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Hadron Structure and QCD: from LOW to HIGH energies

The Role of Higher Twists in Determining Polarized Parton Densities

E. Leader (London), A. Sidorov (Dubna), D. Stamenov (Sofia)

OUTLINE

Peculiarity of the **polarized** DIS

- There are NO charged current (neutrino) DIS data
→ $(\Delta q + \Delta \bar{q})$ and ΔG from inclusive DIS data
- To separate Δq and $\Delta \bar{q}$ → **SIDIS, W** production
- A lot of the present data are at low Q^2 → the role of **HT effects**
- Axial (gluon) anomaly

Connection between theory and experiment

⇒ different approaches to the data fit

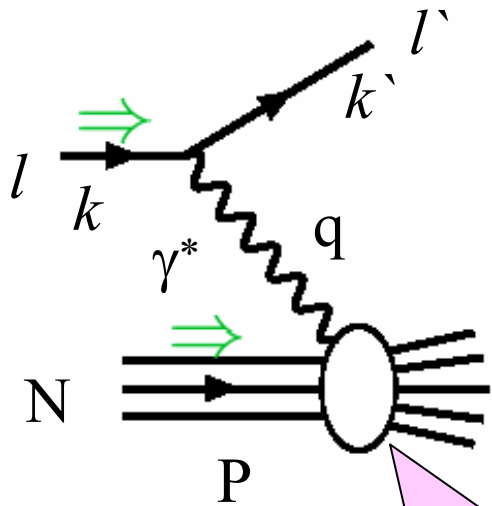
Method of analysis ⇒ $g_1^{pQCD} + HT$

Results - HT effects, NLO polarized parton densities

Conclusions

Inclusive DIS

one of the best tools to study
the structure of **nucleon**



$$Q^2 = -q^2 = 4EE' \sin^2(\theta/2)$$

$$x = Q^2/(2Mv) \quad v = E - E'$$

DIS regime $\implies Q^2 \gg M^2, v \gg M$

pQCD

$F_i(x, Q^2)$ $g_i(x, Q^2)$

unpolarized SF

polarized SF

DIS Cross Section Asymmetries

Measured quantities

$$A_{\parallel} = \frac{d\sigma^{\downarrow\uparrow} - d\sigma^{\uparrow\uparrow}}{d\sigma^{\downarrow\uparrow} + d\sigma^{\uparrow\uparrow}},$$

$$A_{\perp} = \frac{d\sigma^{\downarrow\Rightarrow} - d\sigma^{\uparrow\Rightarrow}}{d\sigma^{\downarrow\Rightarrow} + d\sigma^{\uparrow\Rightarrow}}$$

$$(A_{\parallel}, A_{\perp}) \Rightarrow (A_1, A_2) \Rightarrow (g_1, g_2)$$

where A_1, A_2 are the virtual photon-nucleon asymmetries.

At present, A_{\parallel} is much better measured than A_{\perp}

If A_{\parallel} and A_{\perp} are measured

$$\Rightarrow \frac{g_1}{F_1}$$

If only A_{\parallel} is measured

$$\Rightarrow \frac{A_{\parallel}}{D} \sim (1 + \gamma^2) \frac{g_1}{F_1}$$

$$\gamma^2 = 4M_N^2 x^2 / Q^2 \quad \text{- kinematic factor}$$

NB. γ cannot be neglected in the **SLAC**,
HERMES and **JLab** kinematic regions

As in the unpolarized case the main goal is:

- to test **QCD**
- to extract from the DIS data the **polarized PD**

$$\Delta q(x, Q^2) = q_+(x, Q^2) - q_-(x, Q^2)$$

$$\Delta \bar{q}(x, Q^2) = \bar{q}_+(x, Q^2) - \bar{q}_-(x, Q^2)$$

$$\Delta G(x, Q^2) = G_+(x, Q^2) - G_-(x, Q^2)$$

where "+" and "-" denote the helicity of the parton, along or opposite to the helicity of the parent nucleon, respectively.

The knowledge of the polarized PD will help us:

- to make predictions for other processes like polarized **hadron-hadron** reactions, etc.
- more generally, to answer the question how the helicity of the nucleon is divided up among its constituents:

$$S_z = 1/2 = 1/2 \Delta\Sigma(Q^2) + \Delta G(Q^2) + L_z(Q^2)$$

$$\Delta\Sigma = \Delta u + \Delta\bar{u} + \Delta d + \Delta\bar{d} + \Delta s + \Delta\bar{s}$$

the parton polarizations Δq_a and ΔG are the first moments

$$\Delta q_a(Q^2) = \int_0^1 dx \Delta q_a(x, Q^2) \quad \Delta G(Q^2) = \int_0^1 dx \Delta G(x, Q^2)$$

of the helicity densities: $\Delta u(x, Q^2), \Delta\bar{u}(x, Q^2), \dots, \Delta G(x, Q^2)$

- An important difference between the kinematic regions of the unpolarized and *polarized* data sets

A lot of the present data are at low Q^2 and W^2

$$Q^2 \approx 1-5 \text{ GeV}^2, \quad W^2 > 4 \text{ GeV}^2$$

While in the determination of the PD in the unpolarized case we can cut the low Q^2 and W^2 data in order to eliminate the less known non-perturbative HT effects, it is impossible to perform such a procedure for the present data on the spin-dependent structure functions without losing too much information.

$$O(1/Q^2)$$



HT corrections should be **important !**

DATA

CERN

EMC - A_1^p

SMC - A_1^p, A_1^d

185 exp. p.

DESY

HERMES - $\frac{g_1^p}{F_1^p}, A_1^n, \frac{g_1^d}{F_1^d}$ (preliminary)

206 exp. p.

SLAC

E142, E154 - A_1^n

E143, E155 - $\frac{g_1^p}{F_1^p}, \frac{g_1^d}{F_1^d}$

JLab

Hall A

$\frac{g_1^n}{F_1^n}$

The data on A_1 are really the experimental values of the quantity

$$\frac{A_{||}^N}{D} = (1 + \gamma^2) \frac{g_1^N}{F_1^N} + (\eta - \gamma) A_2^N$$

$$= A_1^N + \eta A_2^N$$

$\gamma \approx \eta$ and A_2 small

very well approximated with even when $\gamma(\eta)$ can not be neglected

$$(1 + \gamma^2) \frac{g_1^N}{F_1^N}$$

Theory

In QCD

$$g_1(x, Q^2) = g_1(x, Q^2)_{LT} + g_1(x, Q^2)_{HT}$$

$$g_1(x, Q^2)_{LT} = g_1(x, Q^2)_{pQCD}$$

$$g_1(x, Q^2)_{HT} = h(x, Q^2)/Q^2 + h^{\text{TMC}}(x, Q^2)/Q^2$$

target mass corrections
which are calculable

J. Blumlein, A. Tkabladze

dynamical HT power corrections

=> non-perturbative effects (model dependent)

In NLO pQCD

$$g_1(x, Q^2)_{pQCD} = \frac{1}{2} \sum_q^{N_f} e_q^2 [(\Delta q + \Delta \bar{q}) \otimes (1 + \frac{\alpha_s(Q^2)}{2\pi} \delta C_q) + \frac{\alpha_s(Q^2)}{2\pi} \Delta G \otimes \frac{\delta C_G}{N_f}]$$

$\delta C_q, \delta C_G$ – Wilson coefficient functions

polarized PD evolve in Q^2

according to **NLO DGLAP** eqs.

Factorization scheme dependence

Beyond the LO approximation the PD are scheme depended !

In the *unpolarized* case $M_n(PD)_{scheme1} = M_n(PD)_{scheme2} + O(\alpha_s)$

In the *polarized* case because of the *gluon anomaly*

$$\Delta G(Q^2) = \int_0^1 dx \Delta G(x, Q^2) \sim \frac{1}{\alpha_s(Q^2)}$$

n=1

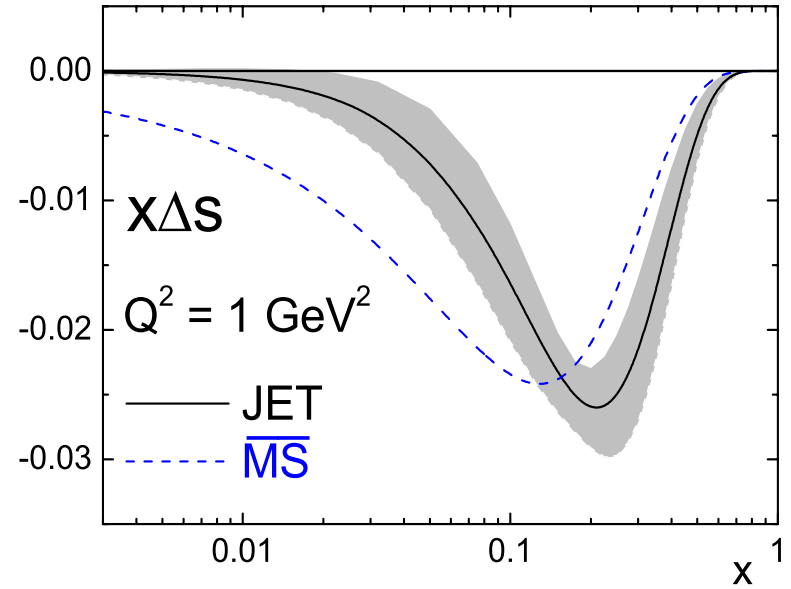
$$\Delta s = \Delta \bar{s}, \quad \Delta G = 0.80$$

$$(\Delta s + \Delta \bar{s})_{JET} = (\Delta s + \Delta \bar{s})_{\overline{MS}}(Q^2) + \frac{\alpha_s(Q^2)}{2\pi} \Delta G$$

$$= (\Delta s + \Delta \bar{s})_{\overline{MS}}(Q^2) + O(1)$$

$$\Delta \Sigma_{JET} = \Delta \Sigma_{\overline{MS}}(Q^2) + N_f \frac{\alpha_s(Q^2)}{2\pi} \Delta G(Q^2)$$

$$= \Delta \Sigma_{\overline{MS}}(Q^2) + O(1)$$



LO is a bad approximation,
at least for $\Delta \bar{q}$

The larger ΔG



the bigger the difference

On theoretical grounds we prefer to use the *JET* scheme (all hard effects are absorbed in the Wilson coefficient functions).

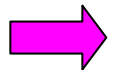
Carlitz, Collins, Mueller (1988)

Efremov, Teryaev (1989); Muller, Teryaev (1997)

Anselmino, Efremov, Leader (1995)

In the JET scheme (as well as in AB scheme)

$\Delta\Sigma(Q^2)$, as well as $(\Delta s + \Delta\bar{s})$, are independent of Q^2



it is meaningful to directly interpret $\Delta\Sigma$ as the contribution of the quark spins to the nucleon spin and to compare its value obtained from **DIS region** with the predictions of the different (constituent, chiral, etc.) quark models at **low** Q^2 .

Connection between Theory and Experiment

GRSV, LSS

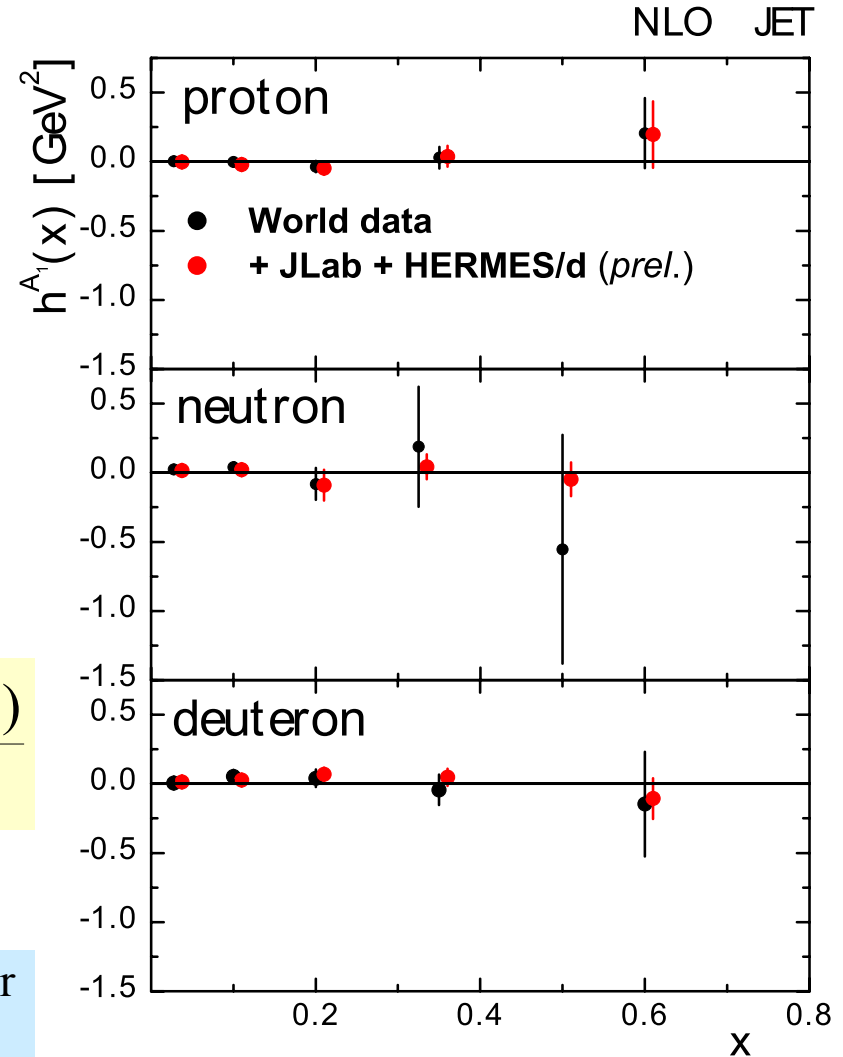
$$\left[\frac{g_1(x, Q^2)}{F_1(x, Q^2)} \right]_{\text{exp}} \Leftrightarrow \frac{g_1(x, Q^2)_{LT}}{F_1(x, Q^2)_{LT}}$$

$$A_1(x, Q^2)_{\text{exp}} \Leftrightarrow (1 + \gamma^2) \frac{g_1(x, Q^2)_{LT}}{F_1(x, Q^2)_{LT}}$$

$$A_1(x, Q^2)_{\text{exp}} \Leftrightarrow (1 + \gamma^2) \frac{g_1(x, Q^2)_{LT}}{F_1(x, Q^2)_{LT}} + \frac{h^{A_1}(x)}{Q^2}$$

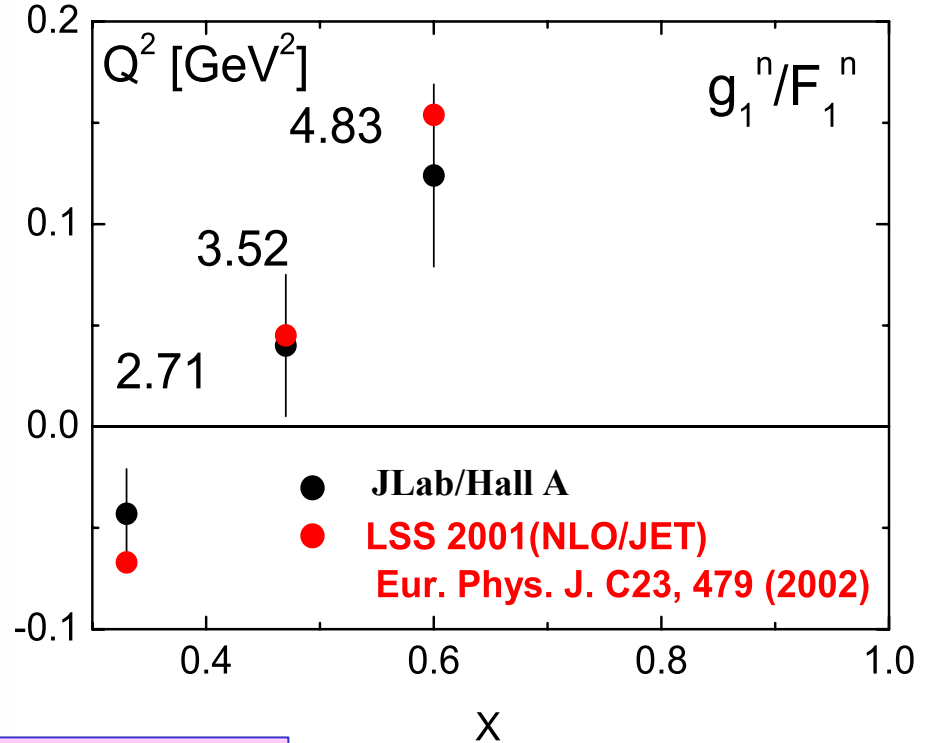
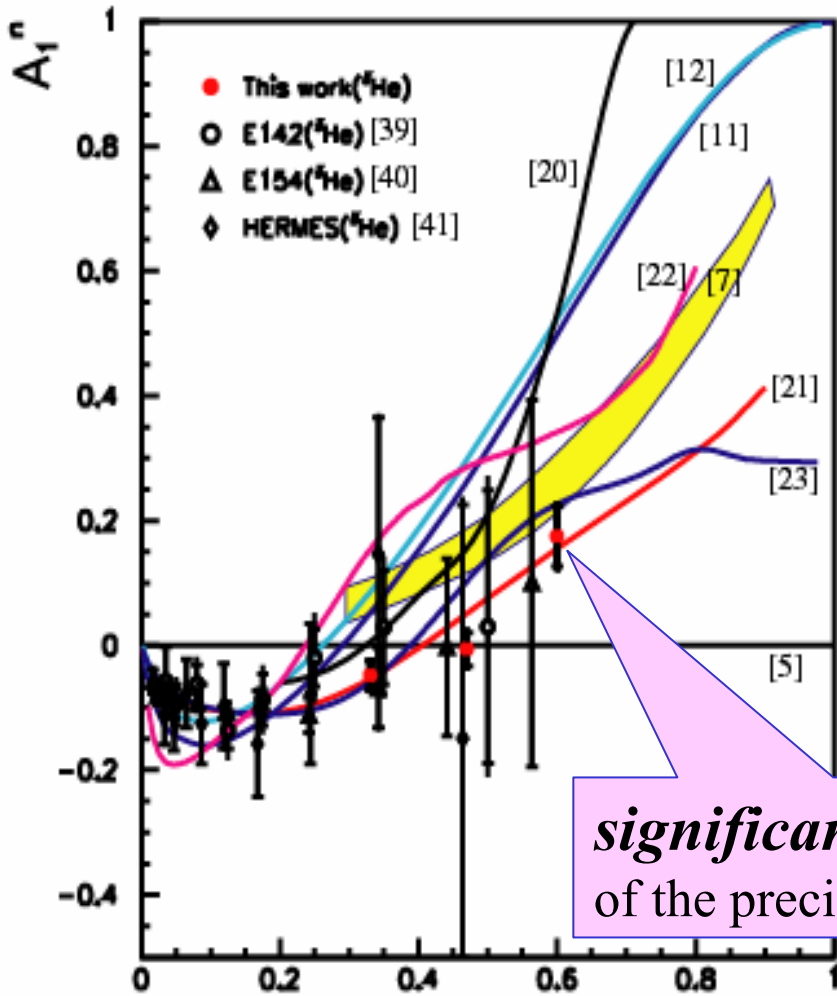
The HT corrections to g_1 and F_1 compensate each other in the ratio $\frac{g_1}{F_1}$ and the PPD extracted by this way are less sensitive to HT effects.

E.Leader, A.Sidorov, D.Stamenov
[hep-ph/0309048]



$$h^{A_1}(x) \approx 0$$

Our predictions for the JLAB experimental values of g_1^n/F_1^n using the LSS'2001 NLO(JET) polarized PD



significant improvement of the precision of the data

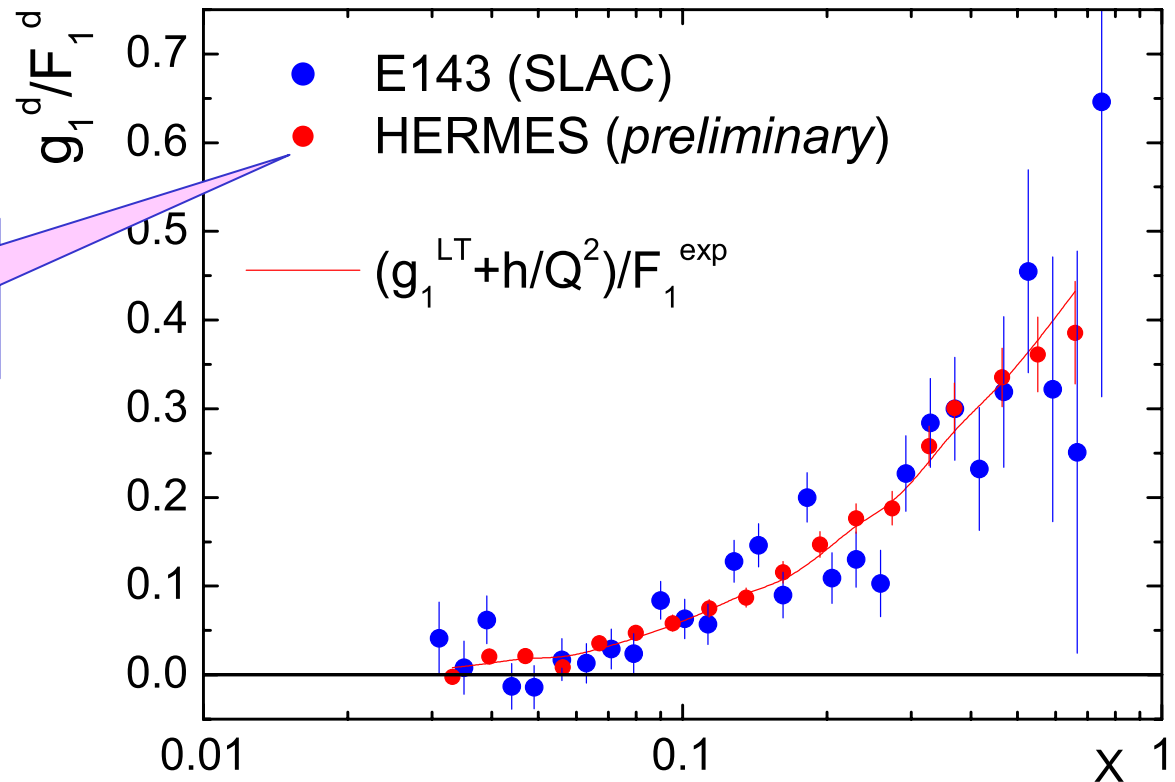
-LSS 2001 ($Q^2 = 5 \text{ GeV}^2$)

[21] Leader, Sidorov, Stamenov, Euro Phys. J. C23, 479 (2002)

Recent results from the fit to the world data including the **JLab** and **HERMES/d** data

- a very good description of the HERMES/d data
 $\chi^2=11.8$ for 18 points
- PD($g_1^{\text{NLO+HT}}$) practically do **NOT** change !!

Ch. Weiskopf
02-043 Thesis (2002)



SMC; Blumlein, Bottcher

$$\left[\frac{g_1(x, Q^2)}{F_1(x, Q^2)} \right]_{\text{exp}} \Leftrightarrow \frac{g_1(x, Q^2)_{LT}}{F_2(x, Q^2)_{\text{exp}}} 2x \frac{[1 + R(x, Q^2)_{\text{exp}}]}{(1 + \gamma^2)}$$

$$A_1(x, Q^2)_{\text{exp}} \Leftrightarrow \frac{g_1(x, Q^2)_{LT}}{F_2(x, Q^2)_{\text{exp}}} 2x [1 + R(x, Q^2)_{\text{exp}}]$$

In this case the "effective higher twist" contribution $h^{A_1}(x)$ is found to be sizeable and important in the fit **(GRSV)**



To extract correctly PPD from g_1 data, the HT corrections to g_1 , $h^{g_1}(x)/Q^2$, have to be included into data fits

AAC; de Florian, Sassot

have used a procedure in which $F_{2\text{exp}} \Rightarrow (F_2)_{LT}$.

We have found that $h^{A_1}(x)$ is also NOT negligible in this case

METHOD of ANALYSIS

HT to g_1 included in model independent way

$$\left[\frac{g_1(x, Q^2)}{F_1(x, Q^2)} \right]_{\text{exp}} \Leftrightarrow \frac{g_1(x, Q^2)_{LT} + h^N(x)/Q^2}{F_2(x, Q^2)_{\text{exp}}} 2x \frac{[1 + R(x, Q^2)_{\text{exp}}]}{(1 + \gamma^2)}$$

NMC

R_{1998} (SLAC)

$$A_1(x, Q^2)_{\text{exp}} \Leftrightarrow \frac{g_1(x, Q^2)_{LT} + h^N(x)/Q^2}{F_2(x, Q^2)_{\text{exp}}} 2x [1 + R(x, Q^2)_{\text{exp}}]$$

$h^p(x_i), h^n(x_i)$ – 10 parameters ($i = 1, 2, \dots, 5$) to be determined from a fit to the data

Input parton densities

$$\Delta f_i(x, Q_0^2) = A_i x^{\alpha_i} f_i^{MRST}(x, Q_0^2)$$

$Q_0^2 = 1 \text{ GeV}^2$, A_i, α_i – free par. ($i = 1, 2, \dots, 4$)



8-2(SR) = 6 par. associated with PD

The inverse Mellin - transformation method has been used to calculate $g_1^N(x, Q^2)_{LT}$ from its moments

SR for n=1 moments of PD

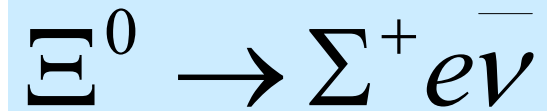
$$g_A = (\Delta u + \Delta \bar{u})(Q^2) - (\Delta d + \Delta \bar{d})(Q^2) = 1.2670 \pm .0035 \quad (1)$$

$$a_8 = (\Delta u + \Delta \bar{u})(Q^2) + (\Delta d + \Delta \bar{d})(Q^2) - 2(\Delta s + \Delta \bar{s})(Q^2) = 3F - D = 0.585 \pm 0.025 \quad (2)$$

The sum rule (1) reflects the isospin SU(2) symmetry, whereas the relation (2) is a consequence of the SU(3) flavour symmetry treatment of the hyperon β -decays.

While isospin symmetry is not in doubt, there is some question about the accuracy of assuming SU(3)_f symmetry in analyzing hyperon β -decays. The results of the recent KTeV experiment at Fermilab on the β -decay of Ξ^0 , $\Xi^0 \rightarrow \Sigma^+ e \bar{\nu}$, however, are all *consistent* with *exact* SU(3)_f symmetry. Taking into account the experimental uncertainties one finds that SU(3)_f breaking is at most of order 20%.

KTeV experiment
Fermilab



β -decay

SU(3)_f prediction for
the form factor ratio g_1/f_1

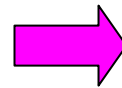
$$\frac{g_1}{f_1} = g_A = 1.2670 \pm .0035$$

Experimental result

$$\frac{g_1}{f_1} = 1.32^{+0.21}_{-0.17} \pm 0.05$$

A good agreement with the *exact* SU(3)_f symmetry !

From exp. uncertainties



SU(3) breaking is
at most of order **20%**

RESULTS OF ANALYSIS

LSS, Phys. Rev. D67 (2003) 074017

Kinematic region - 185 exp. p.

$$0.005 \leq x \leq 0.75 \quad 1 < Q^2 \leq 58 \text{ GeV}^2$$

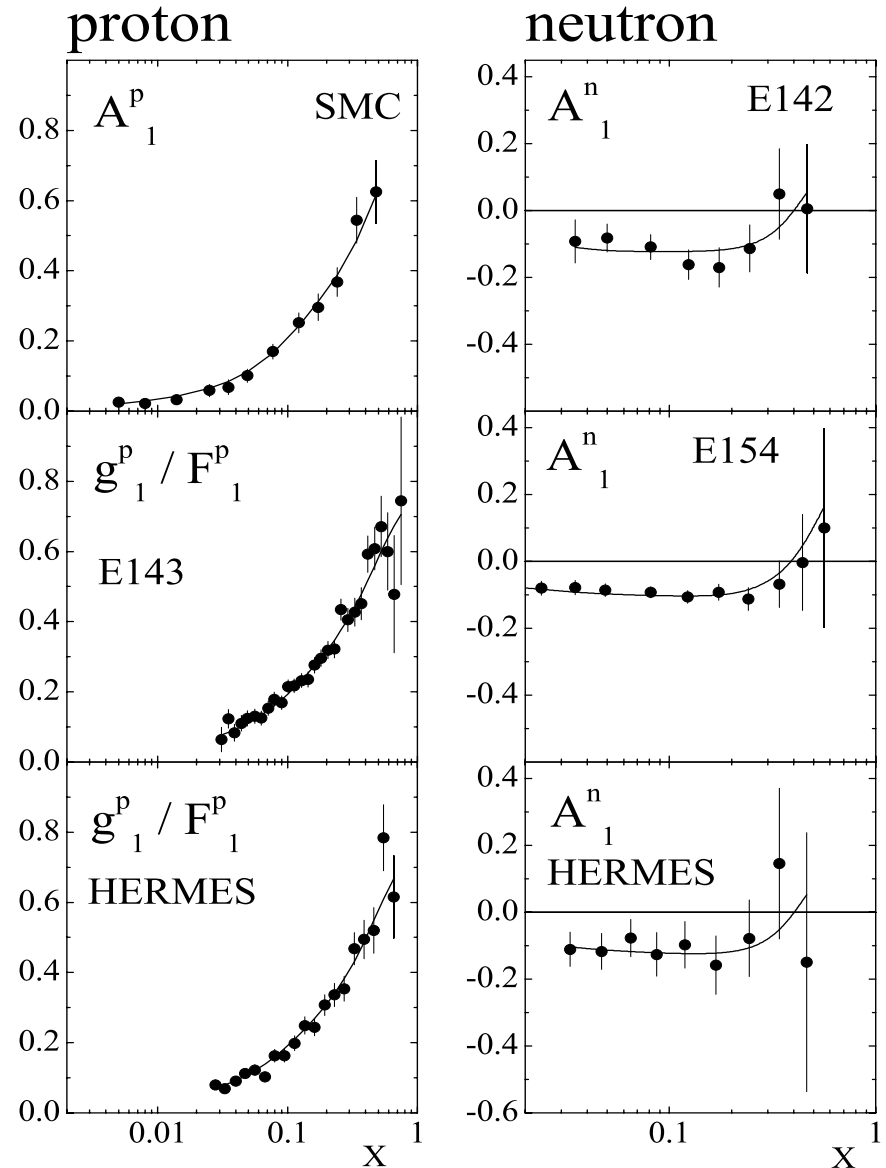
Quality of the fits

A very good description of the world A_1 and g_1 data is achieved.

$$\text{LO} \quad \Rightarrow \quad \chi_{DF,LO}^2 = 0.892$$

$$\text{NLO(JET)} \Rightarrow \chi_{DF,NLO}^2 = 0.858$$

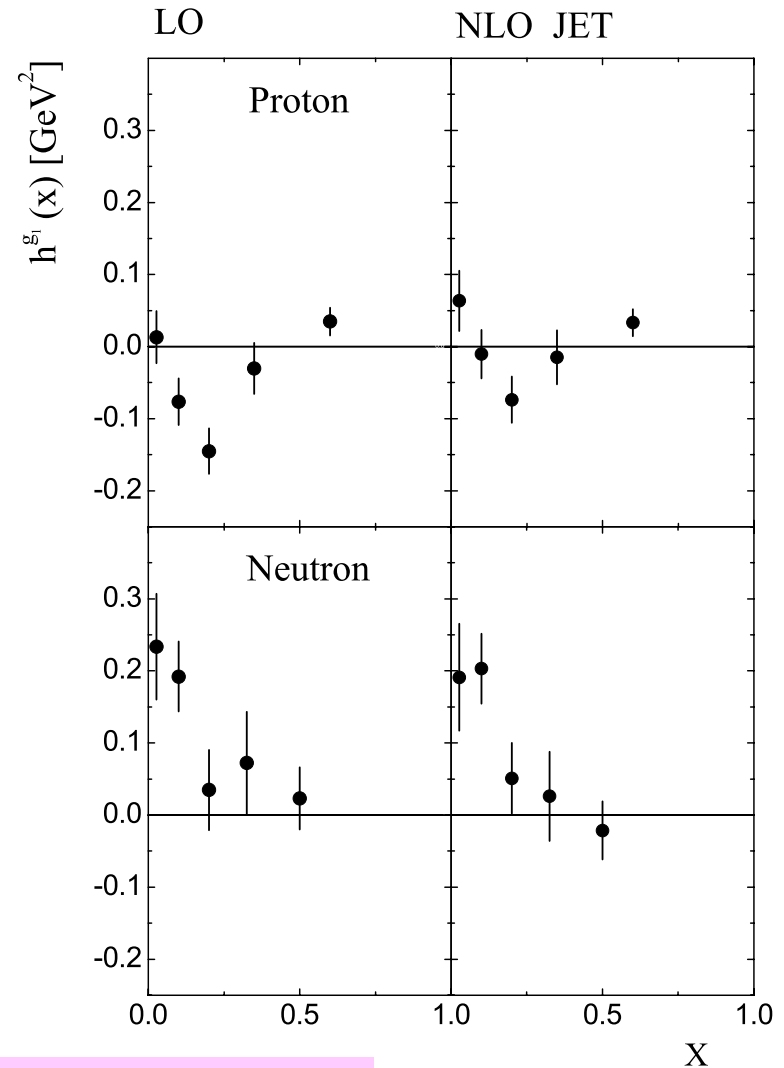
NLO JET



Higher twist effects

Dependence of χ^2 on HT corrections

Fit	LO HT=0	NLO HT=0	LO+HT	NLO+HT
χ^2	244.5	218.8	150.7	145.0
DF	185-6	185-6	185-16	185-16
χ^2 / DF	1.36	1.22	0.892	0.858

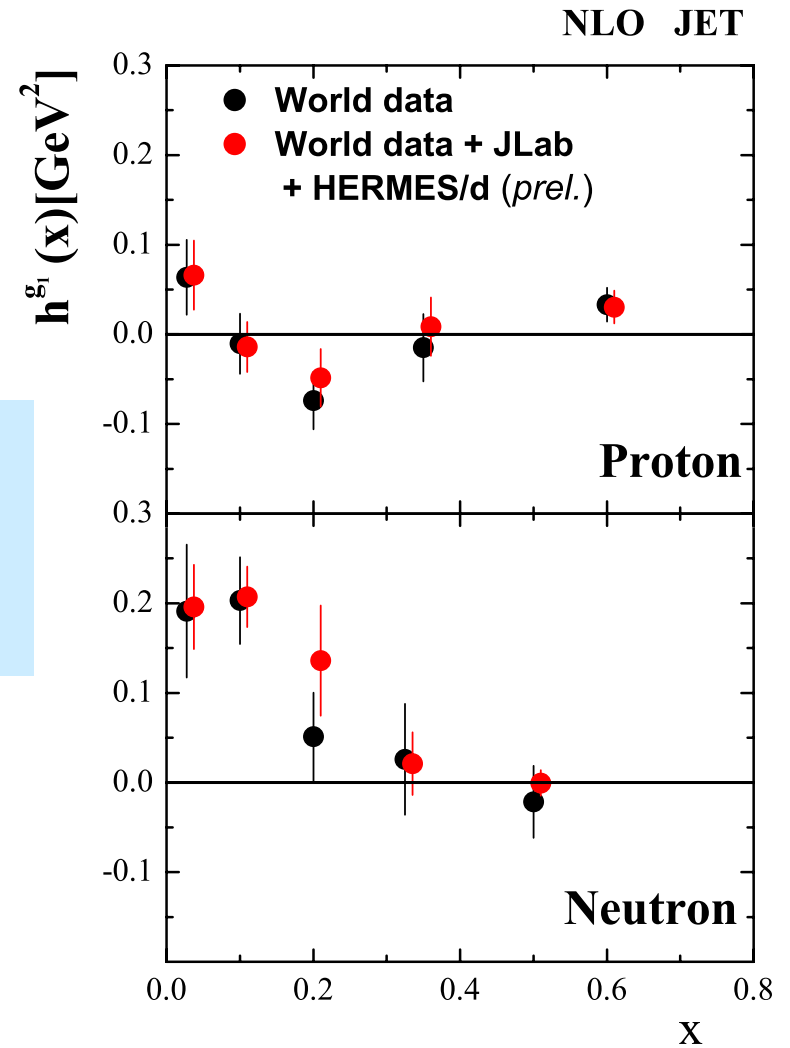


The size of HT corrections to g_1 is NOT negligible

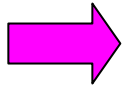
The shape of HT depends on the target

$$g_1(x, Q^2) = g_1(x, Q^2)_{LT} + h^N(x) / Q^2$$

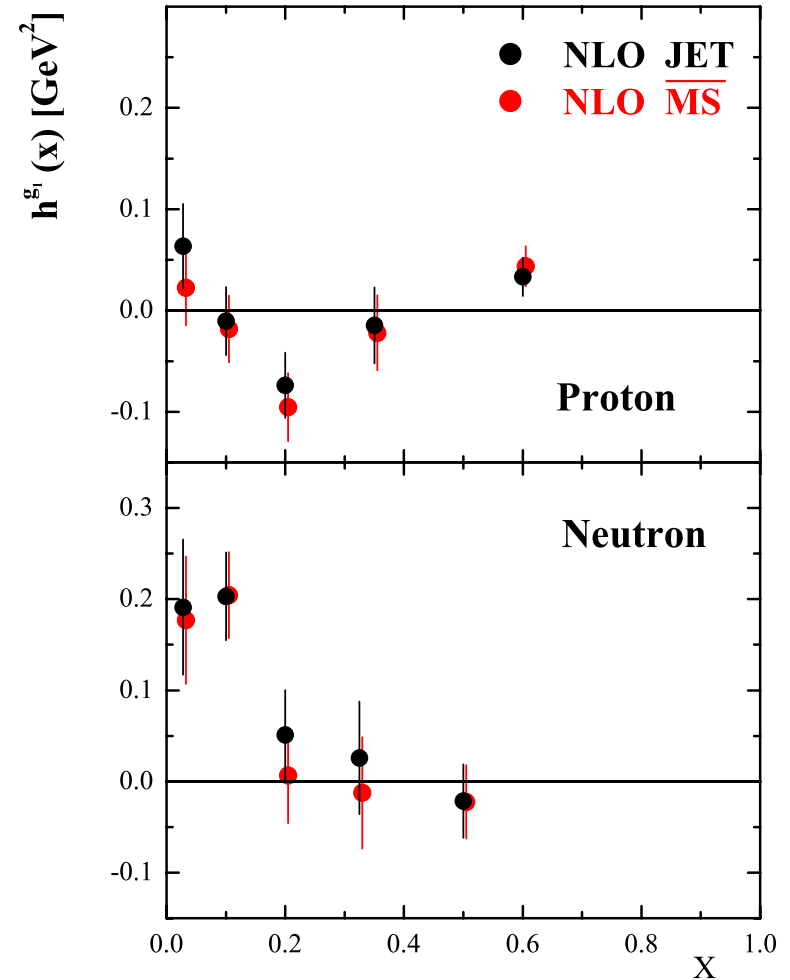
● If JLab/Hall A and HERMES/d data are included in the analysis, the HT corrections to g_1 are better determined, especially for the neutron target



How the choice of the factorization scheme for $(g_1)_{LT}$ influence the higher twist results ?



an estimation of the NNLO effects in $(g_1)_{LT}$



$$g_1(x, Q^2) = g_1(x, Q^2)_{LT} + h^N(x) / Q^2$$

NLO polarized PD

From inclusive DIS data $\Rightarrow (\Delta q + \Delta \bar{q})$ and ΔG

$(\Delta u + \Delta \bar{u}), (\Delta d + \Delta \bar{d})$ well determined

$(\Delta s + \Delta \bar{s})$ reasonably well determined

if accept for a_8 its SU(3) symmetric value

$$a_8 = 3F - D = 0.58$$

ΔG not well constrained,
but it seems to be large

$$PD(g_1^{NLO} + HT) \Leftrightarrow PD(g_1^{NLO} / F_1^{NLO})$$

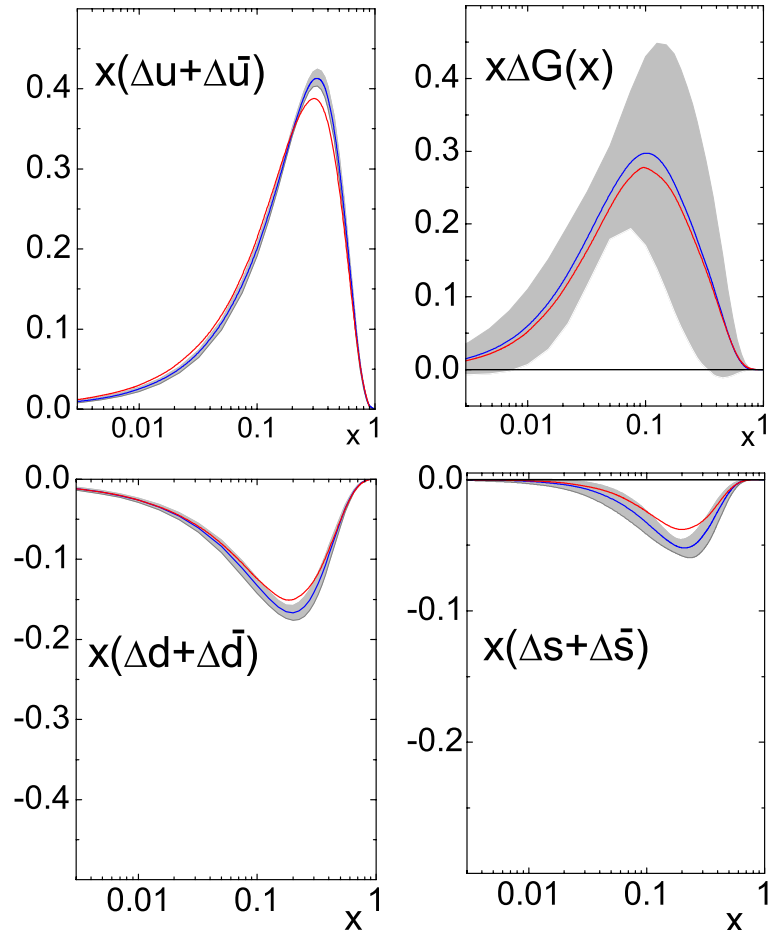
$$\chi_{DF,NLO}^2 = 0.858 \Leftrightarrow \chi_{DF,NLO}^2 = 0.859$$

If F_1 is expressed via $(F_2)_{\text{exp}}$ and R_{exp}
then the HT corrections to g_1
have to be taken into account!

NLO(JET) $Q^2 = 1 \text{ GeV}^2$

— PD ($g_1^{NLO} + HT$)

— PD (g_1^{NLO} / F_1^{NLO})



n=1 moments of PD, JET scheme, $Q^2=1 \text{ GeV}^2$

- the correlations between the parameters are taken into account

N.B. In JET scheme $\Delta\Sigma$,
as well as $(\Delta s + \Delta\bar{s})$,
do NOT depend on Q^2 .

*~ 0.6 at $Q^2 \sim \Lambda^2$
in relativistic CQM*

$$(\Delta u + \Delta\bar{u})(Q^2) = 0.84 \pm 0.03$$

$$(\Delta d + \Delta\bar{d})(Q^2) = -0.43 \pm 0.04$$

$$(\Delta s + \Delta\bar{s}) = -0.09 \pm 0.03$$

$$\Delta G(Q^2) = 0.80 \pm 0.48$$

$$\Delta\Sigma_{JET} = 0.32 \pm 0.06$$

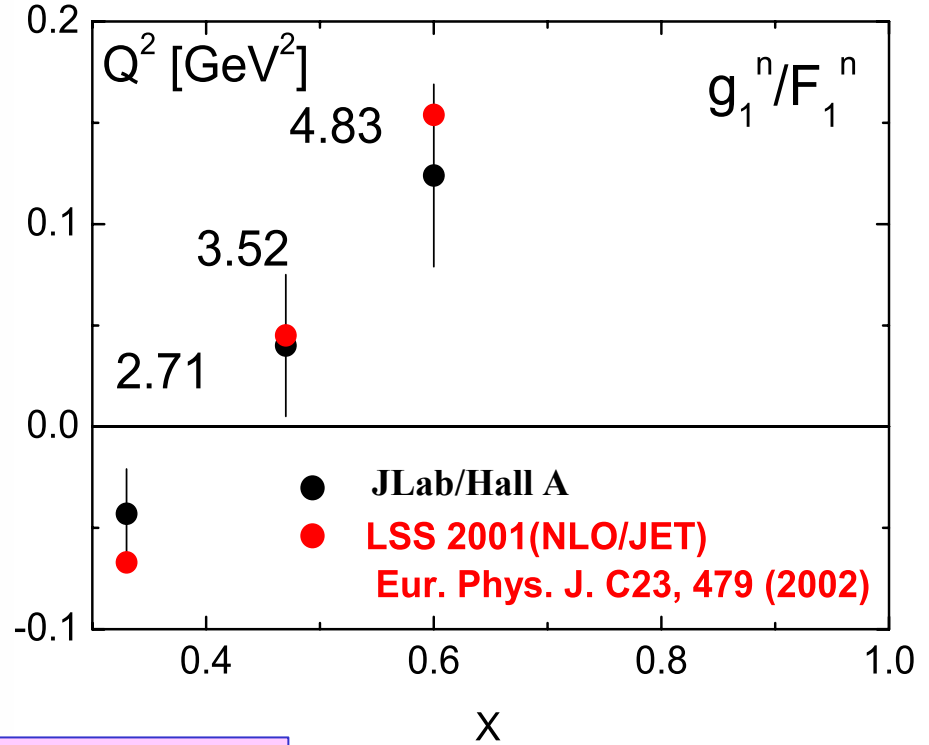
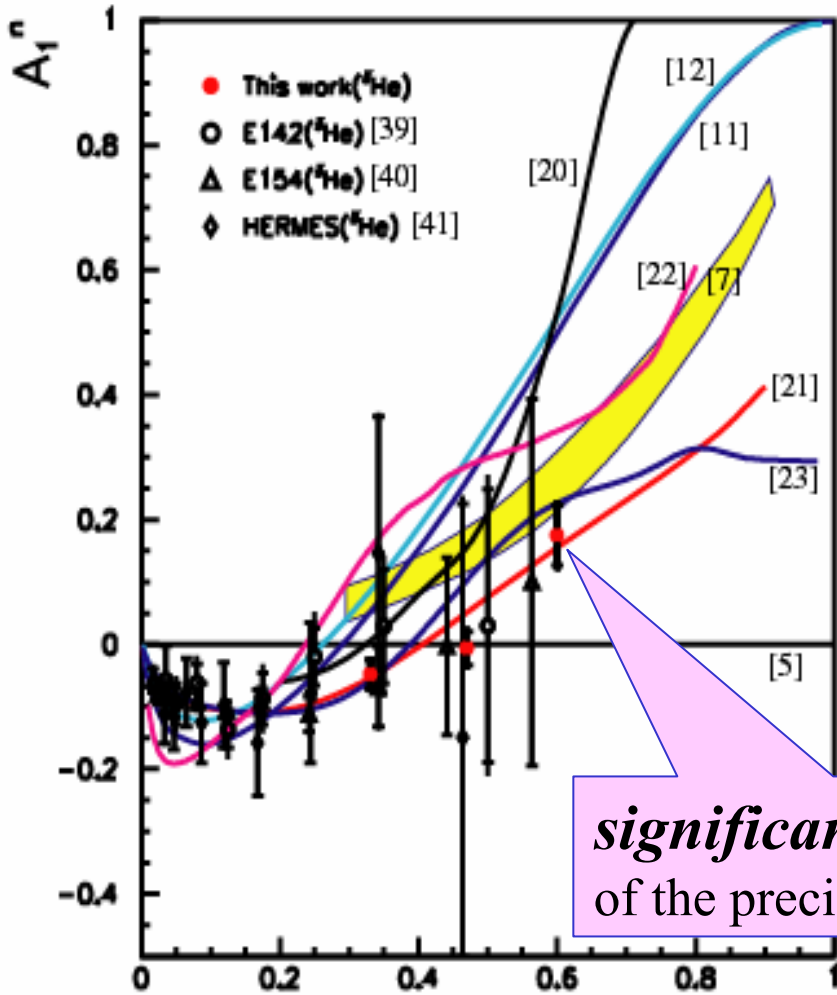
$$(\Delta s + \Delta\bar{s})(Q^2)_{\overline{MS}} = -0.15 \pm 0.05$$

$$a_0(Q^2) = \Delta\Sigma(Q^2)_{\overline{MS}} = 0.14 \pm 0.07$$

- Spin sum rule: $1/2 = \frac{1}{2} 0.32 + 0.80 + \mathbf{L_z} = \mathbf{0.96} + \mathbf{L_z}$

$\mathbf{L_z}$ is *negative*

Our predictions for the JLAB experimental values of g_1^n/F_1^n using the LSS'2001 NLO(JET) polarized PD



significant improvement of the precision of the data

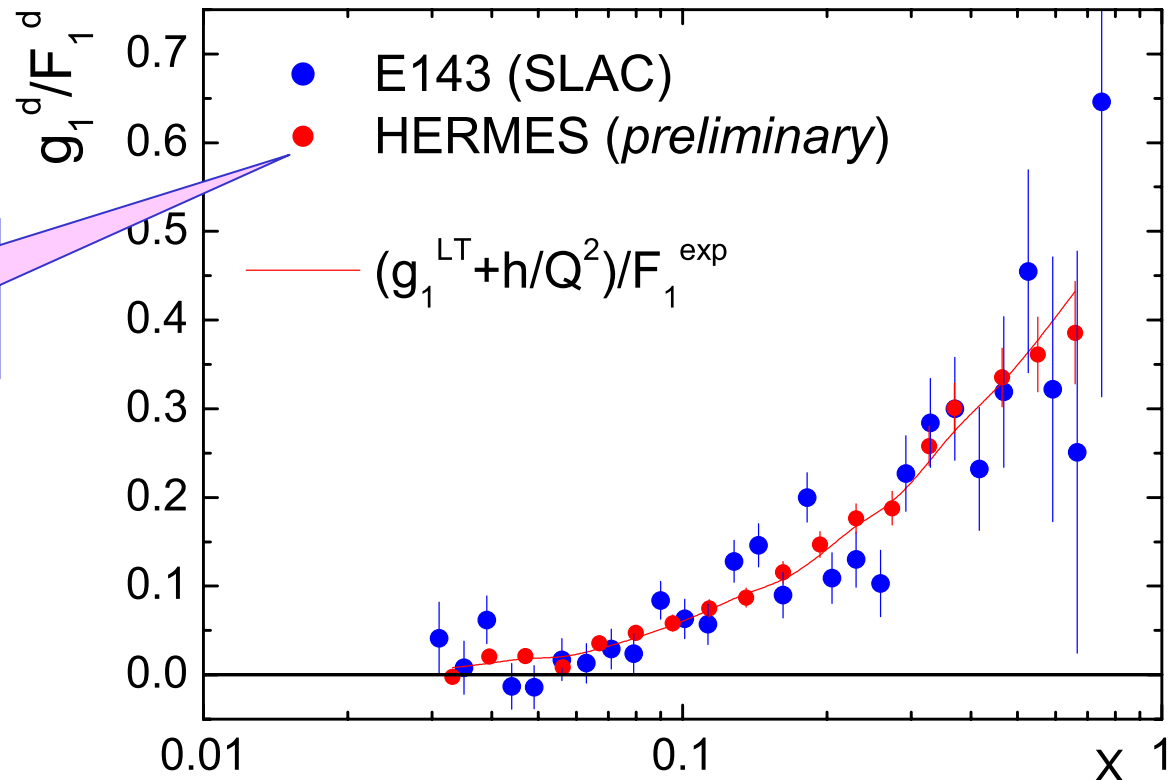
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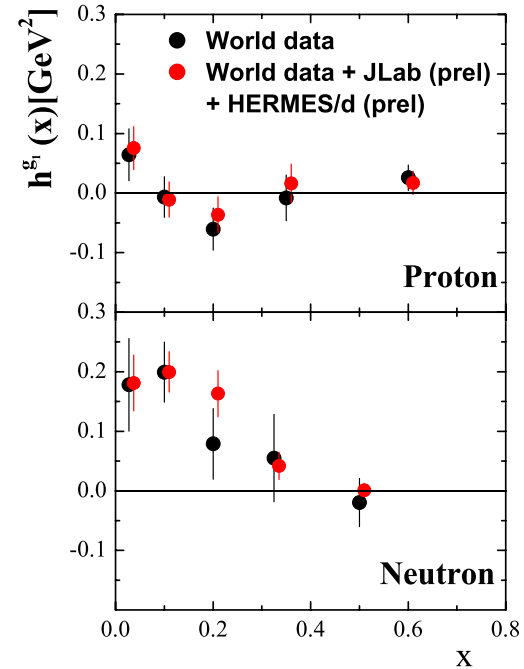
Ch. Weiskopf
02-043 Thesis (2002)



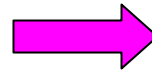
The first moments of HT

$$\Delta_1^p \approx \int_{0.005}^{0.75} h^p(x) dx$$

$$\Delta_1^n \approx \int_{0.015}^{0.60} h^n(x) dx$$



$$\Delta_1^n \approx [0.049 \pm 0.007] \text{ GeV}^2$$

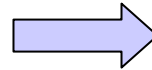


0

In some Bag models

$$\Delta_1^p \approx [0.007 \pm 0.010] \text{ GeV}^2$$

small



In agreement with Instanton approach

$$\Delta_1^{p-n} \approx [-0.042 \pm 0.012] \text{ GeV}^2$$

negative

World data on g_1 + 2 points

$$\Gamma_1^p = \int_0^1 g_1^p(Q^2, x) dx$$

at $Q^2=0.99$ and 1.20 GeV^2

SU(3)

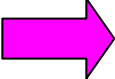
SU(3)

$$a_8 = 3F - D + \Delta = 0.585 + \Delta$$

$$\Delta = -0.15 \pm 0.07$$

CONCLUSIONS

- The fit to the *present* data on g_1 is **essentially improved**, especially in the LO case, when the higher twist terms of g_1 are included in the analysis
- The size of **HT** corrections have been extracted from the data in *model independent* way and found to be NOT negligible
- The HT corrections to g_1 and F_1 compensate each other in **g_1/F_1**
- $PD(g_1^{LT} + HT)$ well consistent with $PD(g_1^{LT} / F_1^{LT})$

 To extract *correctly* the polarized PD from the g_1 data, the HT corrections to g_1 *have* to be taken into account in the analysis.

MORE GENERALLY

- Given the limited range and precision of present $g_1(x, Q^2)$ measurements, one would like
 - ➡ a direct measurement of ΔG (**COMPASS, RHIC**)
- Inclusive DIS measurements are sensitive only to $(\Delta q + \Delta \bar{q})$
 - ➡ thus a new probe is needed to **separate quark and anti-quark polarized PD** from SIDIS, W production
(*HERMES, COMPASS, RHIC*)
- Data at *larger* Q^2 and *smaller* x would be very important for our understanding of the spin properties of the nucleon.