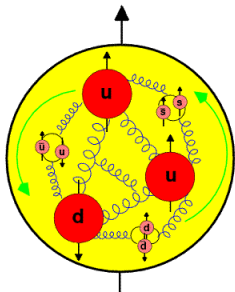


# A short review of spin physics



Barbara Badelek  
University of Warsaw

Low x 2010

Kavala, June 23 – 27, 2010

# A Beautiful Spin (after X. Ji)

- Born with troubles (Stern & Gerlach (1922) vs Goudsmit & Uhlenbeck (1925))
- Is due to space–time symmetry
- Fundamental concept
- **Laboratory to explore physics beyond the SM, e.g.:**
  - Muon “ $g - 2$ ” experiment @ BNL
  - Proton weak charge (Qweak exp @ JLAB)
  - Neutron EDM measurement ...

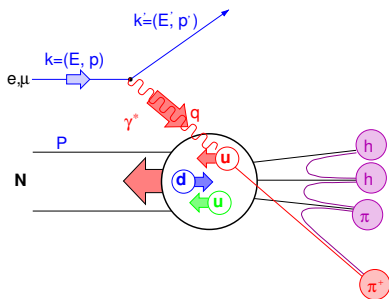
**Tool to measure observables hard to obtain otherwise, e.g:**

- Strangeness content of the nucleon from polarised parity–violating e–p scattering
- Electromagnetic form factors of the nucleon from the recoil polarisation
- Neutron density in large nuclei from parity–violating electron scattering
- and...

# A Beautiful Spin (after X. Ji)...cont'd

- Probe to unravel the nonperturbative QCD dynamics, e.g.:
  - Nucleon spin-dependent structure functions,  $g_1$  and  $g_2$
  - Quark helicity ( $\Delta q(x)$ ) and transversity ( $\Delta_T q(x)$ ) distributions
  - Gluon polarisation,  $\Delta g(x)$
  - Generalised Parton Distributions, GPD
  - Semi-Inclusive Deep Inelastic Scattering, SIDIS
  - (Generalised) Drell-Hearn-Gerasimov-... sum rule
  - Single spin asymmetries

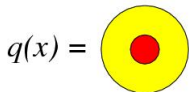
# Nucleon spin structure in the electroproduction



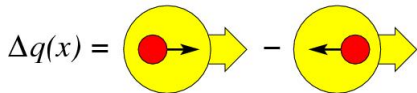
- $\frac{d^2\sigma}{d\Omega dE'} = \frac{\alpha^2}{2Mq^4} \frac{E'}{E} L_{\mu\nu} W^{\mu\nu}$
- Symmetric part of  $W^{\mu\nu}$  – unpol. DIS, antisymmetric – polarised DIS
- Nominally  $F_{1,2}$ ,  $q(x) \longrightarrow g_{1,2}$ ,  $\Delta q(x)$  but...
  - ...anomalous gluon contribution to  $g_1(x)$
  - ... $g_2(x)$  has no interpretation in terms of partons.

# Partonic structure of the nucleon; distribution functions

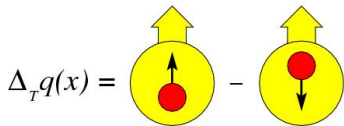
Three **twist-two** quark distributions in QCD (after integrating over the quark intrinsic  $k_t$ )



Quark momentum DF;  
**well known** (unpolarised DIS  $\rightarrow F_{1,2}(x)$ ).



Difference in DF of quarks with spin parallel or antiparallel to the nucleon's spin;  
**known** (polarised DIS  $\rightarrow g_1(x)$ ).



Difference in DF of quarks with spin parallel or antiparallel to the nucleon's spin in the transversely polarised nucleon;  
**unknown** (polarised DIS  $\rightarrow h_1(x)$ ).

Nonrelativistically:  $\Delta_T q(x) \equiv \Delta q(x)$ . **OBS.!**  $\Delta_T q(x)$  are **C-odd and chiral-odd**; may only be measured with another chiral-odd partner, e.g. fragmentation function.

If the  $k_t$  taken into account  $\implies$  8 TMD distr.; one,  $f_{1T}^\perp$  accessible through "Sivers asymmetry".

# Nucleon spin structure: observables in $\vec{\mu}\vec{N}$ scattering

- Inclusive asymmetry,  $A_{meas}$ :

$$A_{meas} = \frac{1}{fP_T P_B} \left( \frac{N^{\leftrightarrow} - N^{\equiv}}{N^{\leftrightarrow} + N^{\equiv}} \right) \approx DA_1 = D \frac{g_1(x, Q^2)}{F_1(x, Q^2)} = D \frac{\sum_q e_q^2 \Delta q(x, Q^2)}{\sum_q e_q^2 q(x, Q^2)}$$

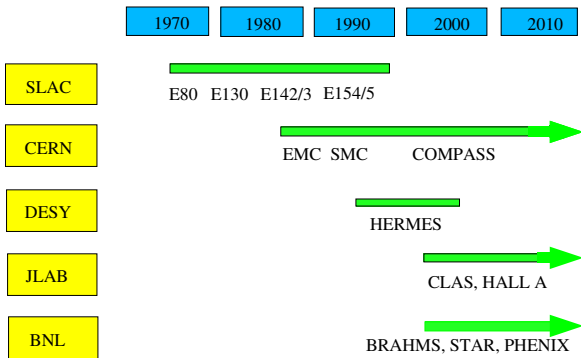
$$\Delta q = q^+ - q^-, \quad q = q^+ + q^-, \quad g_1^d = g_1^N \left(1 - \frac{3}{2}\omega_D\right) = \frac{g_1^p + g_1^n}{2} \left(1 - \frac{3}{2}\omega_D\right);$$

$$\omega_D = 0.05 \pm 0.01$$

- Semi-inclusive asymmetry,  $A_1^h$ :

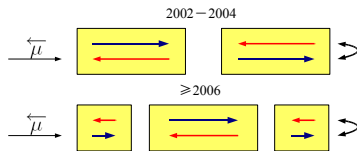
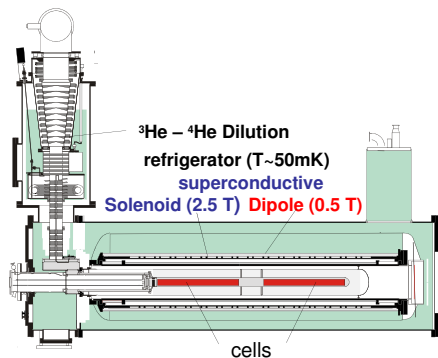
$$A_1^h(x, z, Q^2) \approx D \frac{\sum_q e_q^2 \Delta q(x, Q^2) D_q^h(z, Q^2)}{\sum_q e_q^2 q(x, Q^2) D_q^h(z, Q^2)} \quad z = \frac{E_h}{\nu} \quad D_q^h \neq D_{\bar{q}}^h$$

# Experiments



Experiment	Polarised beam	Polarised target	Energy (GeV)
SLAC	e	p, n, d	$\lesssim 50$
EMC	$\mu$	p	100–200
SMC	$\mu$	p, d	100, 190
HERMES	e	p, n, d	27.5
COMPASS	$\mu$	p, d	160
JLAB	e	p, n, d	$\lesssim 6$

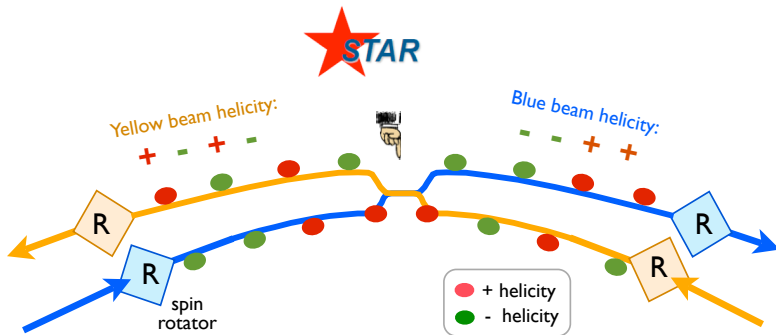
# COMPASS polarised targets



- \* Two (three in 2006, 2007) target cells, oppositely polarised
- \* Polarisation reversed every 8 h (less frequent in 2006, 2007) by field rotation
- \* Material: solid  $^6\text{LiD}$  ( $\text{NH}_3$  in 2007)
- \* Polarisation:  $\sim 50\%$  ( $\sim 90\%$  in 2007), by the Dynamical Nuclear Polarisation
- \* Dilution:  $f \sim 0.4$  ( $\sim 0.15$  in 2007)
- \* Polar acceptance:  $\sim 70$  mrad ( $\sim 180$  mrad in 2006, 2007)



# Polarised pp scattering at RHIC



STAR sees 4 helicity configurations  
 STAR runs 4 parallel measurements

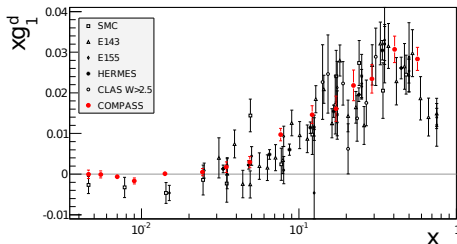
RHIC measured polarization  
 Run 9 @ 2x250 GeV

**Pol yellow 0.40**

**Pol blue 0.38**

syst. pol (blue+yellow)=9.2%

# $g_1(x)$ for proton and deuteron, $Q^2 > 1$ (GeV/c)<sup>2</sup>



Very precise data  
especially at  $x \lesssim 0.01$

From  $\Gamma_1^d$  at  $Q^2 \rightarrow \infty$ :

HERMES:

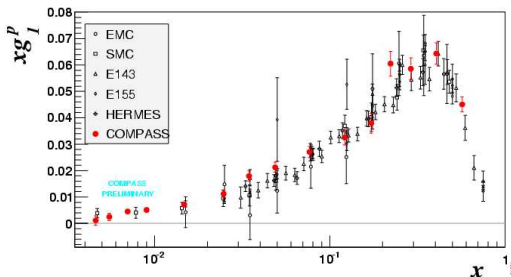
$$a_0 = 0.330 \pm 0.025 \pm 0.011 \pm 0.028$$

COMPASS:

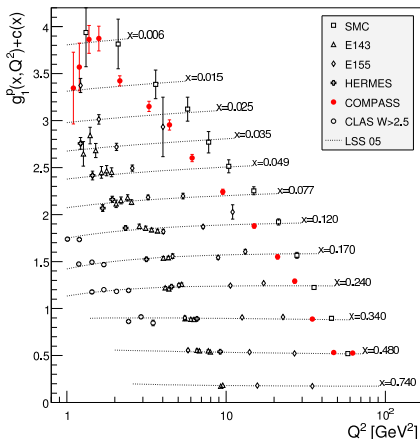
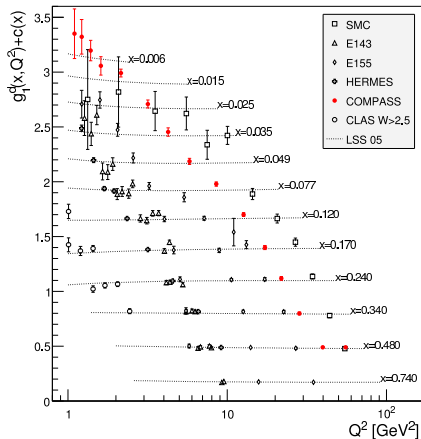
$$a_0 = 0.33 \pm 0.03 \pm 0.05$$

$$\Delta s + \Delta \bar{s} = -0.08 \pm 0.01 \pm 0.02$$

Good agreement  
between the experiments



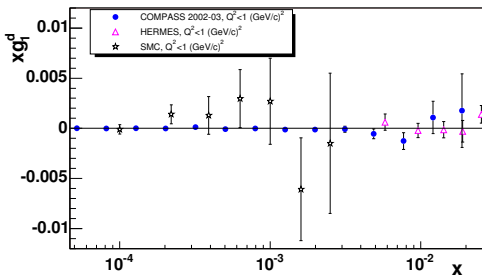
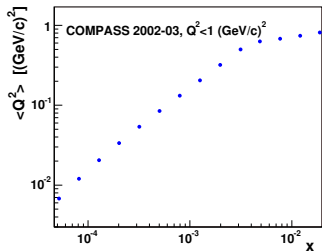
# $g_1(x)$ for proton and deuteron, $Q^2 > 1$ (GeV/c)<sup>2</sup>...cont'd



More data from JLAB/EG1a @ low  $Q^2$ .

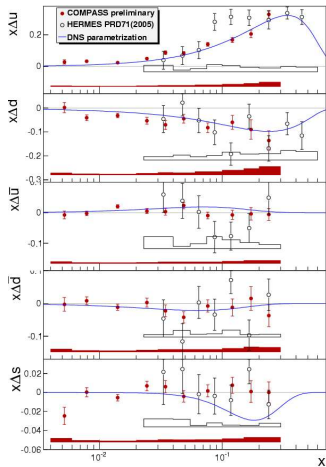
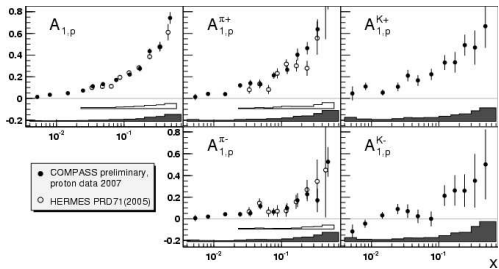
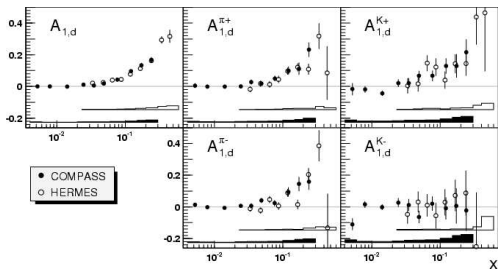
# $g_1^d(x)$ in the nonperturbative ( $Q^2 < 1$ (GeV/c) $^2$ region)

V.Yu. Alexakhin *et al.* (COMPASS) Phys. Lett. B **647** (2007) 330



- Order of magnitude improvement over the statistical precision of the SMC.
- Interplay between perturbative and nonperturbative mechanisms.
- Spin effects in  $g_1^d$  at low  $x$  and  $Q^2$  absent ?

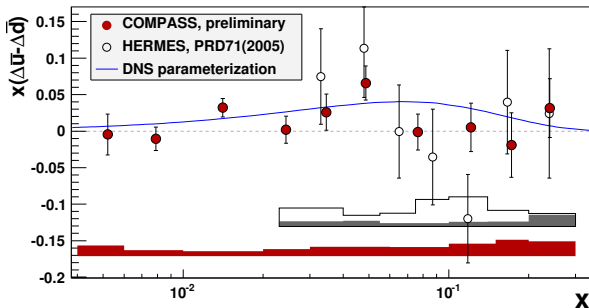
# Flavour separation of helicity distributions (@ LO)



$$Q^2 = 3 \text{ (GeV/c)}^2$$

Fragmentation functions!

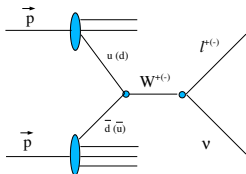
# Is the polarised sea flavour symmetric? $\Delta\bar{u} - \Delta\bar{d} = ?$



- COMPASS:  $\int_{0.004}^{0.3} (\Delta\bar{u} - \Delta\bar{d}) = 0.052 \pm 0.035 \pm 0.013 @ Q^2 = 3 \text{ GeV}^2$ .
- HERMES:  $\int_{0.023}^{0.6} (\Delta\bar{u} - \Delta\bar{d}) = 0.048 \pm 0.057 \pm 0.028 @ Q^2 = 2.5 \text{ GeV}^2$ .
- Presently accessible only in SIDIS.
- Unpolarised sea:  $\int (\bar{u} - \bar{d}) = -0.118 \pm 0.012$

# $W^\pm$ production in $\vec{p}\vec{p}$ scattering @ RHIC

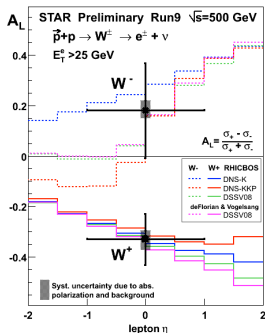
$\vec{p}\vec{p} \rightarrow W^{+(-)} \rightarrow l^{+(-)}\nu X$  run 9 @  $\sqrt{s} = 500$  GeV, preliminary



- $\sigma(W)$  agrees reasonably with theory
- Hard scale set by the lepton  $p_T$
- No FF uncertainties

LO interpretation:

- $A_L^{W^-} = \frac{1}{2} \left( \frac{\Delta\bar{u}}{\bar{u}} - \frac{\Delta d}{d} \right) = 0.18 \pm 0.19 \begin{smallmatrix} +0.04 \\ -0.03 \end{smallmatrix}$  (STAR)
- $A_L^{W^+} = \frac{1}{2} \left( \frac{\Delta\bar{d}}{\bar{d}} - \frac{\Delta u}{u} \right) = -0.33 \pm 0.10 \pm 0.04$  (STAR)  
 $= -0.83 \pm 0.31$  (PHENIX)
- $x(\Delta\bar{u} - \Delta\bar{d}) > 0$  ?

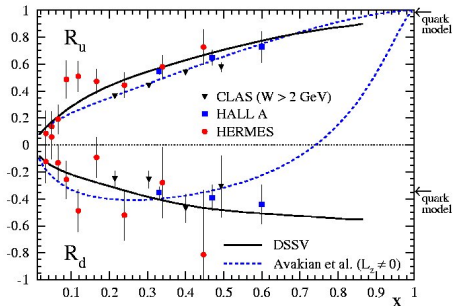
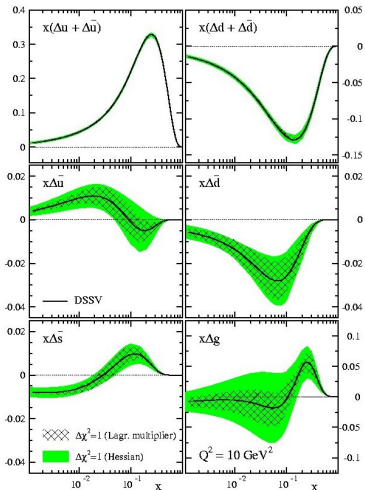


After J. Balewski, DIS2010

# Global parton analyses

Example: DSSV (D. de Florian, R. Sassot, M. Stratmann, V. Vogelsang),  
cf. Phys. Rev. D **80** (2009) 034030.

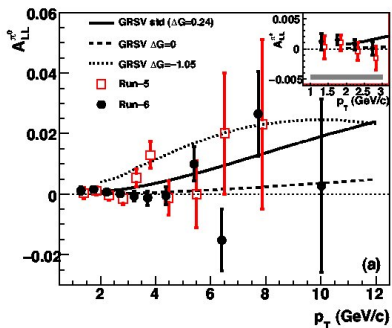
$$R_q = \frac{\Delta u + \Delta \bar{u}}{u + \bar{u}}$$



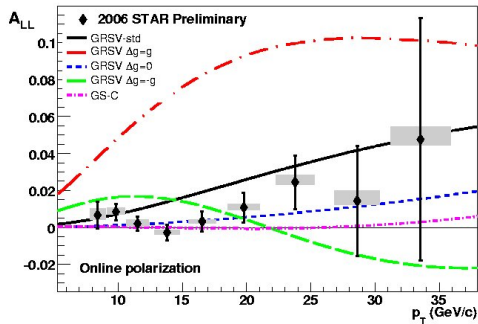
- $\Delta g$  poorly known but small
- ... may still contribute to nucleon spin
- has a node at  $x \sim 0.1$  ?
- $\Delta s > 0$  from SIDIS  
but  $< 0$  required by incl. data (+  $SU_3$ )
- ... thus node in  $\Delta s$  fits.



# $\Delta g$ from the polarised pp scattering @ RHIC



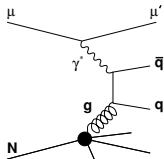
PHENIX  
(high  $p_T$   $\pi^0$  production)



STAR  
(mid-rapidity inclusive jets)

- Confirmed the electroproduction results
- Included in the DSSV2009.

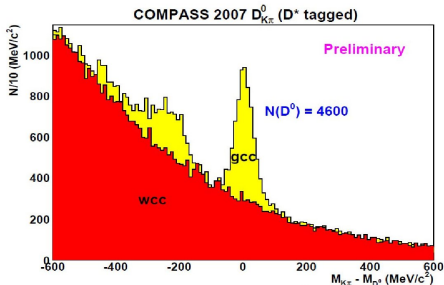
# $\Delta g$ from the PGF in electroproduction



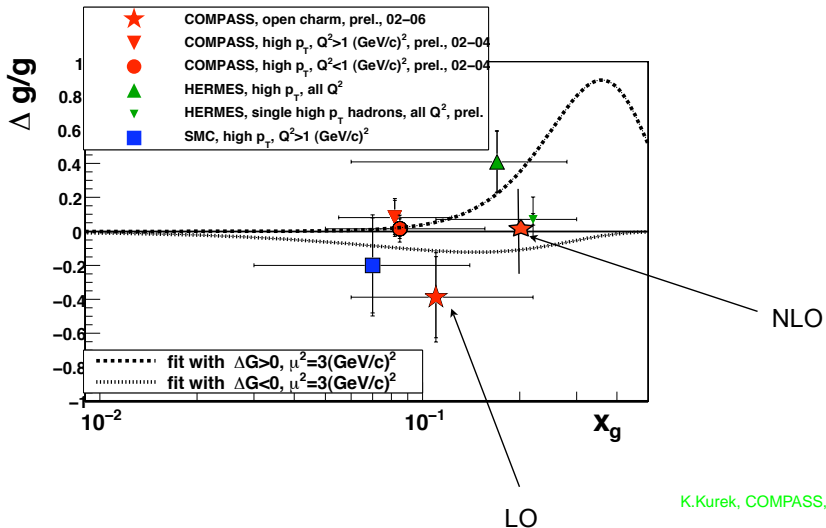
if  $q, \bar{q} \equiv c, \bar{c}$  then  $A_{meas} \sim \langle a_{pgf} \rangle \left\langle \frac{\Delta g}{g} \right\rangle + A_{bckg}$  AROMA  
 if  $q, \bar{q} \equiv \text{light quarks}$  then more MC info needed LEPTO/PYTHIA.

To suppress background in  $c\bar{c}$ :

- only one charm meson candidate
- quasi-real photons
- A weighting method used to optimise the  $\Delta g(x)$  extraction
- Combinatorial background significantly reduced for the  $D^* \rightarrow D^0 + \pi_s \rightarrow K + \pi + \pi_s$ .



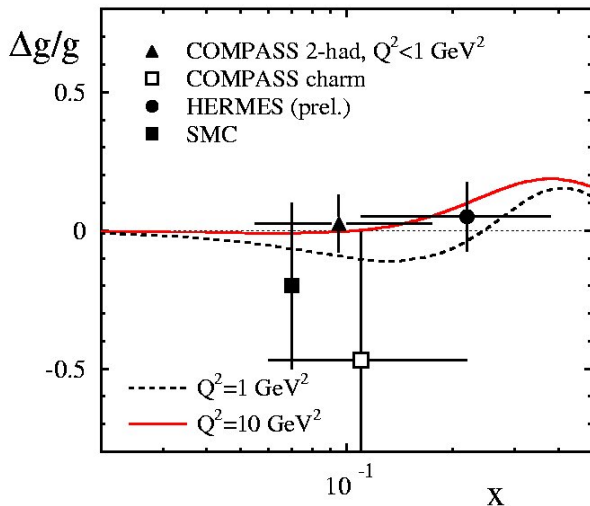
# $\Delta g$ from the PGF in electroproduction, ...cont'd



K.Kurek, COMPASS, DIS2010



# $\Delta g$ from the PGF in electroproduction, ...cont'd



DSSV, arXiv:0904.3821

# Nucleon spin decomposition – “22 years later”

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L$$

Are we approaching the solution of the “proton spin puzzle”?

- Restoration of  $\Delta\Sigma=0.6$  via the axial anomaly improbable.

As a consequence of the “axial anomaly” the measured quantity is:

$$a_0(Q^2) = \Delta\Sigma^{AB} - \left(\frac{3\alpha_s}{2\pi}\right)\Delta G(Q^2)$$

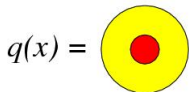
where COMPASS @ 3 GeV<sup>2</sup> gives:  $a_0 = 0.35 \pm 0.03 \pm 0.05$

and the “spin crisis” can be solved ( $\Delta\Sigma \sim 0.6$ ) if  $\Delta G \sim 2.2$  (and  $L \sim -2$ ) at  $Q^2 = 3 \text{ GeV}^2$ .

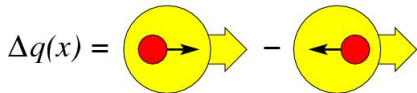
- Global, consistent NLO analysis of  $\Delta G$  needed.
- Independent measurement of  $L$  necessary ( $\implies$  DVCS, lattice QCD?).
- All candidates are contributing about equally to the nucleon spin?

# Partonic structure of the nucleon; distribution functions

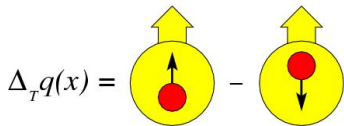
Three **twist-two** quark distributions in QCD (after integrating over the quark intrinsic  $k_t$ )



Quark momentum DF;  
**well known** (unpolarised DIS  $\rightarrow F_{1,2}(x)$ ).



Difference in DF of quarks with spin parallel or antiparallel to the nucleon's spin;  
**known** (polarised DIS  $\rightarrow g_1(x)$ ).



Difference in DF of quarks with spin parallel or antiparallel to the nucleon's spin in the transversely polarised nucleon;  
**unknown** (polarised DIS  $\rightarrow h_1(x)$ ).

Nonrelativistically:  $\Delta_T q(x) \equiv \Delta q(x)$ . **OBS.!**  $\Delta_T q(x)$  are **C-odd and chiral-odd**; may only be measured with another chiral-odd partner, e.g. fragmentation function.

If the  $k_t$  taken into account  $\implies$  8 TMD distr.; one,  $f_{1T}^\perp$  accessible through "Sivers asymmetry".

# Measurements on a transversely polarised target

Properties of  $\Delta_T q(x)$ :

- is chiral-odd  $\implies$  hadron(s) in final state needed to be observed
- simple QCD evolution since no gluons involved
- related to GPD
- sum rule for transverse spin
- first moment gives “tensor charge” (now being studied on the lattice)

Transversity measured e.g. via the Collins asymmetry (asymmetry in the distribution of hadrons):

$$N_h^\pm(\phi_c) = N_h^0 [1 \pm p_T D_{NN} A_{Coll} \sin \phi_c]$$

which in turn gives at LO:

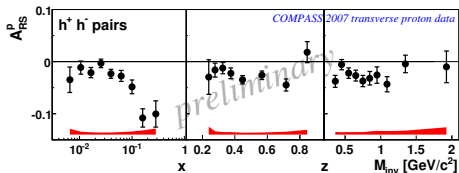
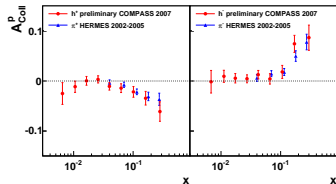
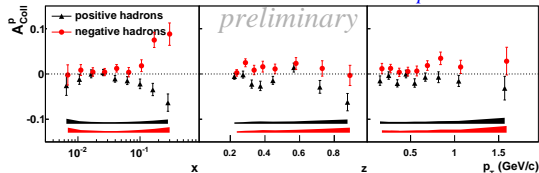
$$A_{Coll} \sim \frac{\sum_q e_q^2 \cdot \Delta_T q \cdot \Delta_T^0 D_q^h}{\sum_q e_q^2 \cdot q \cdot D_q^h}$$

But **transverse fragmentation functions  $\Delta_T^0 D_q^h$  needed to extract  $\Delta_T q(x)$**  from the Collins asymmetry! Recently those FF measured by BELLE.

Properties of the Sivers process: it is related to  $L_q$  in the proton. **Fundamental !**

# Results for the transverse asymmetries

COMPASS 2007 proton data



- Collins 1-h asymmetries for proton large at  $x \gtrsim 0.1$ , consistent with HERMES
- 2-h asymmetry for proton large in the valence region; HERMES sees less.
- Sivers 1-h asymmetries for proton small, contrary to HERMES; needs to be

cleared.

- COMPASS deuteron data: both Collins and Sivers asymmetries very small. These data + Hermes + Belle:  $\Rightarrow \Delta_{Tu} + \Delta_{Td} \sim 0$
- First  $\Delta_{Tq}$  global analyses performed. (cf. Anselmino et al., arXiv:0807.0173)



# Outlook

## Goals:

- Determination of  $\Delta G$ .
- Measurements of GPD via DVCS  $\longrightarrow L_z$ .

## Experimental prospects:

- Short term: more lepton data from COMPASS and JLAB  
more hadron data from RHIC (500 GeV!)
- 5-10 years: COMPASS DVCS and DY programme  
RHIC upgrade  
JLAB upgrade 12 GeV.
- ??? years: electron-ion colliders: eRHIC, ELIC, ENC, LHeC



# EINSTEIN SIMPLIFIED

