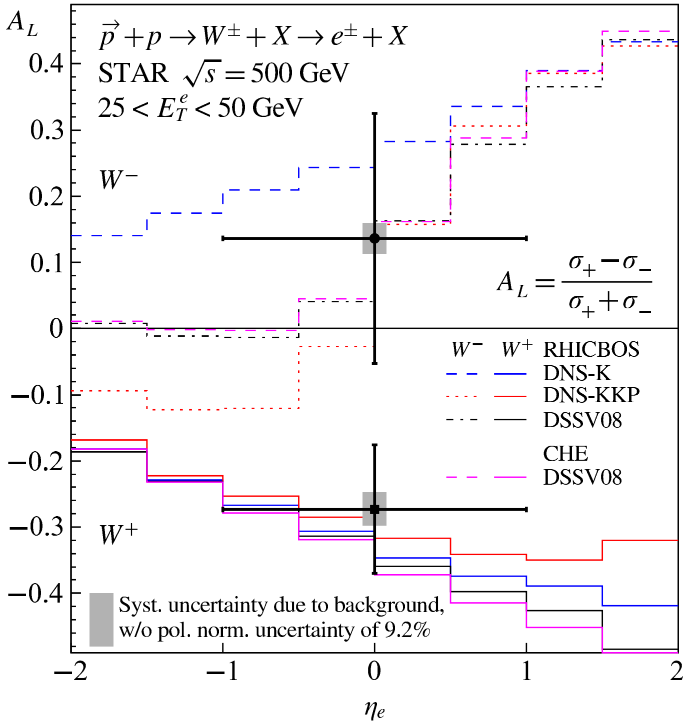
(a)

$$A_L^{W^+} = \frac{\Delta u(x_a)\,\bar{d}(x_b) - \Delta\bar{d}(x_a)\,u(x_b)}{u(x_a)\,\bar{d}(x_b) + \bar{d}(x_a)\,u(x_b)} \quad \to \quad \frac{\Delta u(x)}{u(x)},\quad \frac{\Delta\bar{d}(x)}{\bar{d}(x)}$$

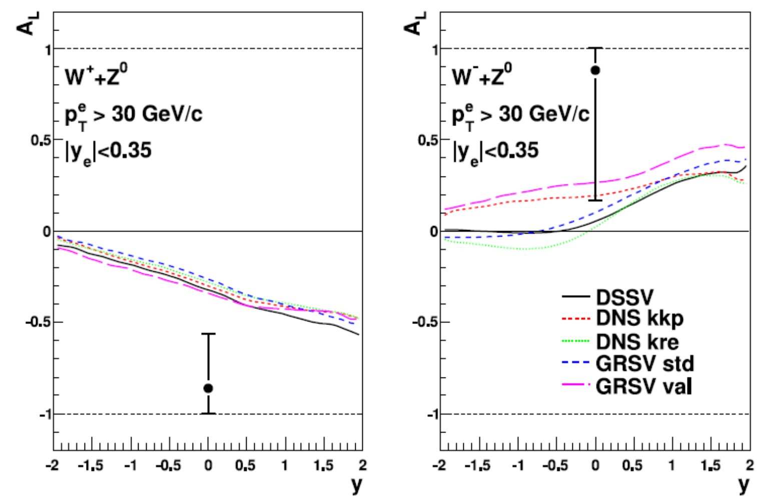
$$A_L^{W^-} = \frac{\Delta d(x_a)\,\bar{u}(x_b) - \Delta\bar{u}(x_a)\,d(x_b)}{d(x_a)\,\bar{u}(x_b) + \bar{u}(x_a)\,d(x_b)} \quad \to \quad \frac{\Delta d(x)}{d(x)},\quad \frac{\Delta\bar{u}(x)}{\bar{u}(x)}$$

- complementary process
- theoretically clean channel
- experimentally challenging

STAR, 2010



PHENIX, 2010

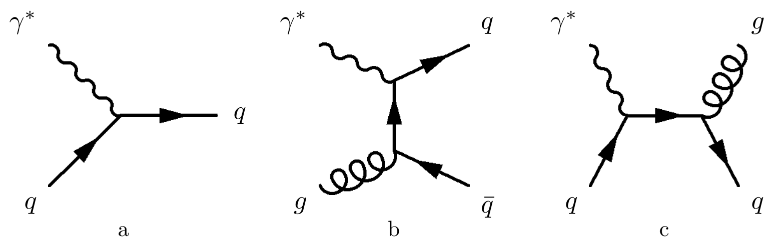


– direct measurement of parity-violating W-coupling to quarks

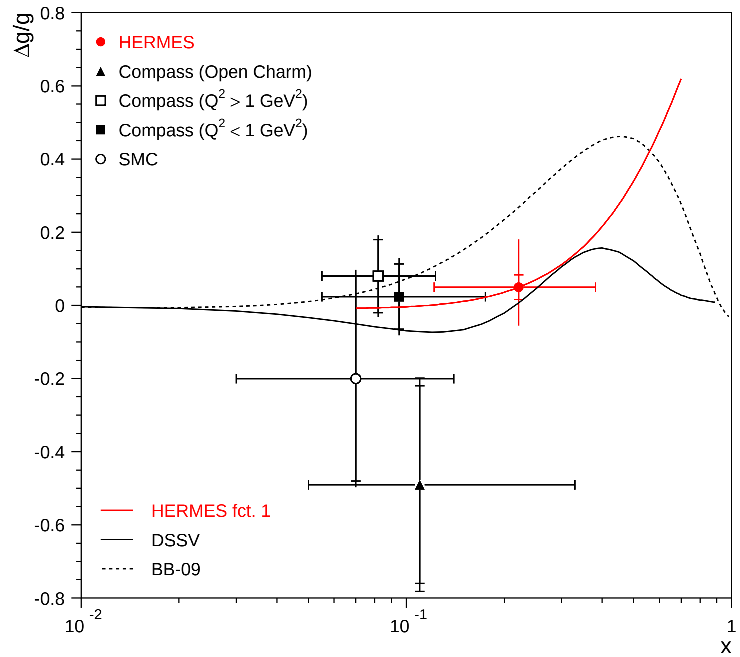
– higher statistics measurements may further constrain $\Delta\bar{u}$, $\Delta\bar{d}$

Gluon Helicity Distribution

- Results from DIS: hunting for boson-gluon fusion, $\gamma^* g \to q\,\bar{q}$



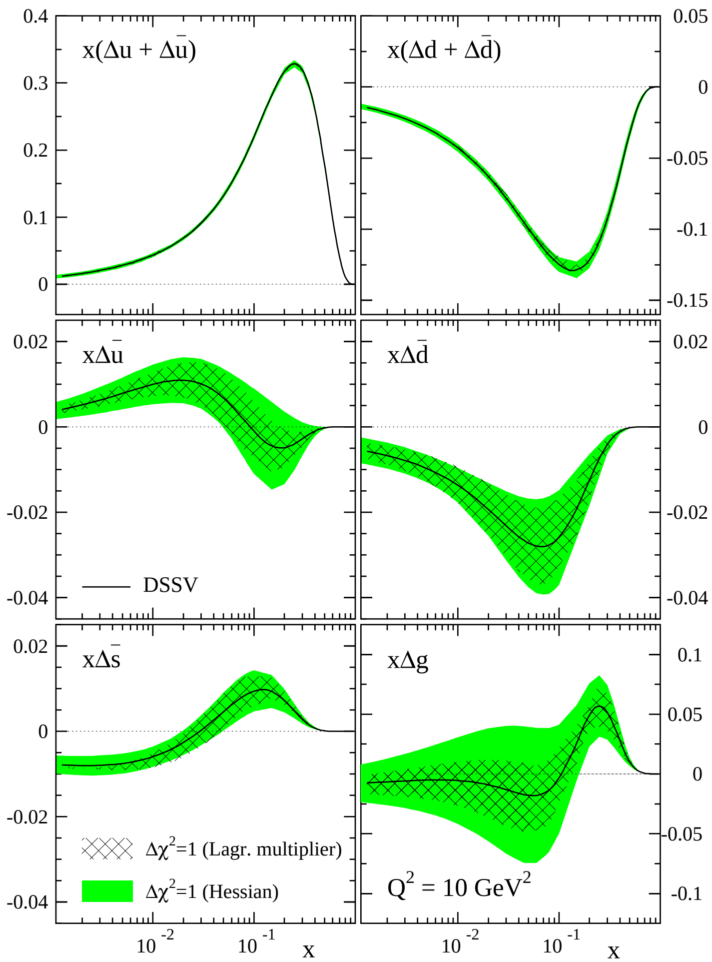
  - inclusive and semi-inclusive DIS
  - open charm production
  - high-p_T hadron pairs
  - dijet production



HERMES, 2010

  - $\Delta g/g$ small (in measured region)
  - agrees with large-N_c prediction: $\Delta g/g \propto 1/N_c$ (Efremov, Goeke, Pobylitsa, 2000)

- RHIC results from pp-collisions $(\vec{p}\,\vec{p} \longrightarrow \text{jet}\, X,\ \ H\, X)$



Global DSSV analysis (de Florian, Sassot, Stratmann, Vogelsang 2008/09)

- strong constraints from RHIC data
- DIS- and pp-data seem consistent
- errors on Δg still large
- in particular, what is Δg at low x ?
  $\longrightarrow$ large uncertainty in spin sum rule

Transversity Distribution

- 'Golden' observable: A_{TT} for $\bar{p}^{\uparrow}\, p^{\uparrow} \to l^{+}\, l^{-}\, X$ and $p^{\uparrow}\, p^{\uparrow} \to l^{+}\, l^{-}\, X$
  (BNL, GSI, IHEP, JINR, J-PARC)

$$A_{TT} \sim \frac{h_1^{q/H_1}(x_a)\, h_1^{\bar{q}/H_2}(x_b) + (x_a \leftrightarrow x_b)}{f_1^{q/H_1}(x_a\, f_1^{\bar{q}/H_2}(x_b) + (x_a \leftrightarrow x_b)}$$

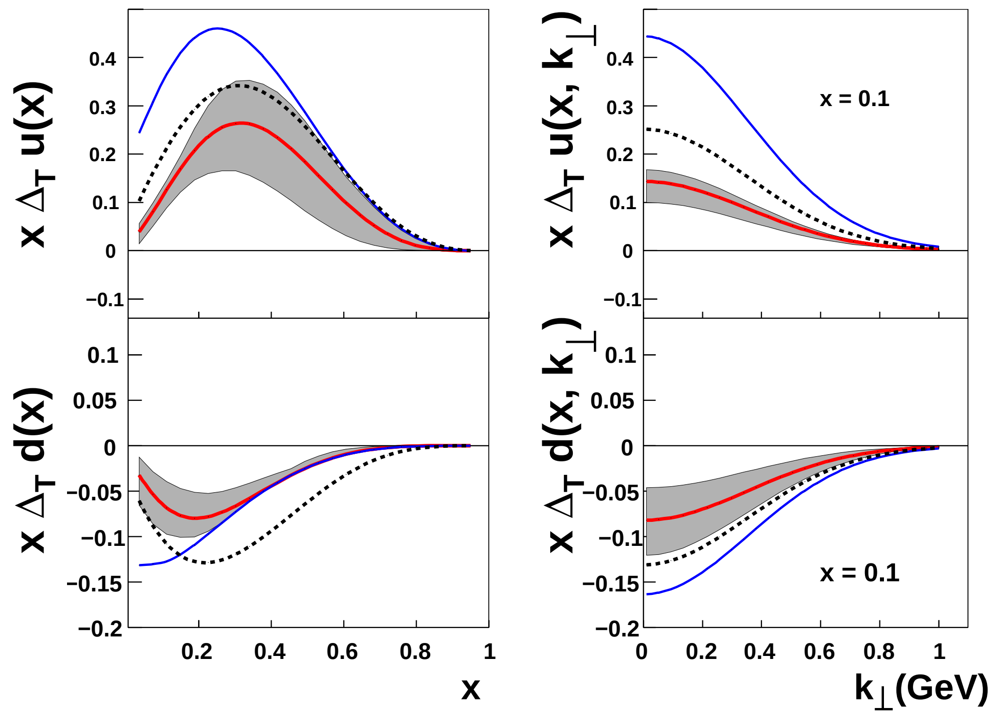
  - collinear factorization, stable upon inclusion of QCD corrections
  - effects up to $30\,\%$ predicted for $\bar{p}^{\uparrow}\, p^{\uparrow} \to l^{+}\, l^{-}\, X$ at GSI
    (Anselmino, Drago, Nikolaev, 2004 / Efremov, Goeke, Schweitzer, 2004)

- Exploiting hyperon-polarization
  $e\, p^{\uparrow} \to e\, \Lambda^{\uparrow} X \qquad p\, p^{\uparrow} \to \Lambda^{\uparrow} X$
  input needed from $e^{+}\, e^{-} \to \Lambda^{\uparrow}\, \bar{\Lambda}^{\uparrow} X$

- Exploiting dihadron fragmentation
  $e\, p^{\uparrow} \to e\, (\pi^{+}\pi^{-})\, X \qquad p\, p^{\uparrow} \to (\pi^{+}\pi^{-})\, X$
  input needed from $e^{+}\, e^{-} \to (\pi^{+}\pi^{-})\, (\pi^{+}\pi^{-})\, X$

- Exploiting chiral-odd photon-coupling (Pire, Szymanowski, 2009)
  $\gamma\, p^{\uparrow} \to l^{+}\, l^{-}\, X$
  twist-3 effect

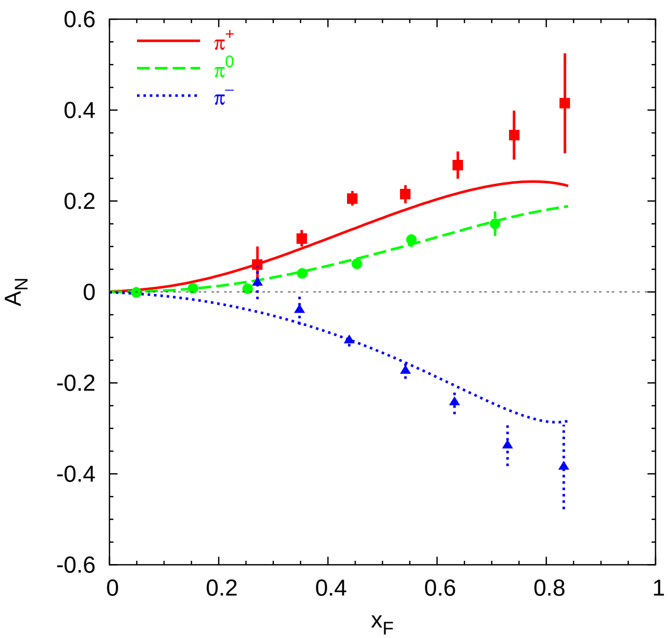
- Exploiting (transverse momentum dependent) Collins effect (Collins, 1992)
  $\longrightarrow$ combined analysis of COMPASS and HERMES data for $e\,N^{\uparrow} \longrightarrow e\,H\,X$ and Belle data for $e^{+}\,e^{-} \longrightarrow H_1\,H_2\,X$ (Anselmino et al, 2008)



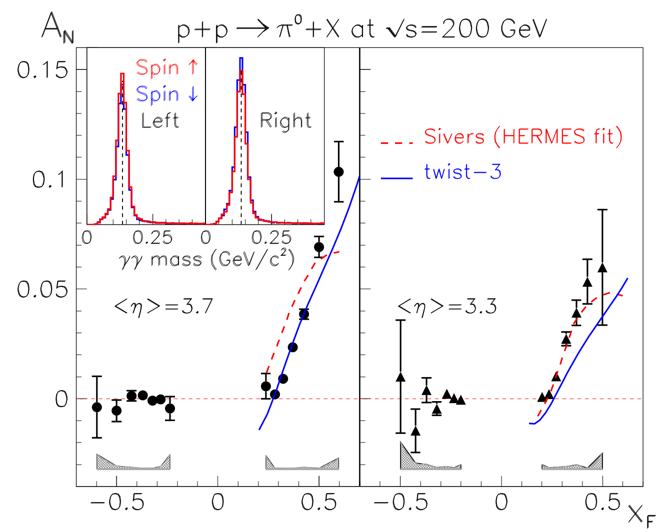
- good/fair agreement with almost all models, but ...
- soft gluon emission should reduce extracted $\Delta_T q$ by about factor of 2 (Boer, 2008)
- how can this puzzle be resolved ?
- new input from theory and experiment required ! (Aybat, Rogers, 2011)

Transverse SSAs in $p\,p^{\uparrow} \;\rightarrow \pi\, X$

$$A_N = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}} \qquad\qquad x_F = \frac{2P_{hL}}{\sqrt{s}}$$



FermiLab, E704, 1990 $\quad \sqrt{s} = 20\,\mathrm{GeV}$



RHIC, STAR, 2008 $\quad \sqrt{s} = 200\,\mathrm{GeV}$

- understanding of these interesting effects in QCD still a challenge
- may be described by collinear twist-3 parton correlators
  (see also Kanazawa, Koike, 2011)
- quantitative relation to SSAs observed by COMPASS and HERMES still unclear
  (see also Kang, Qiu, Vogelsang, Yuan, 2011)

Transverse Momentum Dependent Parton Distributions (TMDs)

- TMD-correlator

$$\Phi^q = \frac{1}{2}\int \frac{dz^-}{2\pi}\,\frac{d^2\vec{z}_T}{(2\pi)^2}\,e^{ik\cdot z}\,\langle P;S|\,\bar{\psi}^q(0)\,\gamma^+\,\mathcal{W}_{TMD}\,\psi^q(z)\,|P;S\rangle\Big|_{z^+=0}$$

$$= f_1^q(x,\vec{k}_T^{\,2}) + \frac{(\vec{S}_T\times\vec{k}_T)\cdot\hat{P}}{M}\,f_{1T}^{\perp q}(x,\vec{k}_T^{\,2})$$

  - partonic nucleon structure beyond collinear approximation
    $\longrightarrow$ 3-D structure in $(x, \vec{k}_T)$-space
  - Sivers function $f_{1T}^{\perp}$ describes strength of spin-orbit correlation
  - spin asymmetry on the level of parton distribution
    $\longrightarrow$ spin asymmetry in observables (e.g., Sivers SSA observed by HERMES and COMPASS)
  - k_T compensated by hadronic scale (M) $\longrightarrow$ no suppression !

- Leading twist: overview

$$\langle \, | \, \bar{\psi}^q \, \gamma^+ \, \psi^q \, | \, \rangle \quad \sim \quad f_1^q - \frac{\varepsilon_T^{ij} \, k_T^i \, S_T^j}{M} \, f_{1T}^{\perp q}$$

$$\lambda \, \langle \, | \, \bar{\psi}^q \, \gamma^+ \gamma_5 \, \psi^q \, | \, \rangle \quad \sim \quad \lambda \, \Lambda \, g_1^q + \frac{\lambda \, \vec{k}_T \cdot \vec{S}_T}{M} \, g_{1T}^q$$

$$s_T^i \, \langle \, | \, \bar{\psi}^q \, i\sigma^{i+} \gamma_5 \, \psi^q \, | \, \rangle \quad \sim \quad \vec{s_T} \cdot \vec{S}_T \, h_1^q + \frac{\Lambda \, \vec{k}_T \cdot \vec{s}_T}{M} \, h_{1L}^{\perp q} - \frac{\varepsilon_T^{ij} \, k_T^i \, s_T^j}{M} \, h_1^{\perp q}$$

$$+ \frac{1}{2M^2} \Big(2 \, \vec{k}_T \cdot \vec{s}_T \, \vec{k}_T \cdot \vec{S}_T - \vec{k}_T^{\,2} \, \vec{s}_T \cdot \vec{S}_T \Big) \, h_{1T}^{\perp q}$$

  - 2 (naive) T-odd TMDs: $f_{1T}^{\perp q}$, $h_1^{\perp q}$
  - dipole pattern generated by $f_{1T}^{\perp q}$, $h_1^{\perp q}$, g_{1T}^q , $h_{1L}^{\perp q}$
  - quadrupole pattern generated by $h_{1T}^{\perp q} \longrightarrow$ 'pretzelosity'
  - various model calculations and very recent lattice calculation of TMDs (Hägler, Musch, Negele, Schäfer, 2009, 2010)
  - nontrivial (model-dependent) relations between TMDs and GPDs (Burkardt, 2002, ... / Lu, Schmidt, 2006 / Meissner, Metz, Goeke, 2007, ... Pasquini, Cazzaniga, Boffi, 2008 / Gamberg, Schlegel, 2009)

- Leading twist TMDs in semi-inclusive DIS

$$\sigma_{UU}: \quad f_1 \otimes D_1 \qquad \cos(2\phi_h)\, h_1^\perp \otimes H_1^\perp$$

$$\sigma_{LL}: \quad g_1 \otimes D_1$$

$$\sigma_{LT}: \quad \cos(\phi_h - \phi_S)\, g_{1T} \otimes D_1$$

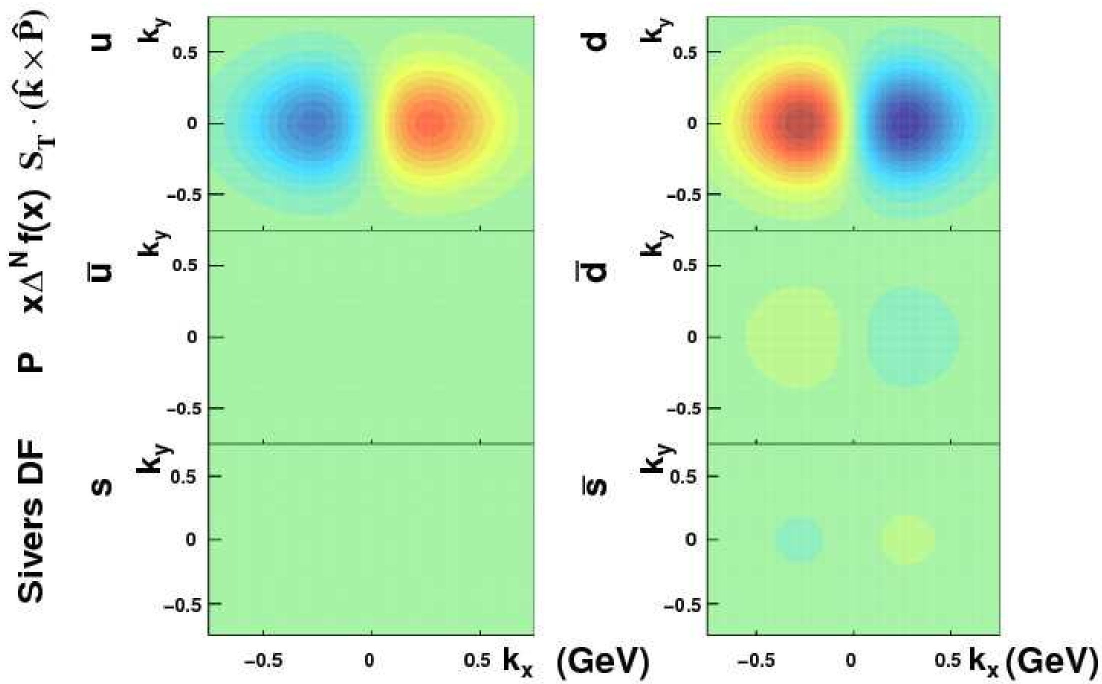
$$\sigma_{UL}: \quad \sin(2\phi_h)\, h_{1L}^\perp \otimes H_1^\perp$$

$$\sigma_{UT}: \quad \sin(\phi_h - \phi_S)\, f_{1T}^\perp \otimes D_1 \qquad \sin(\phi_h + \phi_S)\, h_1 \otimes H_1^\perp$$

$$\sin(3\phi_h - \phi_S)\, h_{1T}^\perp \otimes H_1^\perp$$

  - $H_1^\perp$: Collins fragmentation function (Collins, 1992)
  - complete experiment for TMDs possible ! (likewise for Drell-Yan)
  - various observables already studied at COMPASS, HERMES, JLab
  - potential future Electron Ion Collider would be ideal for TMD-studies (larger kinematical coverage, larger luminosity)

- Example: Sivers function from data on semi-inclusive DIS (Anselmino et al., 2008)
  $\longrightarrow$ 3-D structure of the nucleon: dipole pattern due to Sivers effect $(x = 0.2)$



(Plot from Prokudin; red: positive effect, blue: negative effect)

- though model-dependent, plot generated from data !
- very fascinating aspect of TMD-field !

Sign reversal of the Sivers function

- Prediction based on operator definition (Collins, 2002)

$$f_{1T}^{\perp}\big|_{DY} = - \, f_{1T}^{\perp}\big|_{DIS}$$

- What if sign reversal of $f_{1T}^{\perp}$ is not confirmed by experiment ?
  - would not imply that QCD is wrong !
  - would imply that SSAs not understood in QCD
  - problem with TMD-factorization
  - problem with resummation of large logarithms

    $\longrightarrow$ resummation relevant if more than one scale present

    $\longrightarrow$ CSS resummation in Drell-Yan (Collins, Soper, Sterman, 1985), resum logarithms of the type

$$\alpha_s^k \ln^{2k} \frac{\vec{Q}_T^2}{Q^2}$$

$\longrightarrow$ has also implications for Fermilab and LHC physics

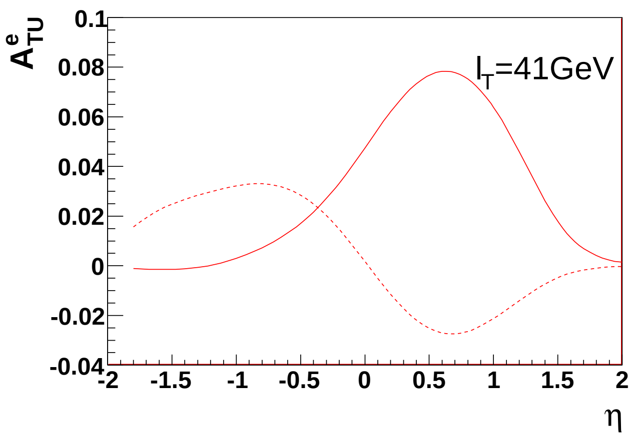
- Prospects for checking the sign reversal
  - Sivers effect should be measurable in DY (up to $10\,\%$)

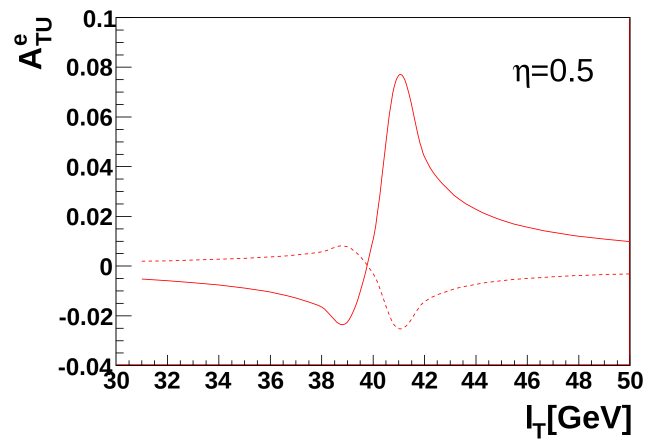
    $\longrightarrow$ potential labs: BNL, CERN, GSI, IHEP, JINR, J-PARC

    $\longrightarrow$ first study: Efremov et al, 2004

    $\longrightarrow$ more recent, comprehensive study: Anselmino et al, 2009

  - Sivers asymmetry for W-production in pp-collisions at RHIC $(p^{\uparrow}\, p \to l^{\pm}\, X)$
    (Metz, Zhou, 2010 / see also Kang, Qiu, 2009)





(full curve: W^--production, dashed curve: W^+-production)

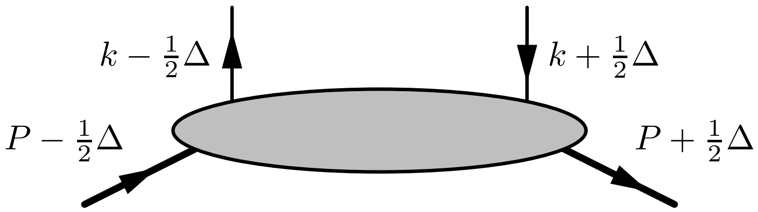
$\longrightarrow$ theoretically as clean as Drell-Yan for what concerns sign change

$\longrightarrow$ measuring this observable would be win-win situation

$\longrightarrow$ is it feasible at RHIC ?

Generalized Parton Distributions (GPDs)

- Appear in QCD-description of hard exclusive reactions:
  deep-virtual Compton scattering, hard exclusive meson production
- Kinematics



$$P = \frac{p + p'}{2} \qquad \Delta = p' - p$$

- GPD-correlator

$$F^q = \frac{1}{2} \int \frac{d\xi^-}{2\pi} e^{ik\cdot z} \langle p';\lambda' | \bar{\psi}\Big(-\frac{z}{2}\Big) \gamma^+ \mathcal{W}_{GPD}\, \psi\Big(\frac{z}{2}\Big) |p;\lambda\rangle \Big|_{z^+=z_T=0}$$

$$= \frac{1}{2P^+} \bar{u}(p',\lambda') \left(\gamma^+ H^q(x,\xi,t) + \frac{i\sigma^{+\mu}\Delta_\mu}{2M} E^q(x,\xi,t) \right) u(p,\lambda)$$

$$x = \frac{k^+}{P^+} \qquad \xi = -\frac{\Delta^+}{2P^+} \qquad t = \Delta^2$$

- Leading twist for (counting like in case of TMDs)

$$\bar{\psi}\,\gamma^+\,\psi \qquad \bar{\psi}\,\gamma^+\gamma_5\,\psi \qquad \bar{\psi}\,i\sigma^{j+}\gamma_5\,\psi$$

- Plenty of data available from CERN, DESY, JLab

- (Nontrivial) modeling of GPDs reached high level of sophistication

- Impact parameter (b_T) representation of GPDs $\longrightarrow$ density interpretation (Soper, 1977 / Burkardt, 2000)
  - Fourier transform of GPD-correlator ($\xi = 0$)

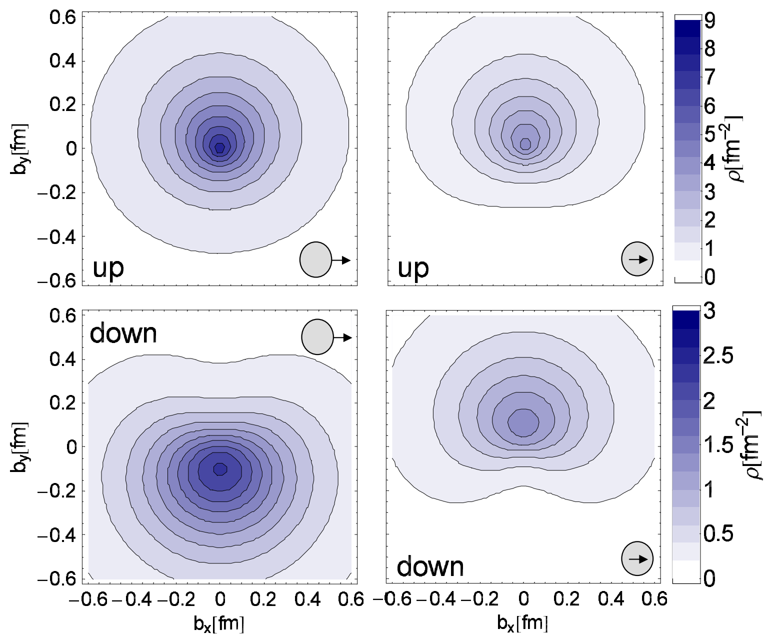
$$
\begin{aligned}
\mathcal{F}^q(x, \vec{b}_T; S) &= \int \frac{d^2 \vec{\Delta}_T}{(2\pi)^2} \, e^{-i\vec{\Delta}_T \cdot \vec{b}_T} \, F^q(x, \vec{\Delta}_T; S) \\
&= \mathcal{H}^q(x, \vec{b}_T^{\,2}) + \frac{\epsilon_T^{ij} b_T^i S_T^j}{M} \Big(\mathcal{E}^q(x, \vec{b}_T^{\,2}) \Big)'
\end{aligned}
$$

$$
\text{with} \quad \mathcal{H}^q(x, \vec{b}_T^{\,2}) = \int \frac{d^2 \vec{\Delta}_T}{(2\pi)^2} \, e^{-i\vec{\Delta}_T \cdot \vec{b}_T} \, H^q(x, 0, -\vec{\Delta}_T^{\,2})
$$

  - term containing $\mathcal{E}^q$ generates (numerically large) dipole pattern $\longrightarrow$ 3-D structure in $(x, \vec{b}_T)$-space
  - taken together with $\mathcal{H}^q$ term leads to distorted distribution
  - at leading twist, one more dipole structure and one quadrupole structure

- Distortion of densities in transverse plane from lattice QCD

QCDSF Collaboration, 2006



left: unpolarized quarks in transversely polarized target

right: transversely polarized quarks in unpolarized target

- distortion stronger for transv. pol. quarks in unpol. nucleon
- distortion stronger for down quarks
- similar results in models
- ultimate aim: transverse quark densities from data

Ji's Spin Sum Rule of the Nucleon

- Sum rule (for longitudinal spin) (Ji, 1996)

$$\frac{1}{2} = \sum_q J^q + J^g = \frac{1}{2}\Delta\Sigma + \sum_q L^q + J^q \qquad \text{with}$$

$$\Delta\Sigma = \sum_q \int dx \Big(\Delta q(x) + \Delta\bar{q}(x)\Big)$$

$$J^q = \frac{1}{2}\int dx\, x \Big(H^q(x,\xi,t=0) + E^q(x,\xi,t=0)\Big)$$

$$J^g = \frac{1}{2}\int dx \Big(H^g(x,\xi,t=0) + E^g(x,\xi,t=0)\Big)$$

  - gauge-invariant decomposition
  - handle on quark orbital angular momentum L^q
  - no decomposition of J^g into spin and orbital part
  - Δg measured by COMPASS, HERMES, RHIC does not enter this sum rule

- Numerical numbers (at scale $\mu = 2\,GeV$)
  - sample lattice QCD result (LHPC, 2010)

$$J^u = 0.236(6) \qquad J^d = 0.0018(37) \qquad L^{u+d} = 0.056(11)$$

  - general trend (from lattice QCD and models that are adjusted to data)

$$J^u > 0 \qquad J^d \approx 0 \qquad L^u < 0 \qquad L^d > 0 \qquad L^{u+d} \approx 0$$

  - numbers may imply (role of antiquarks ?)

$$J^g \approx 70\,\%\,!$$

  - side-remark

    $\longrightarrow$ quark models at lower scales tend to predict: $L^u > 0 \qquad L^d < 0$

    $\longrightarrow$ qualitatively: evolution to larger scales can flip the sign
    (Myhrer, Thomas, 2007,2008 / Altenbuchinger, Hägler, Weise, Henley, 2010)

Alternative Decompositions of the Nucleon Spin

- Gauge-fixed decomposition (light-cone gauge) (Jaffe, Manohar, 1990)

$$\frac{1}{2} = \sum_q \mathcal{J}^q + \mathcal{J}^g \qquad \text{with}$$

$$\sum_q \mathcal{J}^q = \frac{1}{2}\Delta\Sigma + \sum_q \mathcal{L}^q \qquad \mathcal{J}^g = \Delta g + \mathcal{L}^g$$

  - Δg measured by COMPASS, HERMES, RHIC enters this sum rule
  - explicit operator definitions for $\mathcal{L}^q$ and $\mathcal{L}^g$ exist
  - $\mathcal{J}^q \neq J^q \qquad \mathcal{L}^q \neq L^q \qquad \mathcal{J}^g \neq J^g$
    $\longrightarrow$ see also Burkardt and Hikmat BC (2008) for toy model estimate
  - no known connection of $\mathcal{L}^q$ and $\mathcal{L}^g$ with observables
    $\longrightarrow$ no experimental check of sum rule possible
  - $\Delta g \approx 0$ would imply

$$\sum_q \mathcal{L}^q + \mathcal{L}^g \approx 70\,\%\,!$$

- Gauge-invariant decomposition II (Chen et al, 2008/09)
  - split of vector potential A into physical part and pure gauge part
  - decomposition of nucleon spin into 4 terms (like Jaffe-Manohar)
  - decomposition reduces to Jaffe-Manohar result in specific Coulomb gauge
  - no known connection of orbital angular momenta with observables

- Gauge-invariant decomposition III (Wakamatsu, 2010)
  - split of vector potential A into physical part and pure gauge part (like Chen et al)
  - decomposition of nucleon spin into 4 terms
  - decomposition coincides with Ji's sum rule, but proposes in addition

$$L^g = J^g - \Delta g$$

  - $\sum_q J^q \approx 30\,\%$ and $\Delta g \approx 0$ would imply

$$L^g \approx 70\,\%\,!$$

Open Issues — instead of Summary of Tremendous Progress

$\longrightarrow$ plenty of challenges (for experiment and theory), but picked only one per topic

1. Longitudinal Spin Structure
   - What is Δg at low x ?

2. Transverse Spin Structure
   - Can the sign change of the Sivers effect be confirmed — in Drell-Yan (or in W-production) ?

3. GPDs and Spin Sum Rule of the Nucleon
   - Is there an 'optimal' version of the spin sum rule ?