Low *x* spin physics

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Low x Workshop 2007
Helsinki

Outline

1. High energy DIS spin experiments
   - Acceptance
   - Observables
   - Measurements
2. Low x physics in 2007 and beyond (COMPASS)
   - Inclusive g_1 measurements in 2007
   - Semi-inclusive g_1 measurements in 2007
   - Transversity measurements in 2007
   - Muoproduction of ρ^0 and the DVCS
3. Regge model predictions for g_1
4. Low x phenomenology
5. Summary

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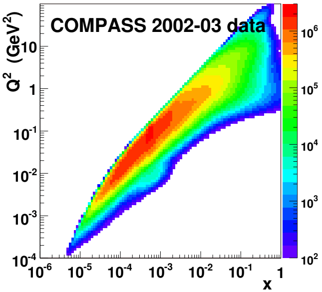
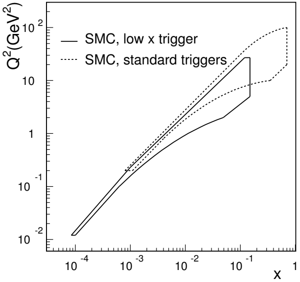
Acceptance

1. E142, E143, E154, E155, E155X at SLAC; electrons of < 50 GeV, targets: protons, deuterons, helium-3;
2. EMC, SMC, COMPASS at CERN; muons of 90 – 280 GeV, targets: protons, deuterons;
3. HERMES at DESY; electrons of 30 GeV, targets: protons, deuterons, (helium-3);
4. STAR, PHENIX at BNL; *pp* collider, $\sqrt{s}$ = 200 GeV;
5. Kinematic variables from incident and scattered leptons in 1, 2, 3; hadrons from target fragmentation often also measured and – in case of HERMES, COMPASS – identified if momenta larger than 1 and 2.5 GeV respectively;
6. background due to μe scattering (at $x = 0.000545$) in 2 (SMC, COMPASS);





Acceptance...cont'd

- "Low x" means $x \lesssim 0.001$; reached by COMPASS but at the expense of $Q^2 < 1$ GeV^2!
- Other fixed target experiments (HERMES, JLAB programme) reach higher x.
- Results from RHICspin only indirectly connected to low x.
- Thus the bulk of the reviewed results is from COMPASS and concerns the deuteron.
- Observe that the gluon polarisation will not be mentioned even if it indirectly does refer to the low x region too!

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- A direct observable, μ-d spin–dependent cross section asymmetry $A^{\mu d}$:

$$A^{\mu d} = \frac{1}{fP_T P_B}\left(\frac{N^{\leftrightarrows} - N^{\leftleftarrows}}{N^{\leftrightarrows} + N^{\leftleftarrows}}\right); \quad f \sim 0.4, \quad P_T \sim 0.5, \quad P_B \sim -0.8$$

- is related to the longitudinal and transverse $\gamma^* d$ asymmetries:

$$\frac{A^{\mu d}}{D} = A_1^d + \eta A_2^d$$

- In the COMPASS kinematics η is small; also the SLAC and SMC measurements show that:

$$\mid \eta A_2^d \mid \ll \mid A_1^d \mid \quad \text{so that :} \quad \frac{A^{\mu d}}{D} \approx A_1^d = \frac{\sigma_0^T - \sigma_2^T}{\sigma_0^T + \sigma_2^T}$$

- Longitudinal spin–dependent structure function:

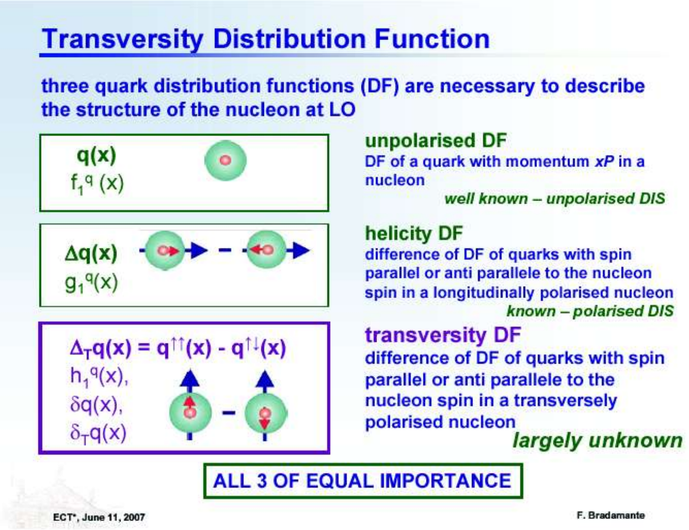
$$g_1^d(x, Q^2) \approx A_1^d(x, Q^2)\frac{F_2^d(x, Q^2)}{2x(1 + R(x, Q^2))}$$

-

$$Here: \quad g_1^d = g_1^N(1 - \frac{3}{2}\omega_D) = \frac{g_1^p + g_1^n}{2}(1 - \frac{3}{2}\omega_D) \quad \text{and} \quad \omega_D = 0.05 \pm 0.01$$

Observables: transversity

Slide from F. Bradamante, ECT 2007



Observables: transversity...cont'd

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)

Asymmetry measured *e.g. via* the Collin's asymmetry (asymmetry in the distribution of hadrons):

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

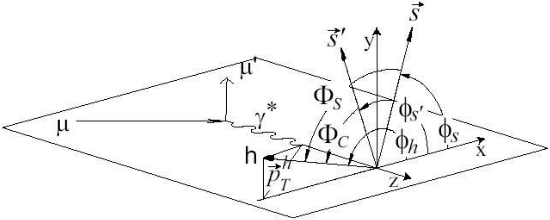
which in turn gives:

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

But hadrons in the final state mean that

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

Definition of ϕ_c:



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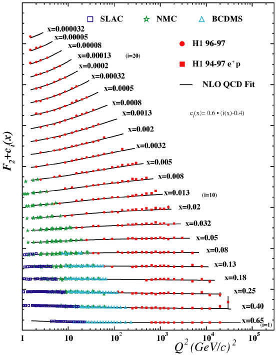
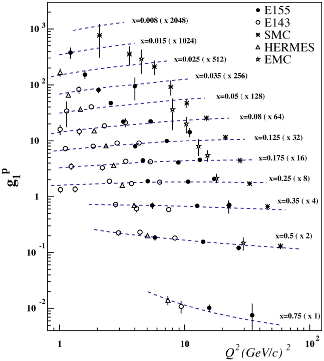
Measurements; inclusive g_1^p

World data on F_2^p



→ *50% of momentum carried by gluons*

World data on g_1^p



→ *20% of proton spin carried by quark spin*

Figure from R.Ent, DIS2006

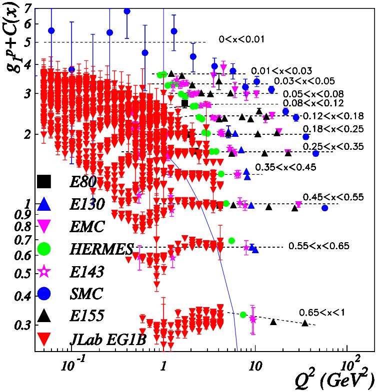
Scaling violation in $g_1(x, Q^2)$ is weak.
For g_1, Q^2 becomes > 1 GeV^2 at $x \gtrsim 0.003$ for SMC, 0.03 for HERMES and for COMPASS.

Measurements; inclusive g_1^p...cont'd

World data on polarized structure function $g_{1p}(x,Q^2)$

CLAS provides a large body of precise g_1 data in the DIS and transition regions that can be used to improve knowledge of twist-2 PDFs.

Phys. Rev.C75:035203, 2007
Phys. Lett. B 641, 11 (2006)



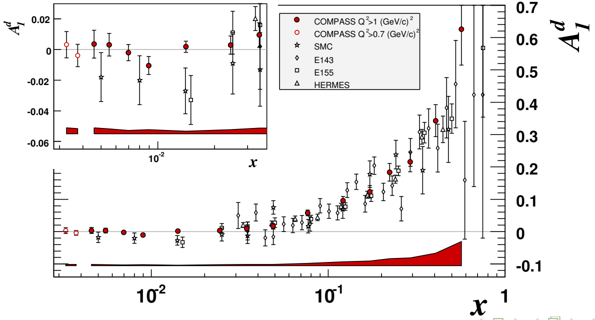
Blue line: W = 2GeV and Q^2=1 GeV^2 limit

Figure courtesy of V. Burkert (JLAB)

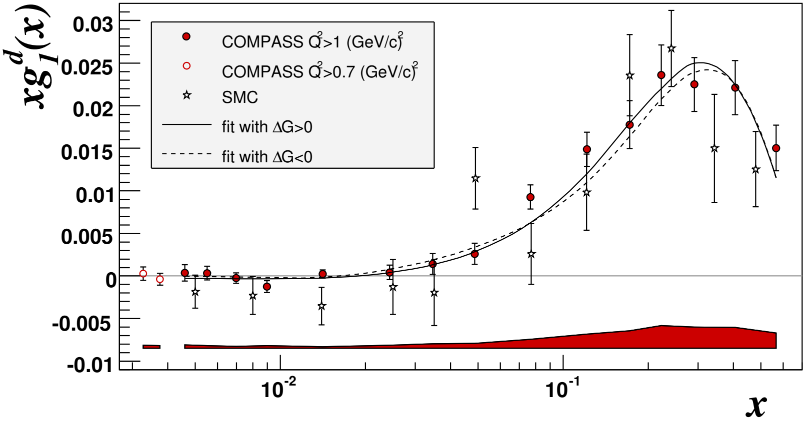
Measurements and QCD analysis of inclusive g_1^d

V.Yu. Alexakhin (COMPASS) *et al.* Phys Lett B**647** (2007) 8

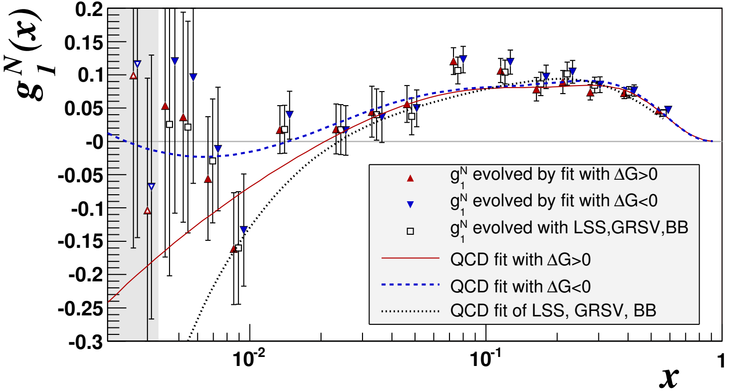
- Two programs: DGLAP evolution of structure functions and evolutions of moments
- NLO $\overline{MS}$ scheme
- World data: 9 experiments, 230 data points (43 from COMPASS)
- $$g_1(x,Q_0^2) = g_1(x,Q_i^2) + \left(g_1^{fit}(x,Q_0^2) - g_1^{fit}(x,Q_i^2)\right)$$
- Two solutions, $\Delta G > 0$ and $\Delta G < 0$ describe data equally well.



Measurements and QCD analysis of g_1^d...cont'd



Measurements and QCD analysis of g_1^d...cont'd

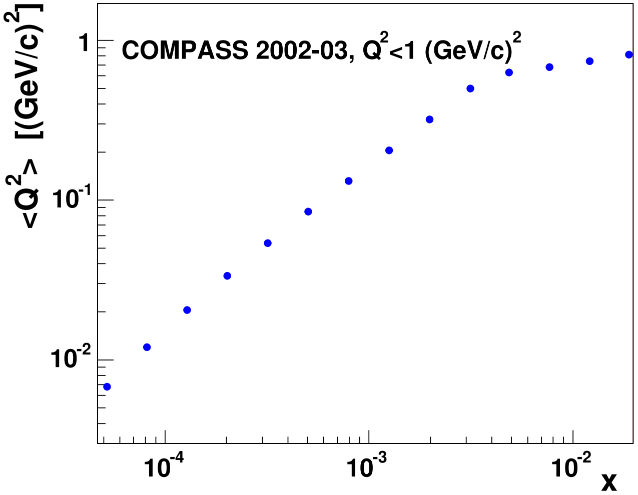


COMPASS g_1^N evolved to $Q^2 = 3$ GeV^2; NLO fits to world data (2006).

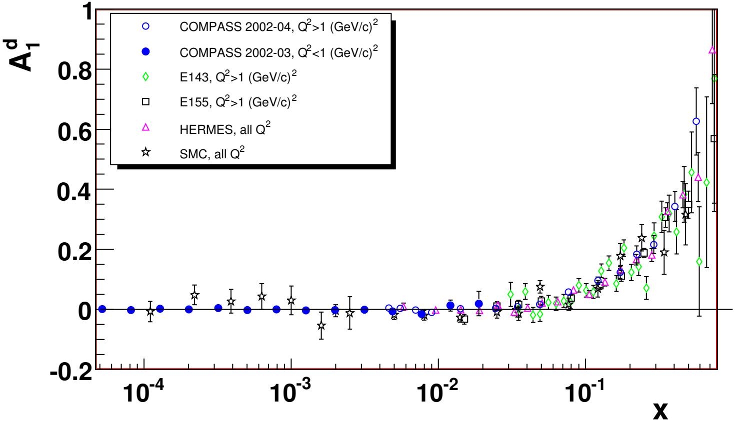
Low x data prefer $\Delta G < 0$? Sign not fixed by the ΔG measurements...

Measurements; A_1^d and g_1^d at small Q^2

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

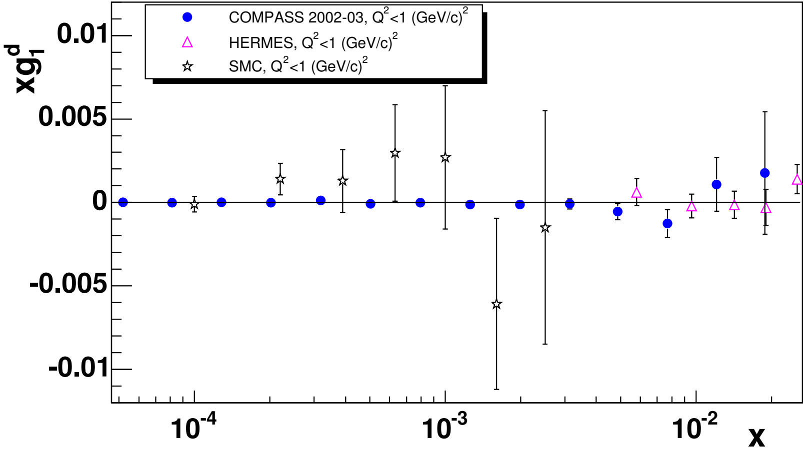


Measurements; A_1^d and g_1^d at small Q^2...cont'd

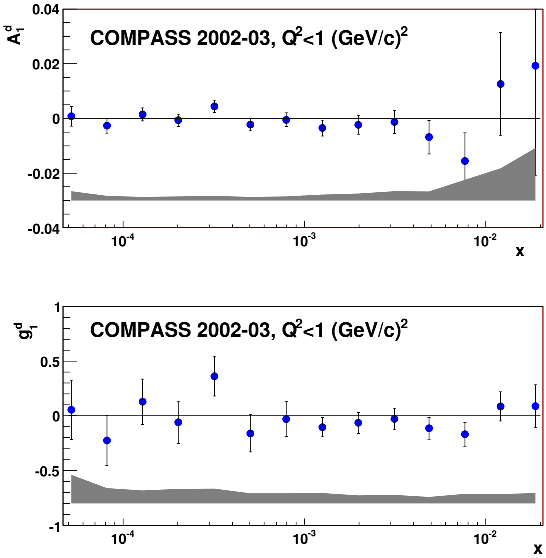


Spin effects in g_1^d at low x and Q^2 absent ?

Measurements; A_1^d and g_1^d at small Q^2...cont'd



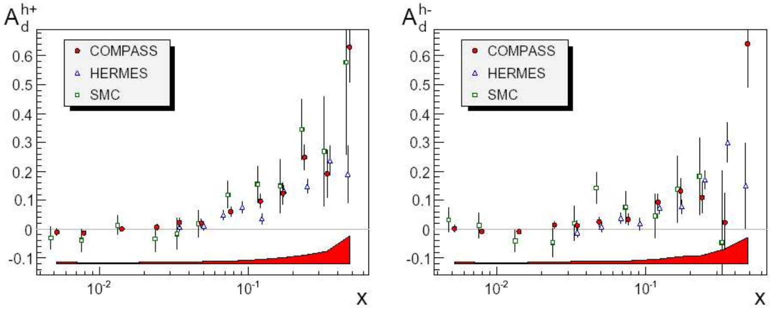
Measurements; A_1^d and g_1^d at small Q^2...cont'd



Measurements; semi–inclusive asymmetries

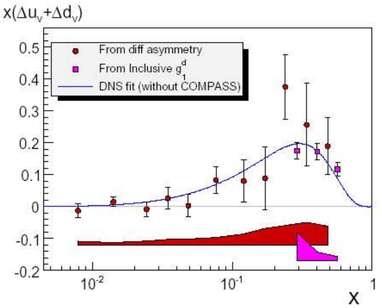
M. Alekseev *et al.* (COMPASS) hep-ex/0707.4077

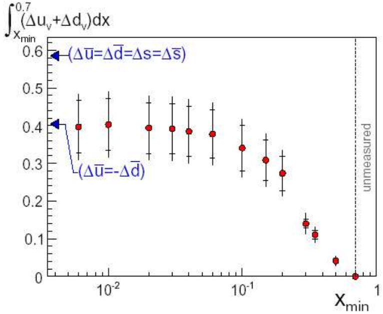
Now apart of the scattered muon also a hadron (hadrons) observed in the final state.



Measurements; semi–inclusive asymmetries...cont'd

- Difference asymmetry: $A^{h^+ - h^-}$
- Fragmentation functions drop out



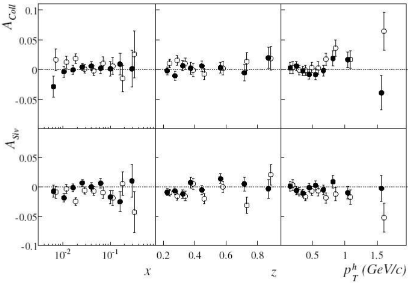


$$\int_{0.006}^{0.7} (\Delta u_v + \Delta d_v)\mathrm{d}x = 0.40 \pm 0.07 \pm 0.05$$

Unmeasured regions contribute neligibly. Non-symmetric sea preferred ?

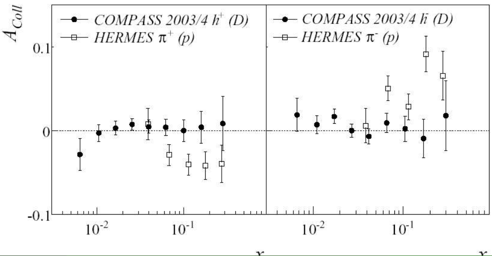
M. Alekseev *et al.* (COMPASS) hep-ex/0707.4077

Measurements; transversity



All hadrons; positive and negative

E.S. Ageev *et al.* (COMPASS) Nucl.Phys.B **765**(2007) 31

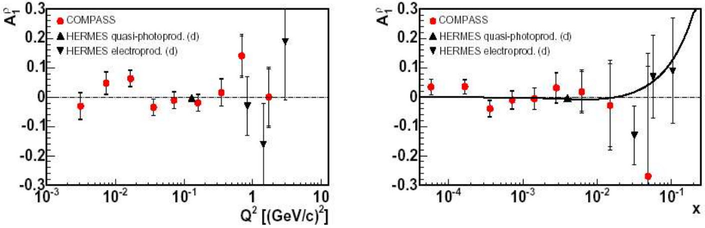


Measurements: exclusive ρ^0 muoproduction

Longitudinal double spin asymmetry A_1^ρ:

$$\mu + N \longrightarrow \mu' + \rho^0 + N'$$

related to spin dependent Generalised Parton Distributions.



At $x \lesssim$ 0.01 contribution of unnatural parity exchanges in the exclusive ρ^0 production small

Figure from M. Alekseev *et al.* (COMPASS) hep-ex/0704.1863, accepted EPJC

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Inclusive g_1^p measurements in 2007

- Shape of g_1^p at low x interesting but unknown! Shape of g_1^{ns} at low x sensitive to $\ln^{(}1/x)$ effects!
- Good accuracy needed ($\longrightarrow$ SMC errors reduced $\sim$ 3 times).

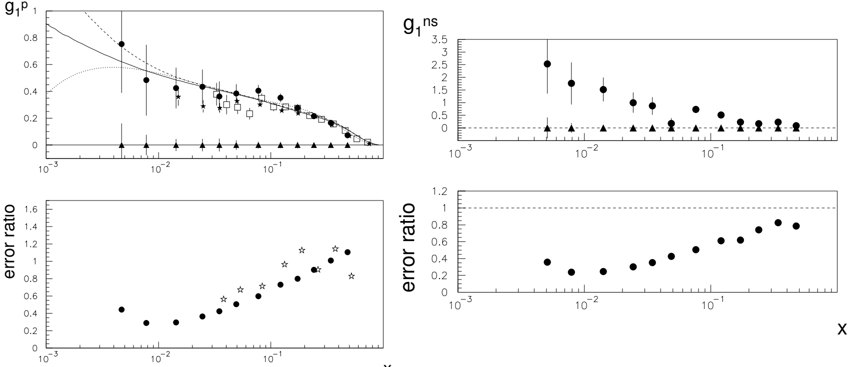

Figure from CERN-SPSC-2007-002

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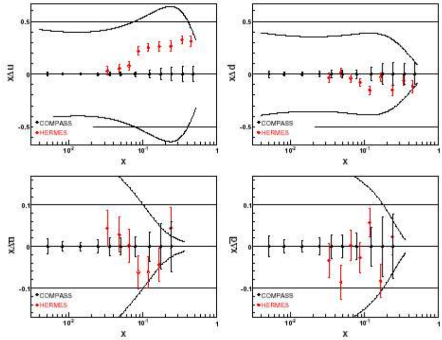
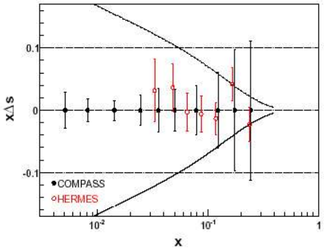
- What is the sign of $\int \mathrm{d}x \, \Delta s(x)$ (it is $>$ 0 HERMES semi-incl. and $<$ incl. data)?
- The 2007 proton run + 2002–2006 deuteron data will give:





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Transversity measurements in 2007

- Presently only HERMES data on the proton (but lower Q^2). Non zero? COMPASS proton results needed.
- Transversity PDFs, $\Delta_T q(x)$, to be extracted.

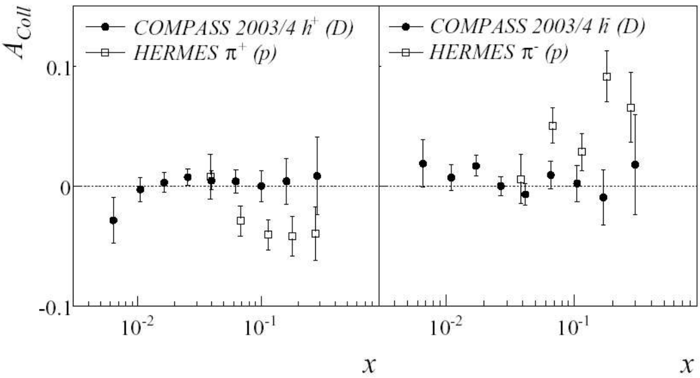

Figure from CERN-SPSC-2007-002

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5 Longer term projects

Other lines of research are presently under consideration as already mentioned in a document submitted January 15, 2006 to the CERN Council Strategy Group:

- The measurements of Generalised Parton Distribution functions with muon beams will, in particular, give access to the orbital momentum contribution to the nucleon spin, as described in the Expression Of Interest submitted (SPSC-2005-007, SPSC-EOI-005).
- The transverse spin effects were unveiled only recently and measurements are very preliminary. The next decade could cover systematic studies.
- The measurements of single spin observables in Drell–Yan processes with hadron beams will allow to check fundamental predictions of QCD. An EOI is being prepared.
- The double charm production with hadron beams will be accessible once a more refined vertex reconstruction is achieved.

From CERN-SPSC-2007-002

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Regge model predictions for g_1

- Regge gives for $x \to 0$ (i.e. $Q^2 \ll W^2$):

$$g_1^i(x, Q^2) \sim \beta(Q^2) x^{-\alpha_i(0)} \quad (1)$$

where i =singlet (s), nonsinglet (ns): $g_1^s = g_1^p + g_1^n, \quad g_1^{ns} = g_1^p - g_1^n$.

- Possible trajectories: I =0 (g_1^s; f_1 trajectory) and I =1 (g_1^{ns}; a_1 trajectory). Expectations: $\alpha_{s,ns}(0) \lesssim 0$ and $\alpha_s(0) \approx \alpha_{ns}(0)$.
- Consequence: for $Q^2 \to 0$, $g_1(W^2) \sim W^{2\alpha(0)}$.
- At large Q^2: the DGLAP evolution and resummation of $\ln^2(1/x)$ generate more singular x dependence than that implied by eq.(1) for $\alpha_{s,ns}(0) \lesssim 0$.
- Other Regge isosinglet contributions to g_1 at low x:
  - a term $\sim$ xln x;
  - a term $\sim 2\ln(1/x) - 1$;
  - a perverse term $\sim 1/(x\ln^2 x)$ got invalidated.

Perturbative QCD effects might modify the Regge expectations. In case of g_1 it creates a more singular low x behaviour than the (nonperturbative) Regge expectations.

Regge model predictions for g_1...cont'd

Testing Regge behaviour of g_1 through its x dependence:

- choose high W^2;
- choose low x (i.e. $Q^2 \ll W^2$ but not necessarily low Q^2);
- choose a bin of Q^2 (i.e. Q^2 =const);
- fit the x dependence of g_1.

  For the SMC:

  - Testing not possible

  For COMPASS:

  - Testing not possible either
- Observe: assuming $g_1 \sim x^0$ to get $x \rightarrow 0$ extrapolation of g_1 to extract g_1 moments is not correct! Evolve g_1 to a common Q^2 before extrapolation!

Brodsky: colour coherence, or at $x \rightarrow 0$

$$\frac{\Delta G(x)}{G(x)} \sim x$$

(spin analogue of hard pomeron with intercept $\sim$ 0.5 ???)

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Low x phenomenology

- Small x behaviour of both g_1^s and g_1^{ns} is controlled by terms corresponding to powers of $\alpha_s \ln^2(1/x)$

  Bartels, Ermolaev, Ryskin, Z.Phys. C70 (1996) 273; Z.Phys. C72 (1996) 627.

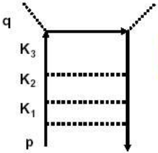
- These terms generate the leading small x behaviour of g_1.
- They go beyond the standard QCD evolution of spin dependent parton densities which does not generate the double but only the single $\ln(1/x)$ terms (due to strong DGLAP (k_T^2) ordering).
- They may be included in the QCD evolution; one of the methods: a formalism based on unintegrated parton distributions, $f(x, k^2)$, where the conventional parton distributions $p(x, Q^2)$ are

$$p(x, Q^2) = \int^{Q^2} \frac{\mathrm{d}k^2}{k^2} f(x, k^2)$$

and k^2 is a transverse momentum squared of the partons

Badełek and Kwieciński, Phys. Lett. B 418 (1998) 229, Kwieciński and Ziaja, Phys. Rev. D 60 (1999) 054004

(B.I. Ermolaev, M. Greco and S.I. Troyan, Eur. Phys. J. C50 (2007) 823)



DGLAP –ordering:

$$\mu^2 < k_{1\perp}^2 < k_{2\perp}^2 < k_{3\perp}^2 < Q^2$$

good approximation for large x when logs of x can be neglected. At x << 1 the ordering has to be lifted

DGLAP small-x asymptotics of g_1 is well-known:

$$g_1 \sim \exp[\ln(1/x) \ln\ln(Q^2/\Lambda_{QCD}^2)]^{1/2}$$

when the initial parton densities are not singular functions of x

When the DGLAP –ordering is lifted and all double logarithms of x are accounted for, the asymptotics is different:

$$g_1 \sim (1/x)^{\Delta} (Q^2/\mu^2)^{\Delta/2}$$

intercept

Bartels- Ermolaev-Manaenkov-Ryskin

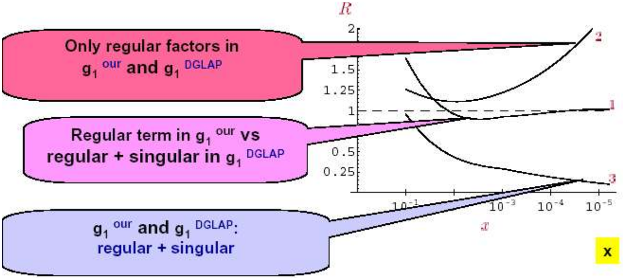
Slide from M. Greco, COMPASS Collaboration Meeting, 10 .XI. 2006

Low x phenomenology...cont'd

Alternatively DGLAP fails at x < 0.05 when the simplest, bare quark fit is used.

Let us numerically compare DGLAP with our approach at finite x, using the same DGLAP fit for initial quark density.

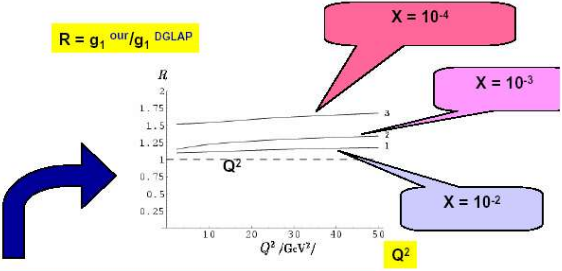
$R = g_1^{\,our}/g_1^{\,DGLAP}$



Slide from M. Greco, COMPASS Collaboration Meeting, 10 .XI. 2006

Low x phenomenology...cont'd

$R = g_1^{\,our}/g_1^{\,DGLAP}$ as function of Q^2 at different x



Q^2-dependence of R is flatter than the x-dependence

Slide from M. Greco, COMPASS Collaboration Meeting, 10 .XI. 2006

Low x phenomenology...cont'd

Comparison between DGLAP and our approach at small x

DGLAP	our approach
Coeff. functions and anom. dimensions are calculated with two-loop accuracy	Coeff. functions and anom. dimensions sum DL and SL terms to all orders
To ensure Regge behaviour, singular terms in x are used in the initial partonic densities	Regge behaviour is achieved automatically, even when the initial densities are regular in x
Equivalent to inserting a phenomenological asymptotic factor into expressions for g_1	Asymptotics of g_1 are never used in expressions for g_1 at finite x
	Warning: asymptotic formulae for g_1 are unreliable at $x > 10^{-5}$

Slide from M. Greco, COMPASS Collaboration Meeting, 10 .XI. 2006

Low x phenomenology...cont'd

Comparison between DGLAP and our approach at any x

DGLAP	our approach
Good at large x because includes exact two-loop calculations but bad at small x as lacks the total resummation of ln(x)	Good at small x , includes the total resummation of ln(x) but bad at large x because neglects some contributions essential in this region

WAY OUT – merging of our approach and DGLAP

1. Expand our formulae for coeff. functions and anom. dimensions into a series in the QCD coupling
2. Replace the first- and second- loop terms of the expansion by corresponding DGLAP –expressions

New, "synthetic" formulae have the advantage of the both approaches and are equally good at large and small x.
Only regular terms in x for the init. part. densities are required

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Low x phenomenology...cont'd

Comparison between our results and BFKL

Both for small x

BFKL	Our approach
describes unpolarized processes, does not contributes to spin-flips and asymmetries	describes polarized processes, contributes to spin-flips and asymmetries
No model-independent BFKL expressions for F_1, F_2	Explicit expressions for g_1 Obtained with Pert QCD
Violates unitarity → saturation required	No unitarity violation
Special arrangements for QCD coupling are needed	QCD coupling is running in each Feynman graph

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COMPASS operates with small Q^2 and small **x**

In order to generalize our results to the region of small Q^2, one should remember that $\ln(Q^2/\mu^2)$ is the result of the integration $\int_{\mu^2}^{Q^2} \frac{dk_\perp^2}{k_\perp^2}$

However it is valid for large Q^2 only. For arbitrary Q^2:

$$\int_{\mu^2}^{Q^2} \frac{dk_\perp^2}{k_\perp^2} \rightarrow \int_0^{Q^2} \frac{dk_\perp^2}{k_\perp^2 + \mu^2} = \ln\left(\frac{Q^2 + \mu^2}{\mu^2}\right)$$

Introduced as a "mass" of virtual quarks and gluons to regulate infrared singularities

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Conclusions I

Total resummation of the double- and single- logarithmic contributions

→ New anomalous dimensions and coefficient functions.

At x→ 0, asymptotics of g_1 is power-like in x and Q^2

New scaling:

$$g_1 \sim (Q^2 / x^2)^{\Delta/2}$$

With init. densities regular in x, DGLAP becomes unreliable at **x=0.05** approximately.

Singular terms in the DGLAP initial parton densities ensure a steep rise of g_1 at small x and mimic the resummation of logs of **x**. With the resummation accounted for, they can be dropped.

x-dependent terms in the regular factors can also be dropped at **x<<1**, so the fits can be reduced down to a constant

DGLAP init. dens. are expected to describe non-Pert QCD . Instead, they basically correspond to Pert QCD. → Non-Pert effects are surprisingly small at **x<<1**

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Low x phenomenology...cont'd

Conclusions II

The region of small Q^2 is also beyond the reach of SA. We predict that g_1 at small Q^2 is almost independent of x, even at $x \ll 1$. Instead, it depends on $2pq$ only. At a certain relation between the initial quark and gluon densities, $g1$ can be pretty close to zero in the range of $2pq$ investigated now experimentally by COMPASS.

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Outline

1. High energy DIS spin experiments
   - Acceptance
   - Observables
   - Measurements
2. Low x physics in 2007 and beyond (COMPASS)
   - Inclusive g_1 measurements in 2007
   - Semi-inclusive g_1 measurements in 2007
   - Transversity measurements in 2007
   - Muoproduction of ρ^0 and the DVCS
3. Regge model predictions for g_1
4. Low x phenomenology
5. **Summary**

Summary

- For the spin data at high energies, low Q^2 region correlated with low x; COMPASS the only source of data.
- Understanding the low x behaviour of the nucleon spin structure, even at low values of Q^2, is very important *per se* but also for practical purposes. '
- Spin effects seem to approach 0 when $x \longrightarrow 0$, at least for $Q^2 \lesssim 1$ GeV^2. This is true for inclusive, semi-inclusive, exclusive ρ^0, and transverse results.
- Phenomenology of g_1 at low x (full resummation of $\log^2(1/x)$ logarithms also extended to low Q^2) quantifies the inclusive results. Also suggests that the inclusive low x, low Q^2 results carry an information about the spin content of the nucleon. But what about nonperturbative effects? Analysis of the SMC results shows there is a room for them.
- COMPASS has a rich programme for both the proton and deuteron targets; muon–proton data taking will continue at least to the end of 2007.

COMPASS history: 2002 – 2007 and beyond

- 2002 160 GeV polarised μ beam & ^{6}LiD long/transv polarisations (time sharing: $\sim$ 80/20)
- 2003 *idem*
- 2004 *idem*
- 2004 hadron beam
- 2005 no SPS beam (several upgrades)
- 2006 160 GeV polarised μ beam & ^{6}LiD long. polarisation
- 2007 160 GeV polarised μ beam & NH_3 transverse and longitudinal polarisation
- 2008 (plans) hadron beam (?)