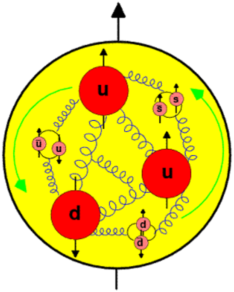
Experimental Studies of the Nucleon Spin Structure: from the Past to the Future



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International Nuclear Physics Conference 2010

Vancouver, July 4–9, 2010

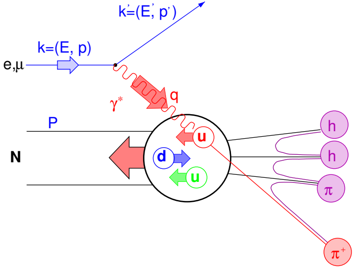
A Beautiful Spin (after X. Ji)

- 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

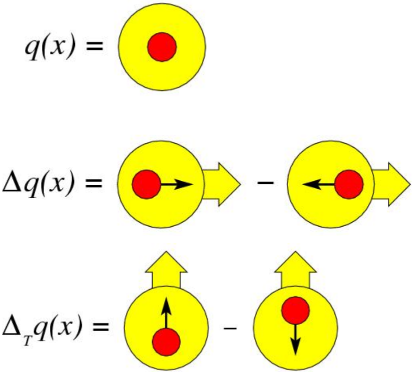


- $Q^2 = -q^2 = -(k-k')^2 \stackrel{lab}{=} EE' \sin^2 \frac{\theta}{2}$
  Partons "visible" at $Q^2 \gtrsim 1$ GeV^2
- $Pq \stackrel{lab}{=} M(E-E') = M\nu$
- $x = \frac{-q^2}{2Pq} \stackrel{lab}{=} \frac{Q^2}{2M\nu}; \quad y = \frac{Pq}{Pk} \stackrel{lab}{=} \frac{\nu}{E}$
- $0 \leq x, y \leq 1$

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

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 $\longrightarrow F_{1,2}(x)$).

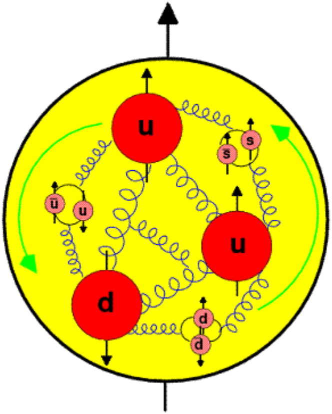
Difference in DF of quarks with spin parallel or antiparallel to the nucleon's spin;
known (polarised DIS $\longrightarrow g_1(x)$).

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

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 $\Longrightarrow$ 8 TMD distr.; one, $f_{1T}^{\perp}$ accessible through "Sivers asymmetry".

Partonic structure of the nucleon: where does its spin come from?



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

The European Muon Collaboration, EMC, @ CERN, 1988:
J. Ashman *et al.*, Phys. Lett. B **206** (1988)364

$a_0 = \Delta\Sigma =$0.12 $\pm$ 0.09 $\pm$0.14 (expected: $\sim$0.6 if Δs = 0).

Here: $\Delta\Sigma = \Delta u + \Delta d + \Delta s$ and

$$\Delta q = \int \Delta q(x) dx, \quad \Delta G = \int \Delta g(x) dx$$

Nucleon spin structure: observables in $\vec{l}\vec{N} \to l'X$

- Inclusive asymmetry, A_{meas}:

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

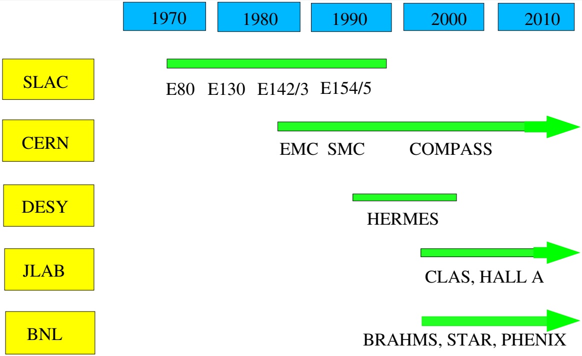
$$\Delta q = q^+ - q^-, \quad q = q^+ + q^-, \qquad g_1^d = g_1^N(1 - \frac{3}{2}\omega_D) = \frac{g_1^p + g_1^n}{2}(1 - \frac{3}{2}\omega_D);$$

$$\omega_D = 0.05 \pm 0.01$$

- Semi–inclusive asymmetry, A^h_{meas}:

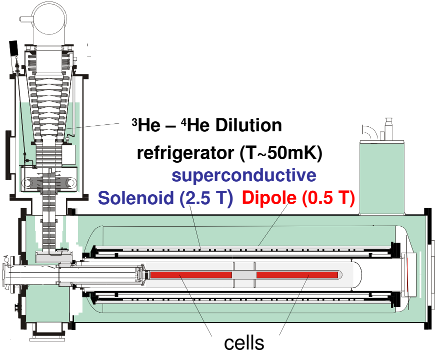
$$A^h_{meas}(x,z,Q^2) \approx D\,\frac{\sum_q e_q^2 \Delta q(x,Q^2) D_q^h(z,Q^2)}{\sum_q e_q^2 q(x,Q^2) D_q^h(z,Q^2)} \qquad z = \frac{E_h}{\nu} \qquad D_q^h \neq D_{\bar{q}}^h$$

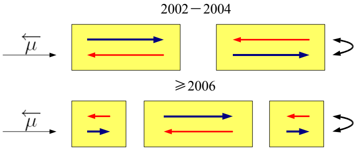
Experiments



Experiment	Polarised beam	Polarised target	Energy (GeV)
SLAC	e	p, n, d	$\lesssim 50$
EMC	μ	p	100–200
SMC	μ	p, d	100, 190
HERMES	e	p, n, d	27.5
COMPASS	μ	p, d	160
JLAB	e	p, n, d	$\lesssim 6$
BNL	p	p	$\lesssim 250 + \lesssim 250$

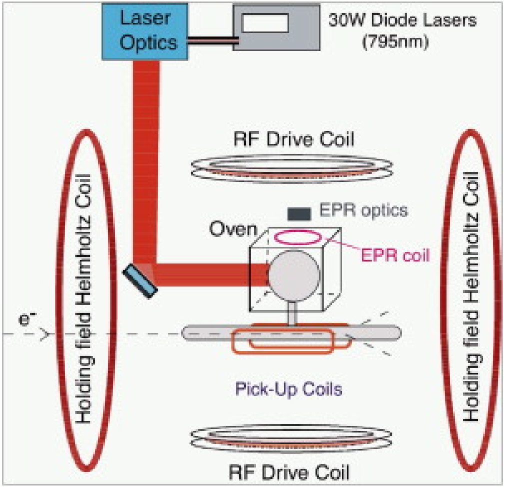
After G.Mallot, COMPASS





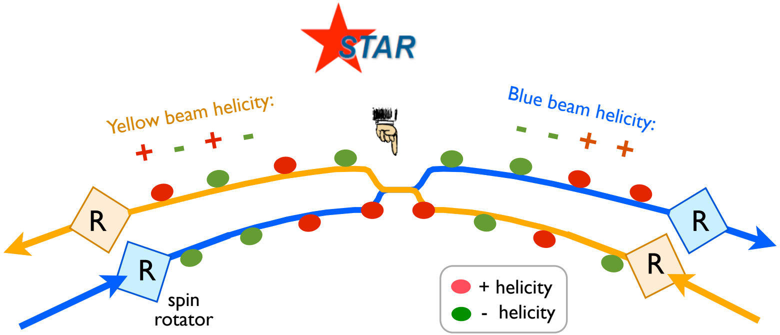
* Two (three in 2006, 2007) target cells, oppositely polarised
* Polarisation reversed every 8 h (less frequent in 2006, 2007) by field rotation
* Material: solid ^{6}LiD (NH_3 in 2007)
* Polarisation: ~ 50% (~90% in 2007), by the Dynamical Nuclear Polarisation
* Dilution: f~0.4 (~0.15 in 2007)
* Polar acceptance: ~70 mrad (~180 mrad in 2006, 2007)

Polarised ^{3}He gas target at JLAB



From Kuhn, Chen and Leader, Prog. Part. Nucl. Phys. **63** (2009) 1

$\vec{p}\vec{p}$ scattering at RHIC

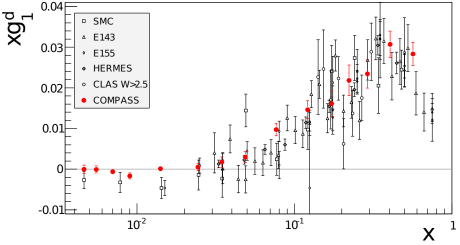


RHIC measured polarization
Run 9 @ 2x250 GeV
Pol yellow 0.40
Pol blue 0.38
syst. pol (blue+yellow)=9.2%

STAR sees 4 helicity configurations
STAR runs 4 parallel measurements

Ws @ STAR, results and perspectives	Jan Balewski, MIT

$g_1(x)$ for proton and deuteron, $Q^2 > 1\ (\mathrm{GeV}/c)^2$



Very precise data
especially at $x \lesssim$ 0.01

From Γ_1^d at $Q^2 \to \infty$:

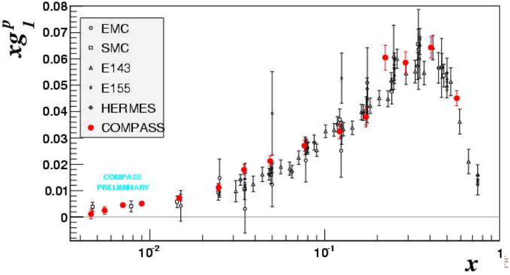
HERMES:

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

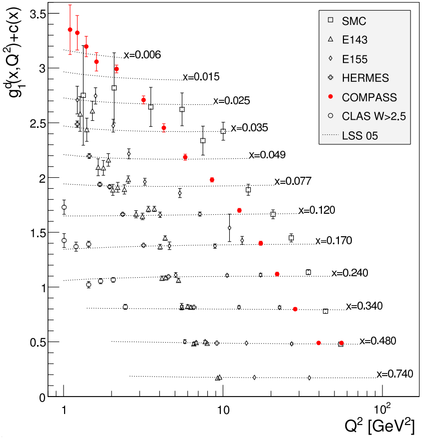
COMPASS:

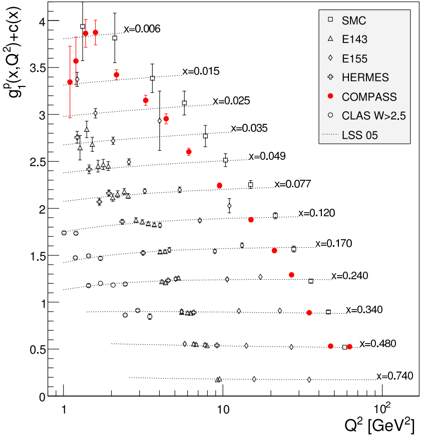
$$a_0 = 0.33 \pm 0.03 \pm 0.05$$

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



Good agreement
between the experiments

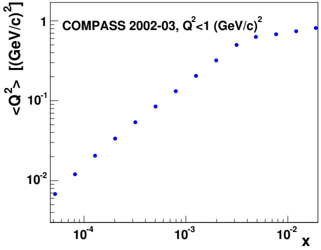


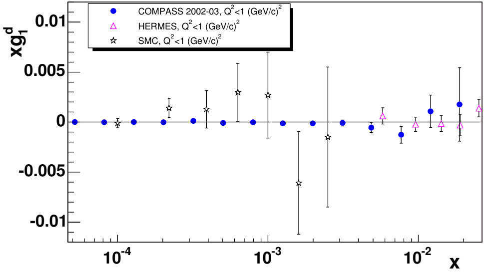


More data from JLAB/EG1a @ low Q^2.

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

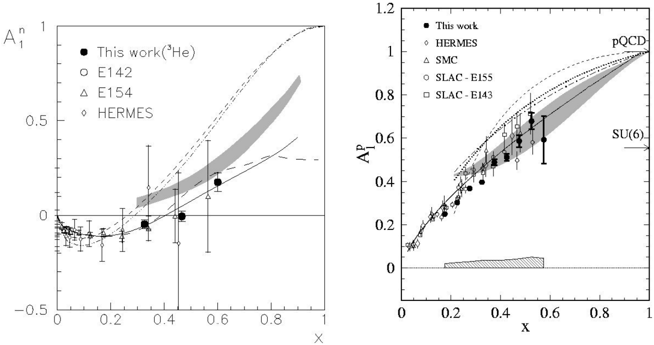
V.Yu. Alexakhin *et al.* (COMPASS) Phys. Lett. B **647** (2007) 330





- 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 ?

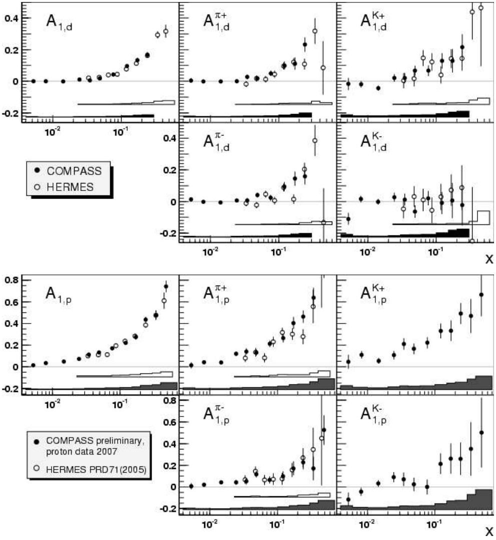
A_1^n and A_1^p at high $x, Q^2 > 1$ GeV^2

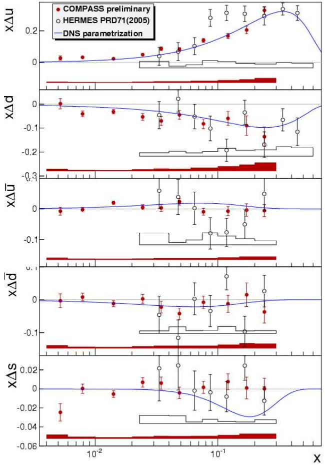


$A_1^n \neq 1$ @ $x \rightarrow 1, \Longrightarrow$ SU(6) symmetry breaking??

JLAB, Hall A, PRL 92 (2004) 012004 and JLAB CLAS, PL B 641 (2006)

Flavour separation of helicity distributions (@ LO)

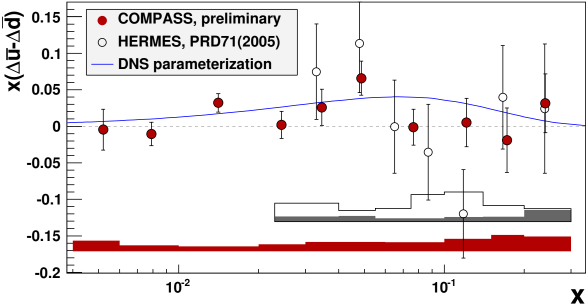




$Q^2 = 3\ (\text{GeV/c})^2$

Fragmentation functions!

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



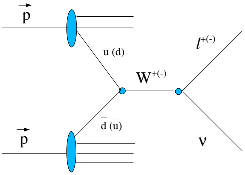
- COMPASS: $\int_{0.004}^{0.3} (\Delta\bar{u} - \Delta\bar{d})\,\mathrm{d}x = 0.052 \pm 0.035 \pm 0.013$ @ $Q^2 = 3$ GeV^2.

  HERMES: $\int_{0.023}^{0.6} (\Delta\bar{u} - \Delta\bar{d})\,\mathrm{d}x = 0.048 \pm 0.057 \pm 0.028$ @ $Q^2 = 2.5$ GeV^2.
- Presently accessible only in SIDIS.
- Unpolarised sea: $\int_{0}^{1} (\bar{u} - \bar{d})\,\mathrm{d}x = -0.118 \pm 0.012$ @ $Q^2 = 54$ GeV^2

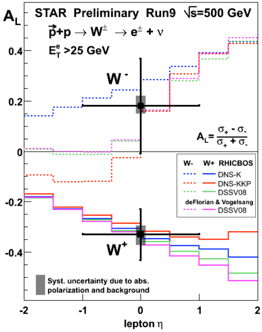
  FNAL E866, Phys. Rev. D64 (2001) 052002

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



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



LO interpretation:

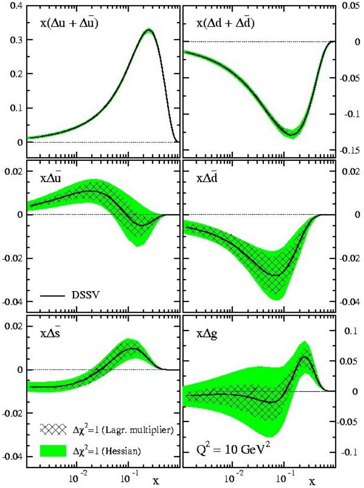
- $A_L^{W^-} = \frac{1}{2}\left(\frac{\Delta\bar{u}}{\bar{u}} - \frac{\Delta d}{d}\right) = 0.18 \pm 0.19\ ^{+0.04}_{-0.03}$ (STAR)
- $A_L^{W^+} = \frac{1}{2}\left(\frac{\Delta\bar{d}}{\bar{d}} - \frac{\Delta u}{u}\right) = -0.33 \pm 0.10 \pm 0.04$ (STAR)
  $= -0.83 \pm 0.31$ (PHENIX)
- $x(\Delta\bar{u}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

After J. Balewski, DIS2010

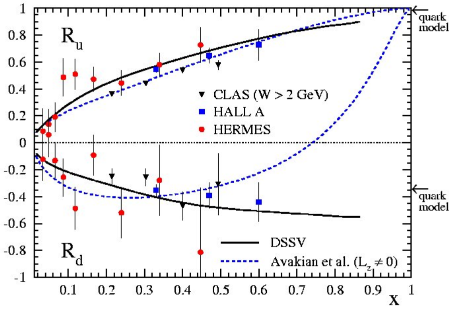
Global parton analyses

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

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

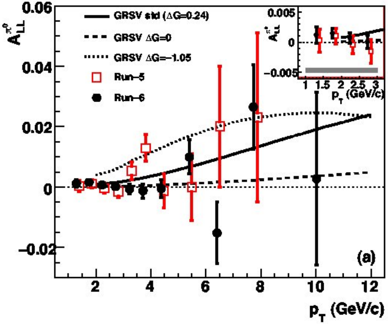


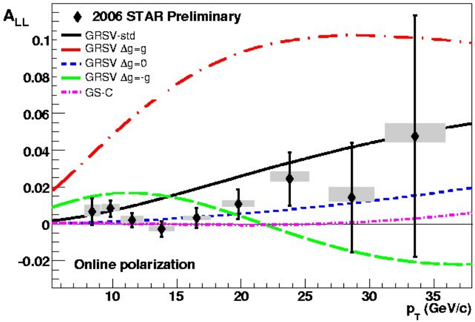
CLAS EG1b Phys. Lett. B641 (2006) 11



- Δg poorly know 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 Δs fits.

ΔG from the $\vec{\mathrm{p}}\vec{\mathrm{p}}$ scattering @ RHIC



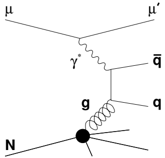


PHENIX PRL, 103 (2009) 012003
(high p_T π^0 production)

STAR PRL, 100 (2008) 23 2003
(mid-rapidity inclusive jets)

- Confirmed the electroproduction results
- Included in the DSSV2009.

Δg from the PGF in electroproduction

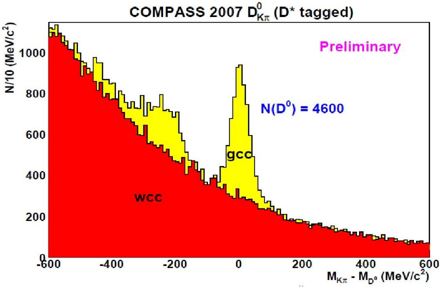


if $q,\bar{q} \equiv c,\bar{c}$ then $A_{meas} \sim \langle a_{pgf} \rangle \left\langle \frac{\Delta g}{g} \right\rangle + A_{bckg}$ AROMA

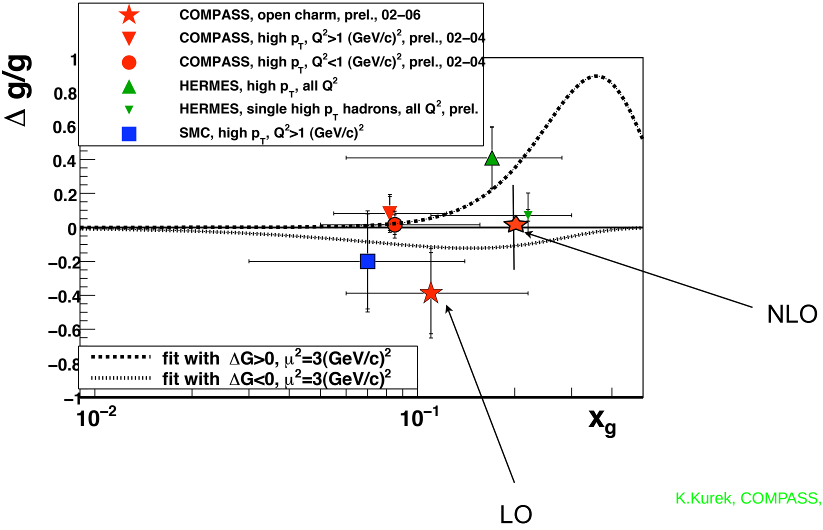
if $q,\bar{q} \equiv$light quarks then more MC info needed LEPTO/PYTHIA.

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 $D^* \to D^0 + \pi_s \to K + \pi + \pi_s$.

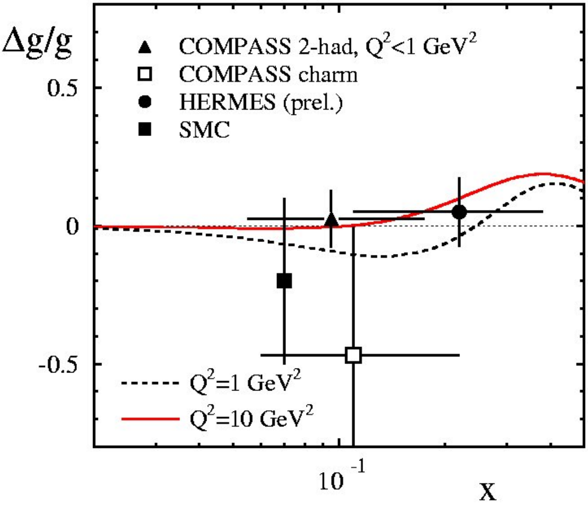


Δg from the PGF in electroproduction, ...cont'd



K.Kurek, COMPASS, DIS2010

Δg 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:

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

  where COMPASS @ 3 GeV^2 gives: $a_0 =$ 0.35±0.03±0.05

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

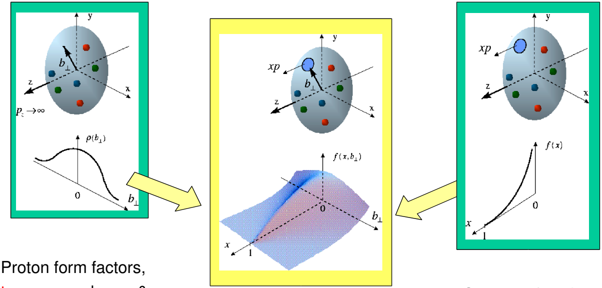
- Global, consistent NLO analysis of ΔG needed.
- Independent measurement of L necessary ($\Longrightarrow$ DVCS, lattice QCD?).
- All candidates are contributing about equally to the nucleon spin?

Ways of constraining the orbital angular momentum

- Measurement of asymmetries sensitive to e.g. the k_T of the partons (Sievers asymmetry)
- QCD calculations on the lattice $\Longrightarrow$ $L \approx 0$?
- X. Ji: evolution equations for J_q and J_g give the asymptotic ($\mu^2 \to \infty$) solutions $\Longrightarrow$ L cannot be negligible ?
- Extract from the full, 3D decription of the proton $\Longrightarrow$ GPDs

3D picturing of the proton *via* GPD

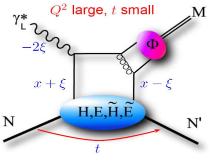
D. Mueller, X. Ji, A. Radyushkin, A. Belitsky, …
M. Burkardt, … Interpretation in impact parameter space



Proton form factors, transverse charge & current densities

Correlated quark momentum and helicity distributions in transverse space - GPDs

Structure functions, quark longitudinal momentum & helicity distributions

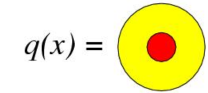


- Four GDPs $(H, E, \widetilde{H}, \widetilde{E})$ for each flavour and for gluons
- All depend on 3 variables: x, ξ, t;   DIS @ $\xi = t = 0$
- $H, \widetilde{H}$ conserve nucleon helicity; $E, \widetilde{E}$ flip nucleon helicity
- H, E refer to unpolarised distributions; $\widetilde{H}, \widetilde{E}$ refer to polarised distr.

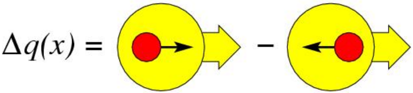
After V.D. Volker, LANL 2007

Partonic structure of the nucleon; distribution functions

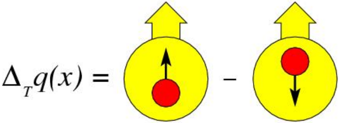
Three twist-two quark distributions in QCD (after integrating over the quark intrinsic k_t)



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 $\Longrightarrow$ 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 $\Longrightarrow$ 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):

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

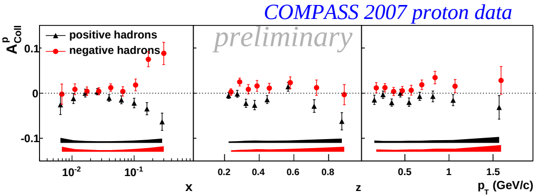
which in turn gives at LO:

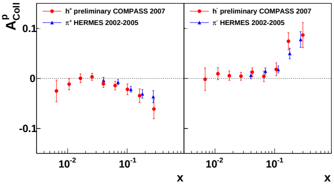
$$A_{Coll} \sim \frac{\sum_q e_q^2 \cdot \Delta_T q \cdot \Delta_T^0 D_q^h}{\sum_q e_q^2 \cdot q \cdot D_q^h}$$

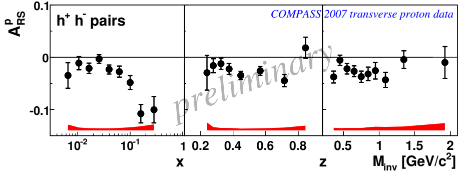
But transverse fragmentation functions $\Delta_T^0 D_q^h$ needed to extract $\Delta_T q(x)$ from the Collins assymmetry! Recently those FF measured by BELLE.

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

Results for the transverse asymmetries







- 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.
- Indication of Sivers 1–h asymmetries for π^+ on proton, @ $x > 0.032$; similar to HERMES; needs to be cleared.

- COMPASS deuteron data: both Collins and Sivers asymmetries very small. These data + Hermes + Belle: $\Longrightarrow \Delta_T u + \Delta_T d \sim 0$
- First $\Delta_T q$ global analyses performed. (cf. Anselmino et al., arXiv:0807.0173)

Outlook

Goals:

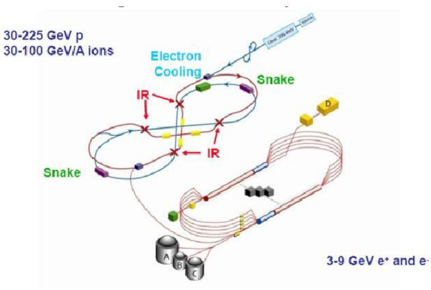
- Determination of ΔG.
- Measurements of GPD via DVCS $\Longrightarrow L_z$.

Experimental prospects:

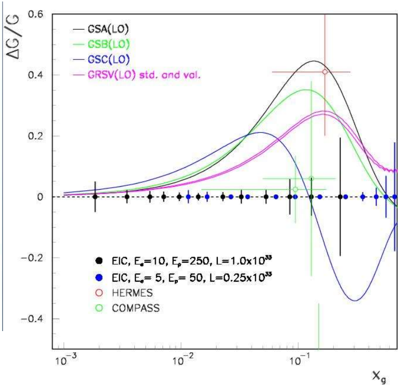
- Short term: more lepton data from COMPASS and JLAB
  more hadron data from RHIC (500 GeV!)
- 5-10 years: COMPASS DVCS and DY programme
  RHIC upgrade
  JLAB upgrade 12 GeV.
- ??? years: electron-ion colliders: eRHIC, ELIC, ENC, LHeC

Future: Electron–Ion Collider, EIC

- LHeC @ CERN
- eRHIC @ BNL
- ELIC @ JLAB
- MANUEL @ FAIR (GSI)



ELIC



www.eic.bnl.gov/docs/EIC-WhitePaper2007.pdf