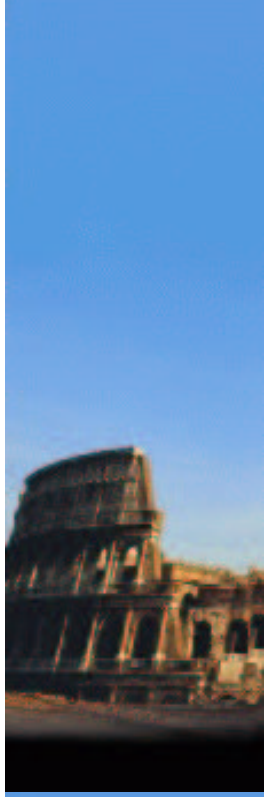

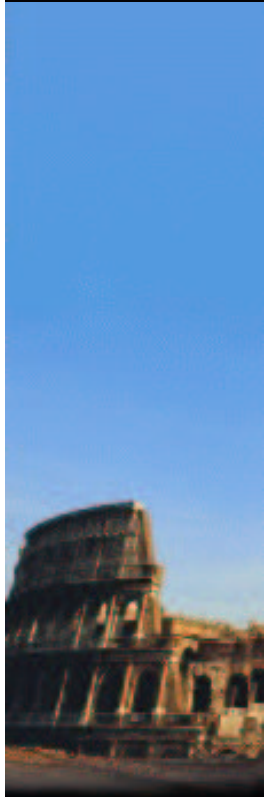

Polarized Structure Functions

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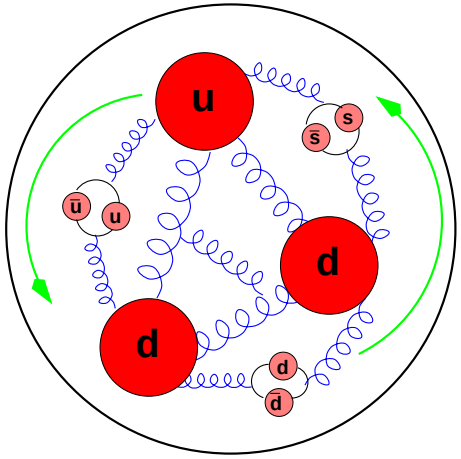
LP01 Rome 23-28 July 2001

Motivation

the spin structure of the nucleon:

$$\langle S_z^{\mathrm{N}} \rangle = \frac{1}{2} = J_q + J_g$$
$$= \frac{1}{2}\Delta\Sigma + L_q + \Delta G + L_g$$



$\Delta\Sigma$ is found to be small in inclusive DIS experiments

- ∼1980: SLAC: connection of nucleon spin with quarks
- 1988: EMC: *"spin crisis"* $\Delta\Sigma = 0.12 \pm 0.17 \approx 0$?
- 1988−2000: SLAC, CERN, DESY: $\Delta\Sigma \approx 0.2 \ldots 0.4 > 0$

possible contributions to $\langle S_z \rangle$ still unknown

- strange sea polarization Δs ?
- gluon polarization ΔG ?
- orbital angular momentum $L_{q,g}$?

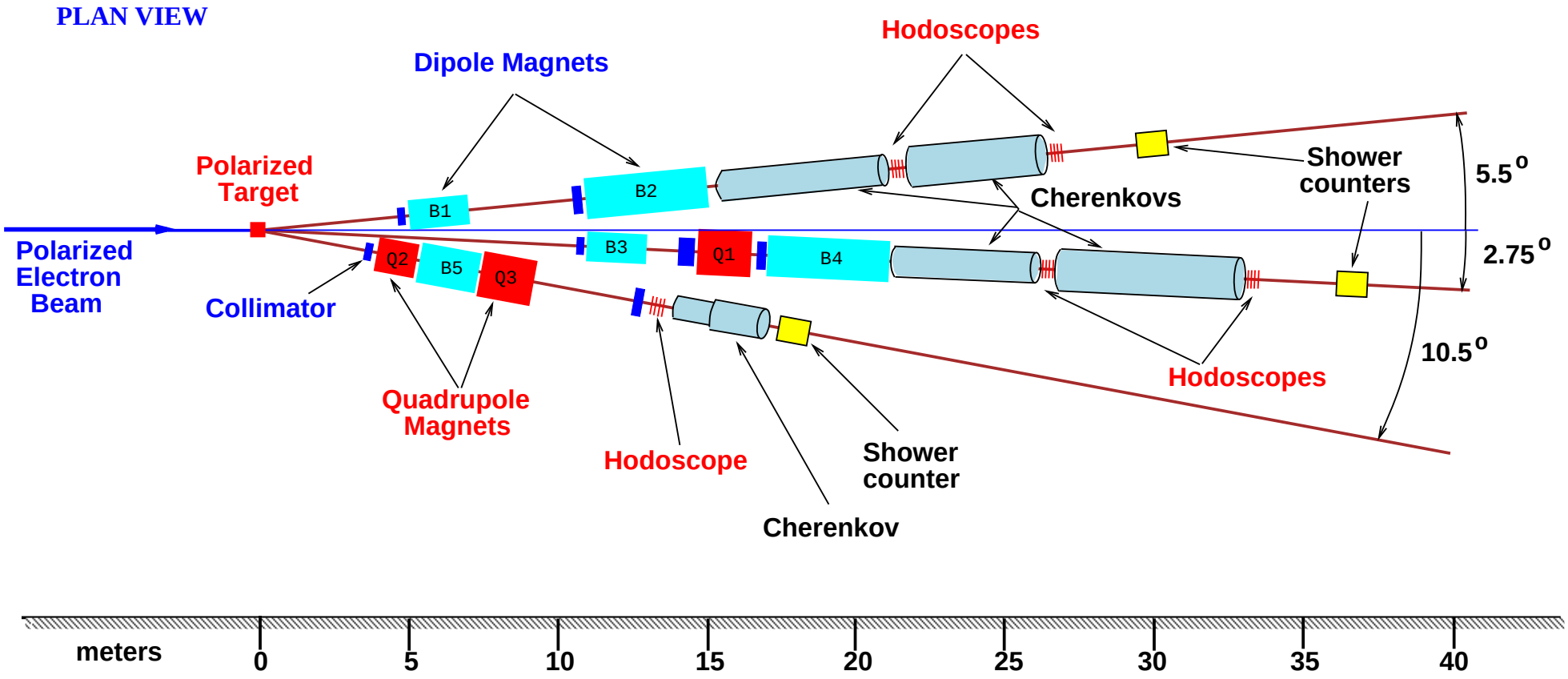
Outline

- Experiments and Kinematics
- Asymmetries and Structure Functions $g_{1,2}$
- QCD and Gluon Polarization ΔG
- Semi-inclusive Spin Physics
- Prospects of Current Experiments
- Conclusion

Deep Inelastic lp and pp Spin Experiments

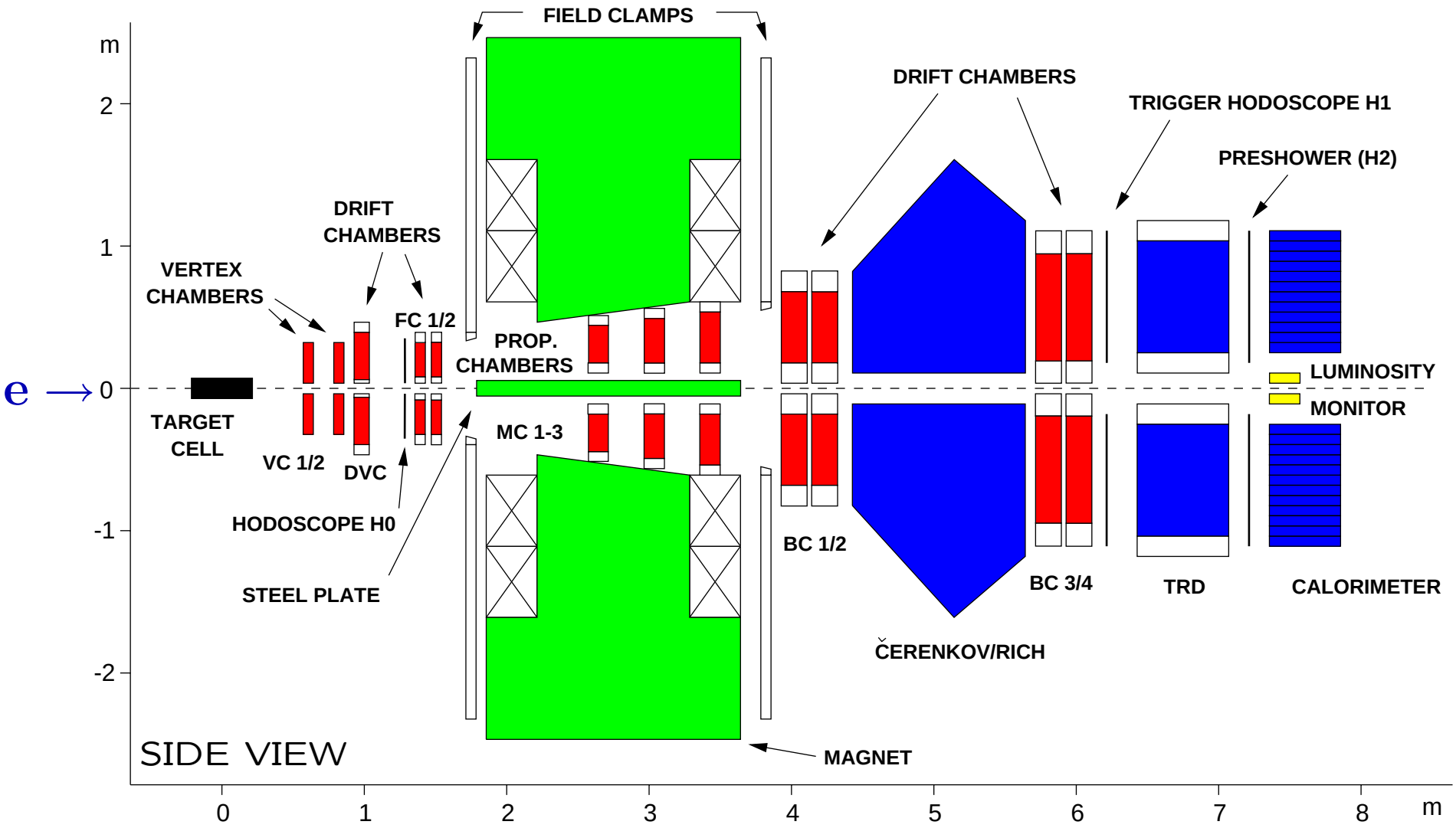
Lab	Exp.	Year	Beam	P %	Target	P %	f
SLAC	E80	75	10-16 GeV e^-	85	H-butanol	50	0.13
	E130	80	16-23 GeV e^-	81	H-butanol	58	0.15
	E142	92	19-26 GeV e^-	39	^{3}He	35	0.35
	E143	93	10-29 GeV e^-	85	NH_3	70	0.15
					ND_3	25	0.24
	E154	95	48 GeV e^-	83	^{3}He	33	0.55
	E155	97	48 GeV e^-	81	NH_3	90	0.15
					LiD	22	0.36
	E155X	99	30 GeV e^-	83	NH_3	70	0.16
					LiD	22	0.36
CERN	EMC	85	200 GeV μ^+	79	NH_3	78	0.16
	SMC	92	100 GeV μ^+	82	D-butanol	35	0.19
		93	190 GeV μ^+	80	H-butanol	86	0.12
		94/95		81	D-butanol	50	0.20
		96		77	NH_3	89	0.16
DESY	HERMES	95	28 GeV e^+	55	^{3}He	46	1.0
		96/97		55	H	88	1.0
		98	28 GeV e^-	55	D	85	1.0
		99/00	28 GeV e^+	55	D	85	1.0
DESY	HERMES	01	28 GeV e^+	55	H	85	1.0
CERN	COMPASS	01	160 GeV μ^+	80	NH_3	90	0.16
					LiD	50	0.50
BNL	RHIC	01	200 GeV p	70	200 GeV p	70	1.0

E155 Spectrometers

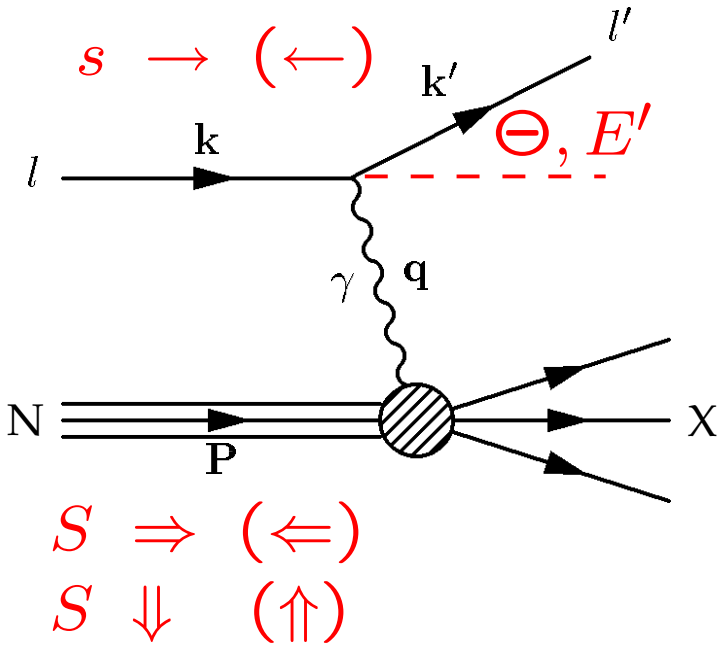


The HERMES Experiment at DESY

forward spectrometer $(0.04 < |\Theta| < 0.22$ mrad)



Deep Inelastic Lepton-Nucleon Scattering (DIS)



$$Q^2 = -q^2 \overset{\text{lab}}{=} 4EE' \sin^2 \frac{\Theta}{2}$$

$$y = \frac{Pq}{Pk} \overset{\text{lab}}{=} \frac{E - E'}{E}$$

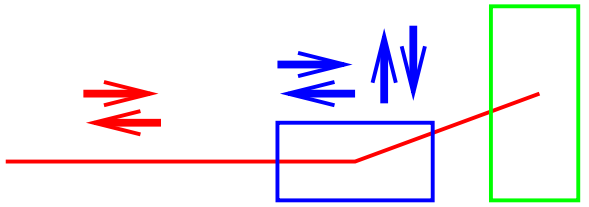
$$\nu \overset{\text{lab}}{=} E - E'$$

$$x = \frac{Q^2}{2Pq} \overset{\text{lab}}{=} \frac{Q^2}{2M\nu}$$

$$W^2 \overset{\text{lab}}{=} -Q^2 + M^2 + 2M\nu$$

Spin Structure Functions in DIS

form cross section asymmetries w.r.t. orientations of beam and target spins



measured asymmetries:

$$A_{||} = \frac{\sigma^{\rightleftarrows} - \sigma^{\rightrightarrows}}{\sigma^{\rightleftarrows} + \sigma^{\rightrightarrows}} \qquad A_{\perp} = \frac{\sigma^{\Downarrow\rightarrow} - \sigma^{\Uparrow\rightarrow}}{\sigma^{\Downarrow\rightarrow} + \sigma^{\Uparrow\rightarrow}}$$

relation to virtual photon asymmetries A_1 and A_2:

$$A_{||} = D(A_1 + \eta A_2) \qquad A_{\perp} = d(\zeta A_1 + A_2)$$

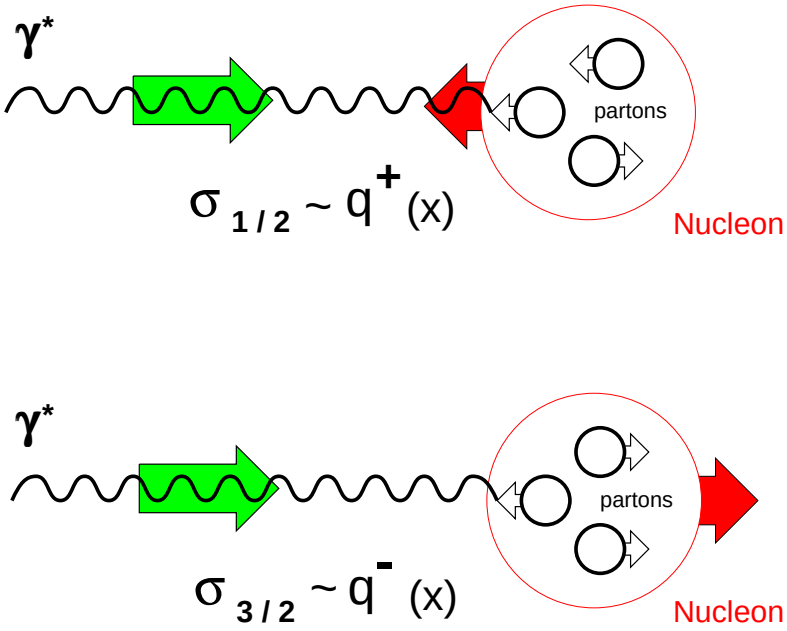
relation to spin structure functions g_1 and g_2:

$$A_1 = \frac{(g_1 - \gamma^2 g_2)}{F_1} \approx \frac{g_1}{F_1} \qquad A_2 = \gamma \frac{(g_1 + g_2)}{F_1}$$

D, d : photon depolarization factors ($D \approx y$)

η, γ, ζ : kinematic factors ($\eta \approx \gamma \xrightarrow{Q^2 \gg M^2} 0$)

Partonic Interpretation



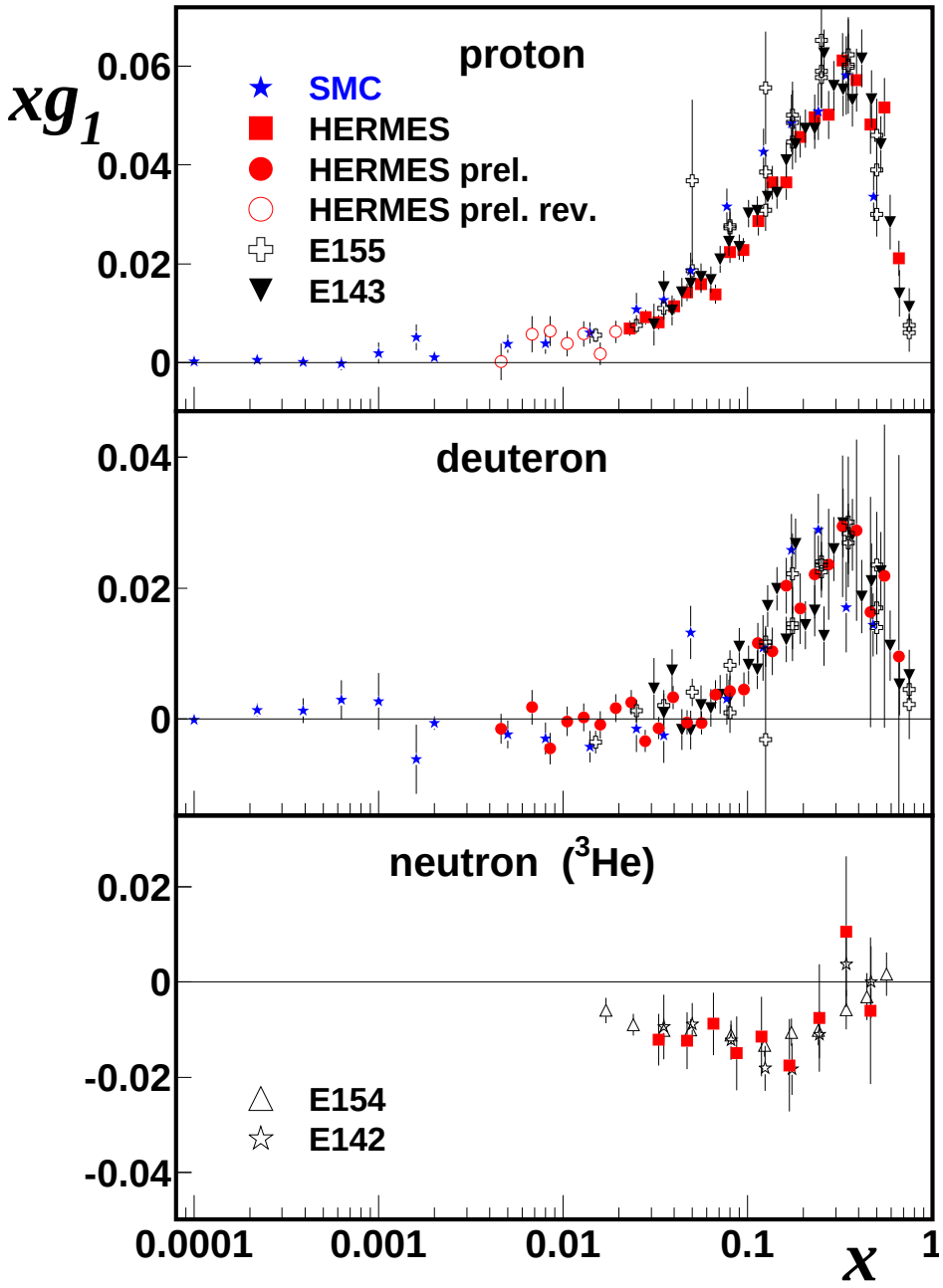
QPM:

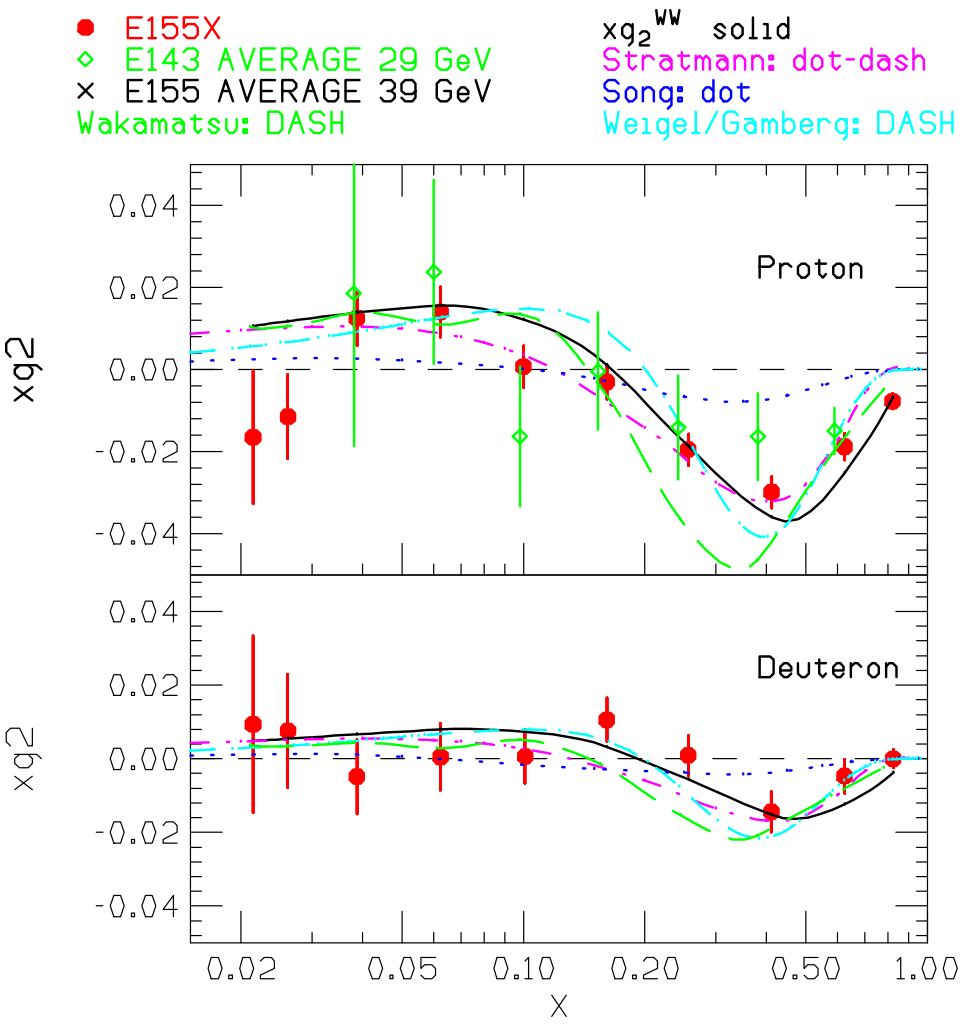
$$
\begin{aligned}
q(x) &= q^+(x) + q^-(x) \\
F_1(x) &= \frac{1}{2}\sum_f e_f^2 q_f(x) \\
F_2 &= 2xF_1 \\
\Delta q(x) &= q^+(x) - q^-(x) \\
g_1(x) &= \frac{1}{2}\sum_f e_f^2 \Delta q_f(x) \\
g_2 &= 0
\end{aligned}
$$

simple physical interpretation of g_1 in terms of quark helicity distributions $\Delta q_f(x)$

BUT no simple partonic picture for g_2

World Data on xg_1 and xg_2



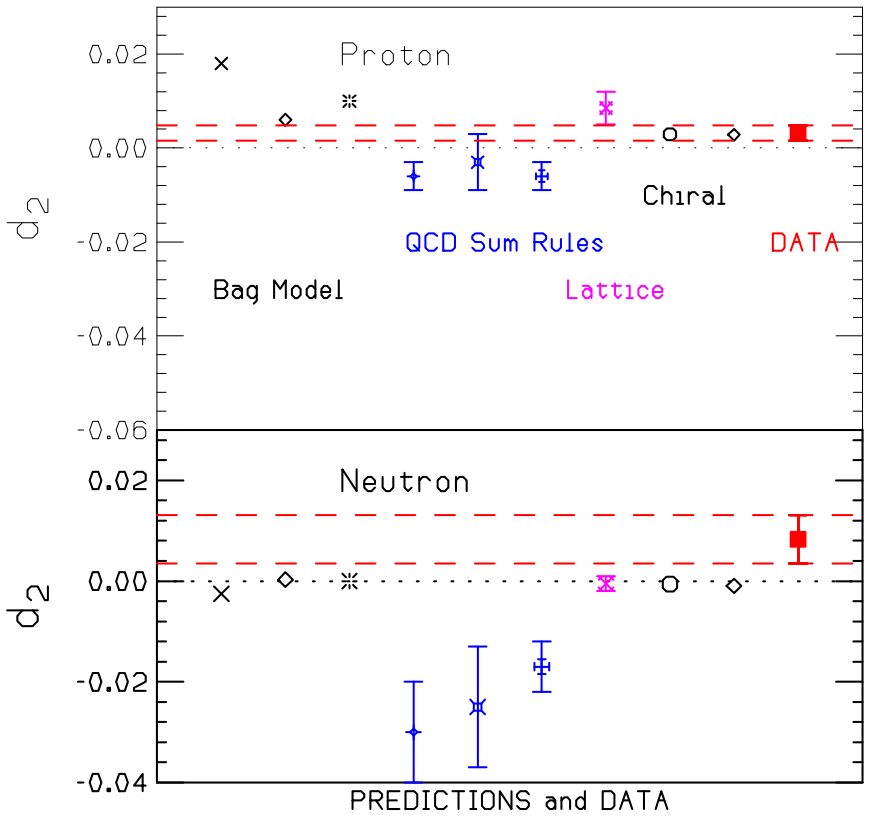


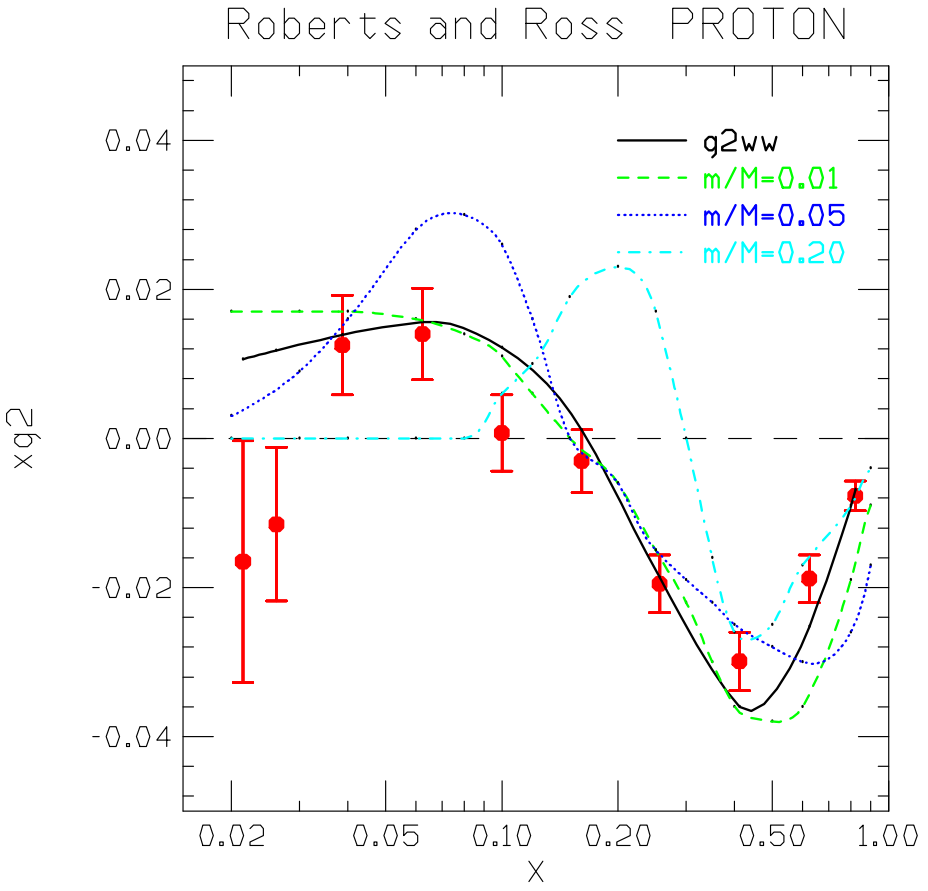
new: HERMES prelim., E155X
data at $\langle Q^2 \rangle$: 0.02-58 GeV^2

Interpretations of g_2

$$g_2(x,Q^2) = g_2^{WW}(x,Q^2) + \overline{g_2}(x,Q^2)$$

- g_2^{WW} includes twist-2 contribution: $g_2^{WW} \propto -g_1$
- $\overline{g_2}$ includes quark-gluon correlations $\rightsquigarrow$ twist-3 matrix element d_2





d_2: 0.0032 ± 0.0016 (p)
d_2: 0.0083 ± 0.0048 (n)

sensitive to m_q/M

Interpretation of g_1 in NLO pQCD

g_1 well described in QCD improved QPM (NLO)

$$g_1^{p(n)} = \frac{1}{9}\left\{\Delta C_{NS} \otimes \left[\pm\frac{3}{4}\,\mathbf{\Delta q_3} + \frac{1}{4}\mathbf{\Delta q_8}\right] + \Delta C_S \otimes \mathbf{\Delta\Sigma} + 2N_f \Delta C_G \otimes \mathbf{\Delta G}\right\}$$

with usual notations ($N_f = 3$):

$$\begin{aligned}
\Delta\Sigma(x,Q^2) &= (\Delta u + \Delta\bar{u}) + (\Delta d + \Delta\bar{d}) + (\Delta s + \Delta\bar{s}) \\
\Delta q_3(x,Q^2) &= (\Delta u + \Delta\bar{u}) - (\Delta d + \Delta\bar{d}) = 6(g_1^p - g_1^n) \\
\Delta q_8(x,Q^2) &= (\Delta u + \Delta\bar{u}) + (\Delta d + \Delta\bar{d}) - 2(\Delta s + \Delta\bar{s}) \\
\Delta G(x,Q^2) &\quad \text{in NLO only; } \Delta C_G^0 = 0 \text{ in LO}
\end{aligned}$$

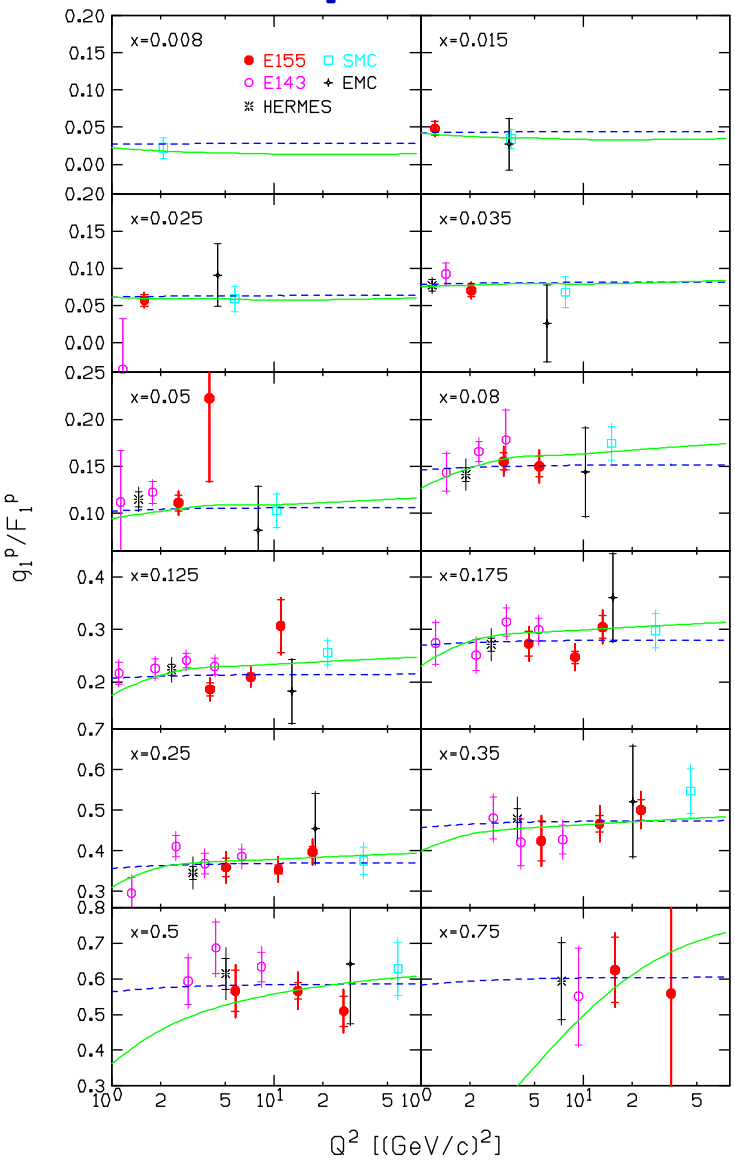
in principle linear combinations of polarized PDF's and ΔG can be determined due to their different Q^2 evolution

BUT at NLO mixing of $\Delta\Sigma$ and ΔG $\rightsquigarrow$ factorization scheme dependence :
$\Rightarrow$ $\overline{\text{MS}}$ scheme: $\Delta\Sigma$ not conserved
$\Rightarrow$ AB or JET scheme: $\Delta\Sigma$ conserved

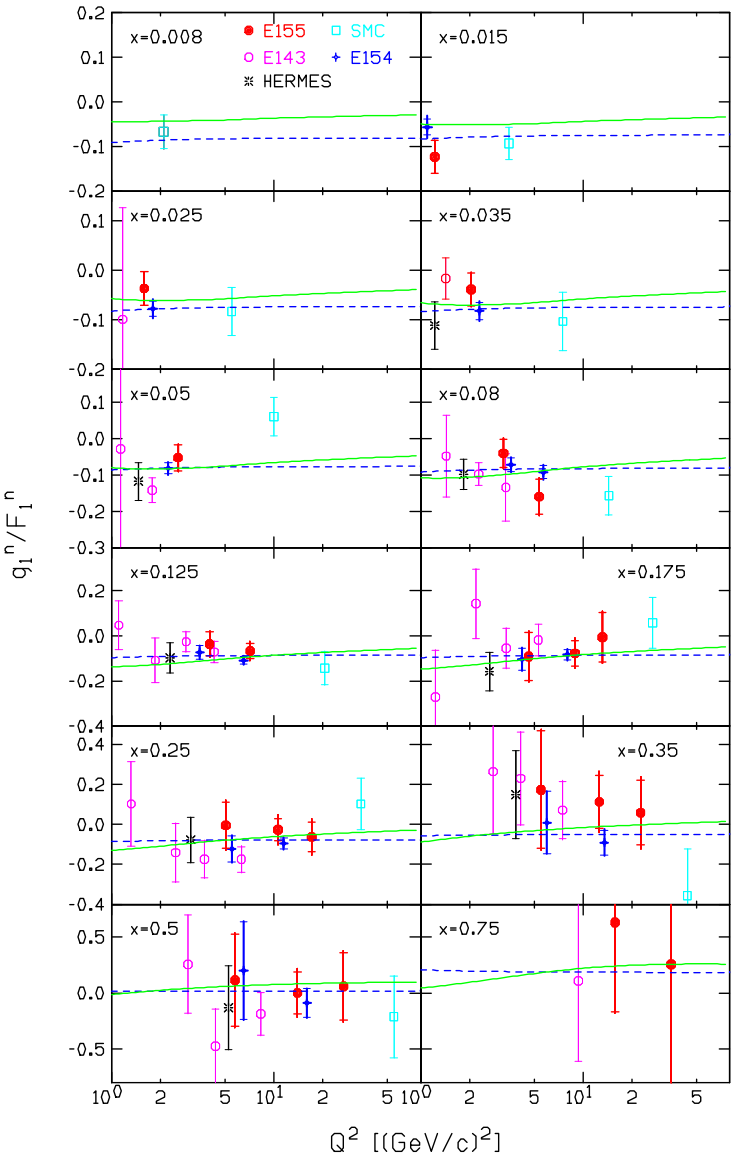
$$\Delta\Sigma(Q^2)_{\overline{\text{MS}}} = \Delta\Sigma_{\text{AB(JET)}} - N_f\frac{\alpha_s(Q^2)}{2\pi}\Delta G(Q^2)$$
$$\Delta G(Q^2)_{\overline{\text{MS}}} = \Delta G(Q^2)_{\text{AB(JET)}}$$

Q^2 Dependence of $A_1 \approx g_1/F_1$

proton



neutron



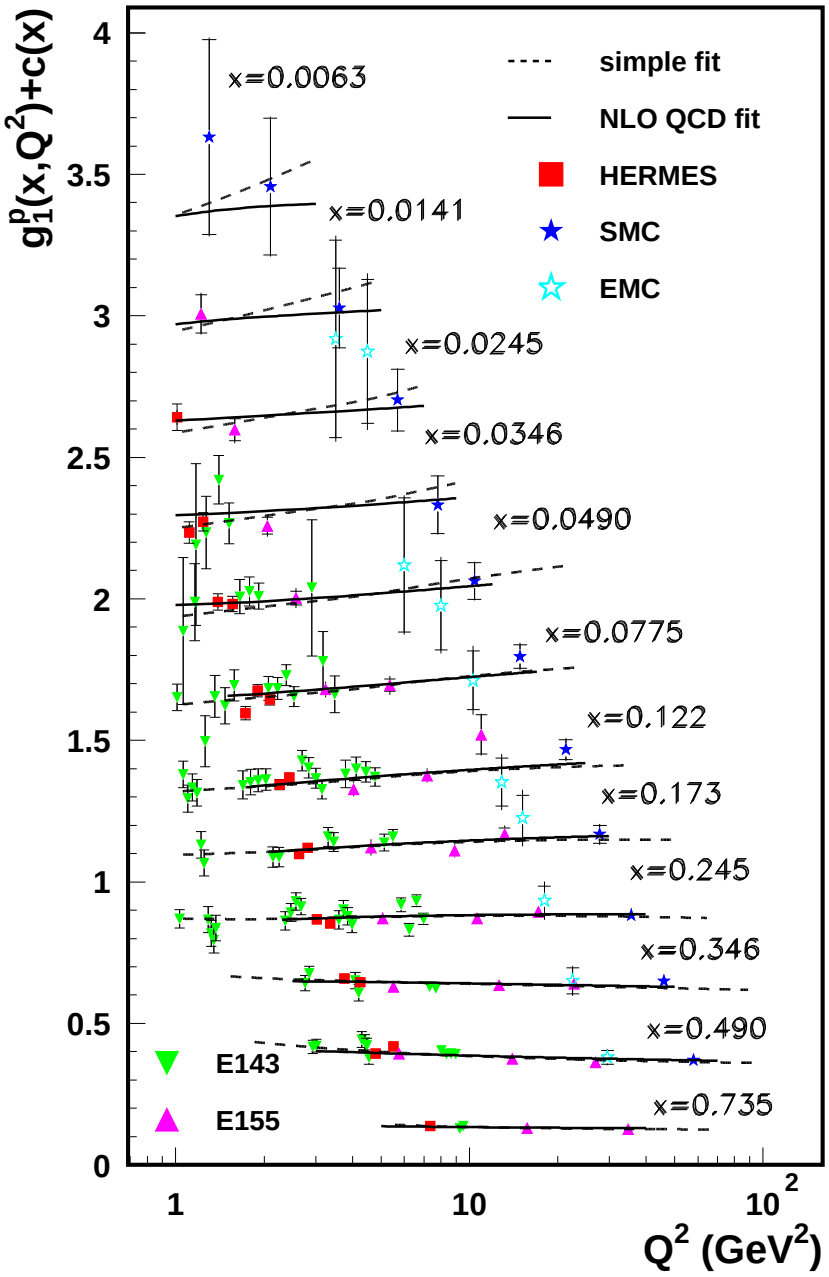
— simple fit

— NLO fit

[E155, hep-ph/0007248]

$\rightsquigarrow$ ratios $g_1/F_1^{p,n}$ independent of Q^2 in DIS region within current uncertainties

Q^2 Dependence of g_1^p



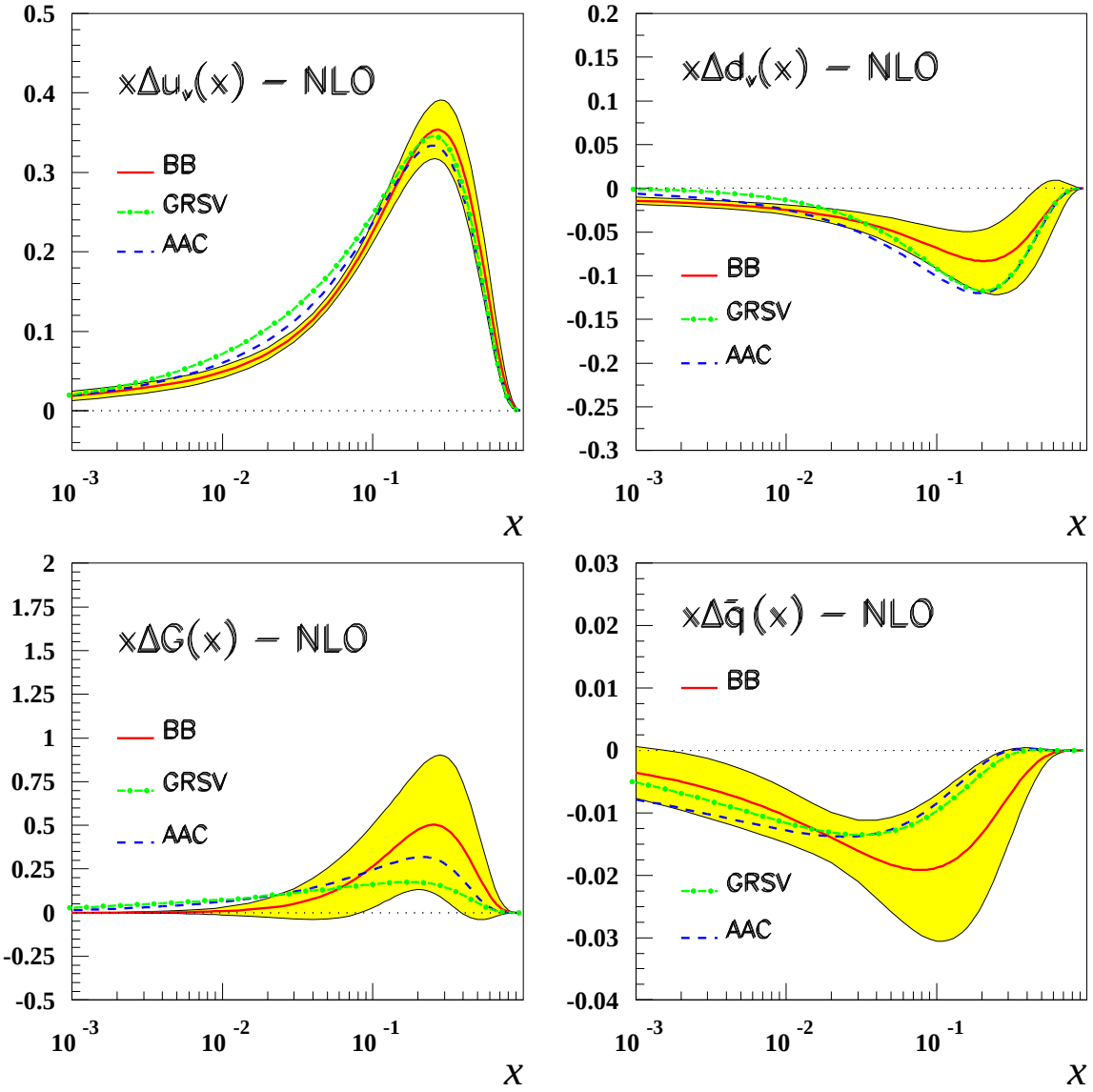
$\rightsquigarrow$ Q^2 dependence of g_1^p similar to the Q^2 dependence of F_1^p

NLO pQCD fit of $g_1^{p,d,n}$ data with $Q^2 > 1$ GeV^2

Fits to $g_1(x, Q^2)$ in NLO pQCD using SU(3)$_f$

updated NLO QCD ($\overline{\text{MS}}$) fits at $Q^2 = 4$ GeV^2

NEW: propagated statistical uncertainties (yellow bands - BB)



BB: Blümlein, Böttcher, DIS2001

GRSV: Glück et al., hep-ph/0011215

AAC: Goto et al., hep-ph/0001046

$\Rightarrow$ determination of $\alpha_s(M_Z^2) = 0.114 \pm 0.005(\text{stat}) \,^{+0.009}_{-0.006}(\text{scales})$ (BB)

Sensitivity to broken SU(3)$_f$

present NLO analyses use information from neutron and hyperon β-decays to constrain non-singlet first moments

$$a_3 = \Delta q_3 = F + D = 1.267 \pm 0.0035 \quad \text{(Bjorken sum rule)}$$
$$a_8 = \Delta q_8 = 3F - D = 0.585 \pm 0.025$$

however, result for a_8 depends on assumption of SU(3) flavour symmetry among hyperons, which is known to be inexact...

sensitivity to SU(3) flavour symmetry breaking, in JET scheme, $Q^2 = 1$ GeV^2 [Leader, Stamenov, Sidorov,DIS2001, hep-ph/0004106]

a_8	χ^2/dof	$\Delta\Sigma$	ΔG	$\Delta s + \Delta\bar{s}$
0.40	0.82	0.34 $\pm$ 0.05	0.13 $\pm$ 0.14	-0.02 $\pm$ 0.01
0.585	0.83	0.40 $\pm$ 0.04	0.57 $\pm$ 0.14	-0.06 $\pm$ 0.01
0.86	0.82	0.40 $\pm$ 0.06	0.84 $\pm$ 0.30	-0.15 $\pm$ 0.02

gluon and strange quark polarizations strongly dependent on SU(3) symmetry assumption $\rightsquigarrow$ direct measurements needed

HERMES : ΔG from Photon-Gluon Fusion (LO)

$\gamma g \to q\bar{q}$: select h^+h^- pairs with large p_T^{h1} >1.5 GeV, $p_T^{h2} > 0.5$ GeV

$\rightsquigarrow$ negative asymmetry $A_{||}$ interpreted in terms of $\Delta G/G$ (PGF) and $\Delta q/q$ (QCDC) contributions using PYTHIA model

$\rightsquigarrow$ $\Delta G/G$ positive

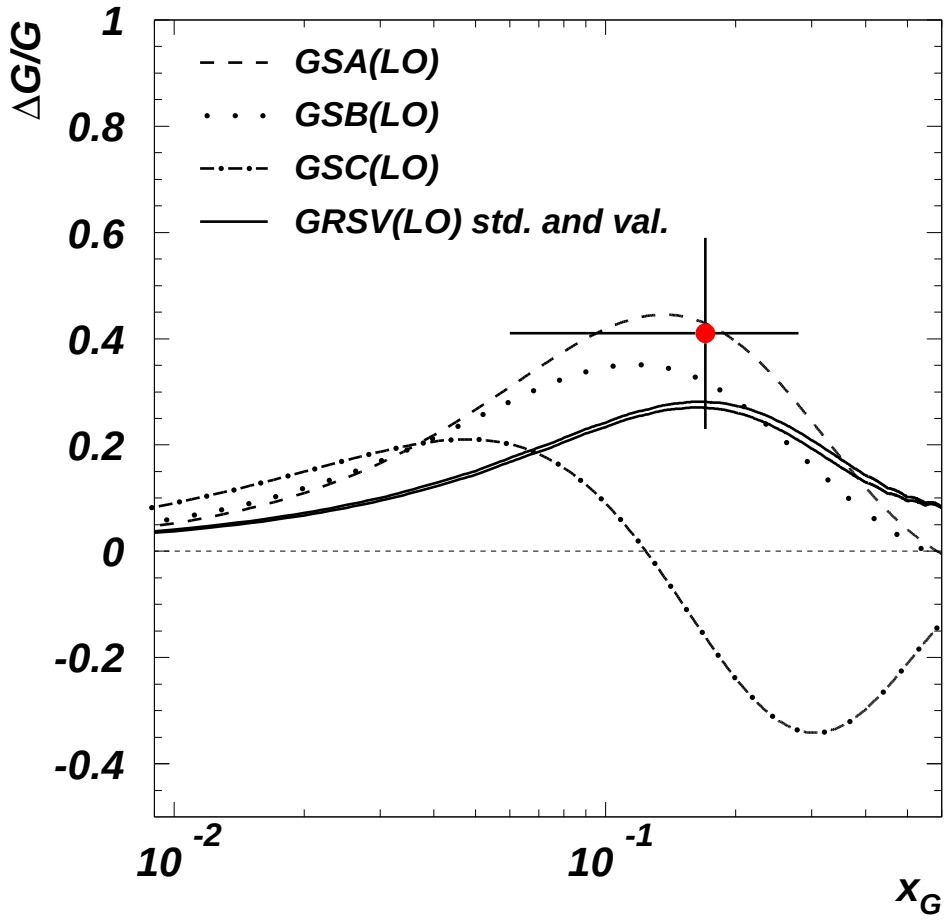
at $\langle x_g \rangle = 0.17$ and $\langle p_T^2 \rangle = 2.1$ GeV^2

$\Delta G/G = 0.41 \pm 0.18(stat.) \pm 0.03(exp.syst.)$

[HERMES, PRL84(2000)2584]

ongoing:

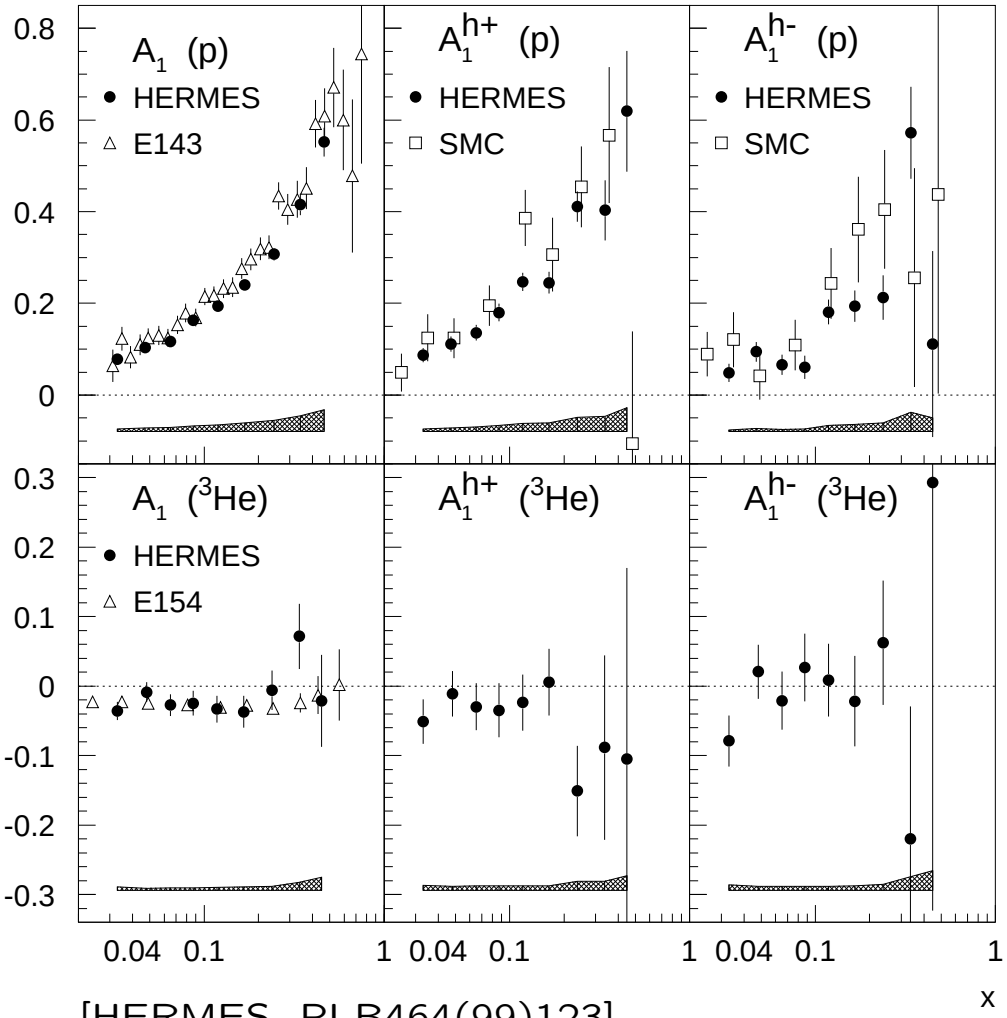
$\Delta G/G$ analysis based on new high statistics deuteron data of HERMES run periods 1998-2000



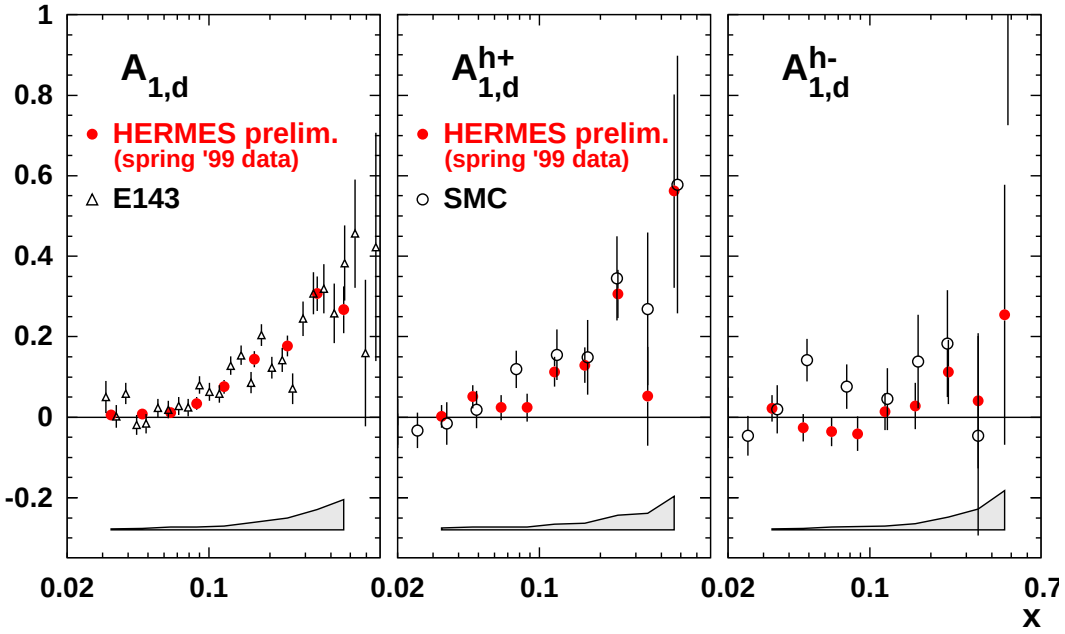
GS: Gehrmann, Stirling, PRD53(1996)6100

Semi-Inclusive Asymmetries

$$A_1^h \approx \frac{g_1^h}{F_1^h}(x,Q^2) = \frac{\int_{z_{min}}^1 dz \sum_q e_q^2 \Delta q(x,Q^2) \cdot D_q^h(z,Q^2)}{\int_{z_{min}}^1 dz \sum_q e_q^2 q(x,Q^2) \cdot D_q^h(z,Q^2)} \quad \text{(LO pQCD)}$$



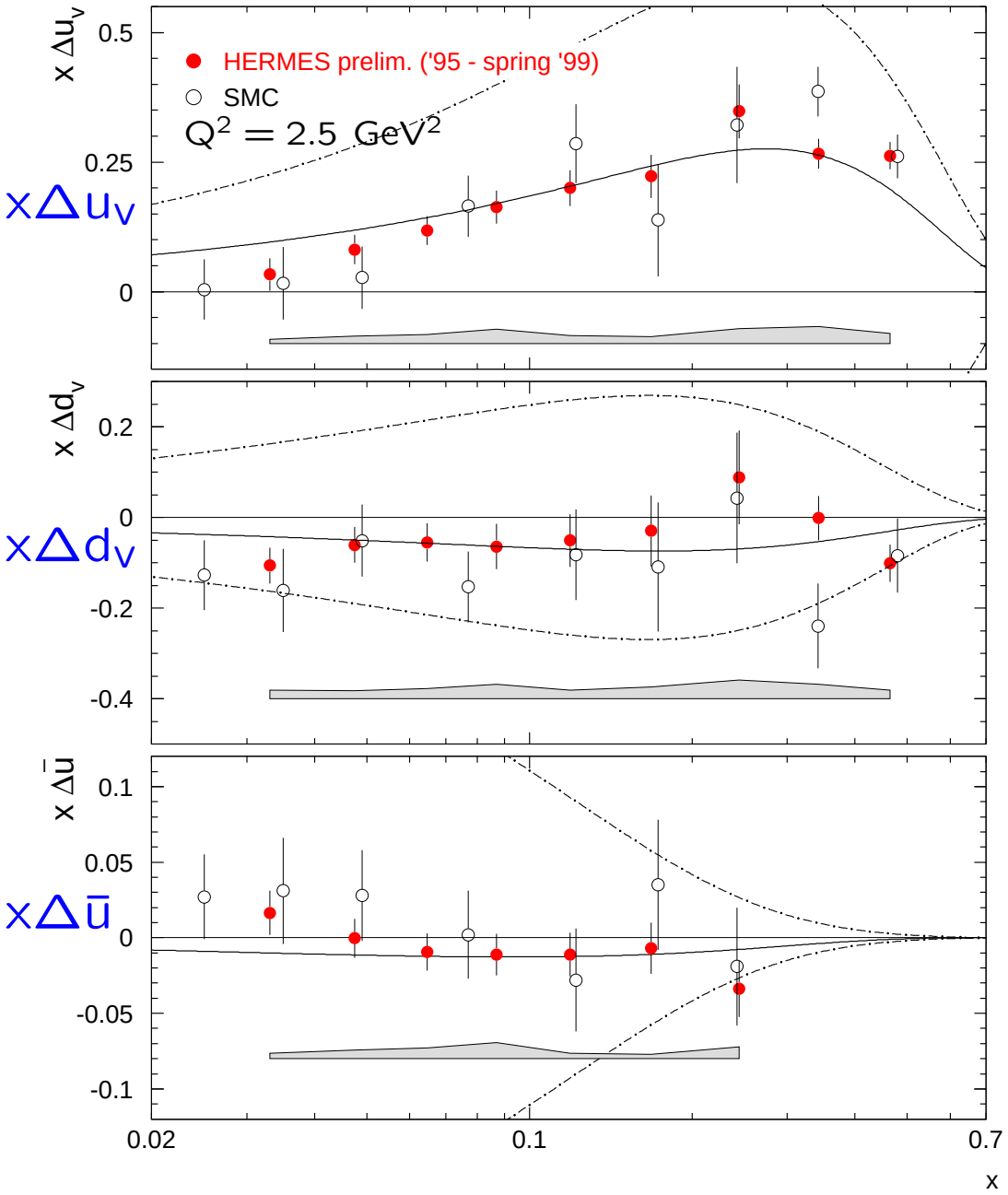
[HERMES, PLB464(99)123]



new:HERMES deuteron prelim.

bands: HERMES syst. uncertainty

Polarized Quark Distributions (LO)



flavour tagging:

$A_1(h^{\pm})$ on proton dominated by $\Delta u(x)$

$A_1(h^{\pm})$ on neutron dominated by $\Delta d(x)$

sensitivity to $\Delta\bar{u}$ and $\Delta\bar{d}$ $\lesssim$ 10% at $x < 0.2$

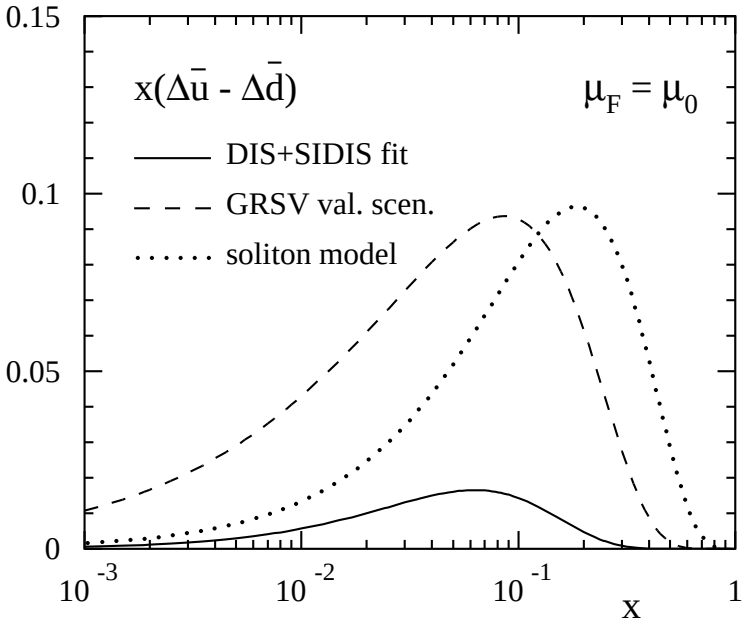
$\Delta\Sigma = 0.30 \pm 0.04 \pm 0.09$

[HERMES, PLB464(99)123]

polarized quark sea not yet separated

solid lines: GSA LO
dashed lines: positivity limits
bands: HERMES syst. uncertainty

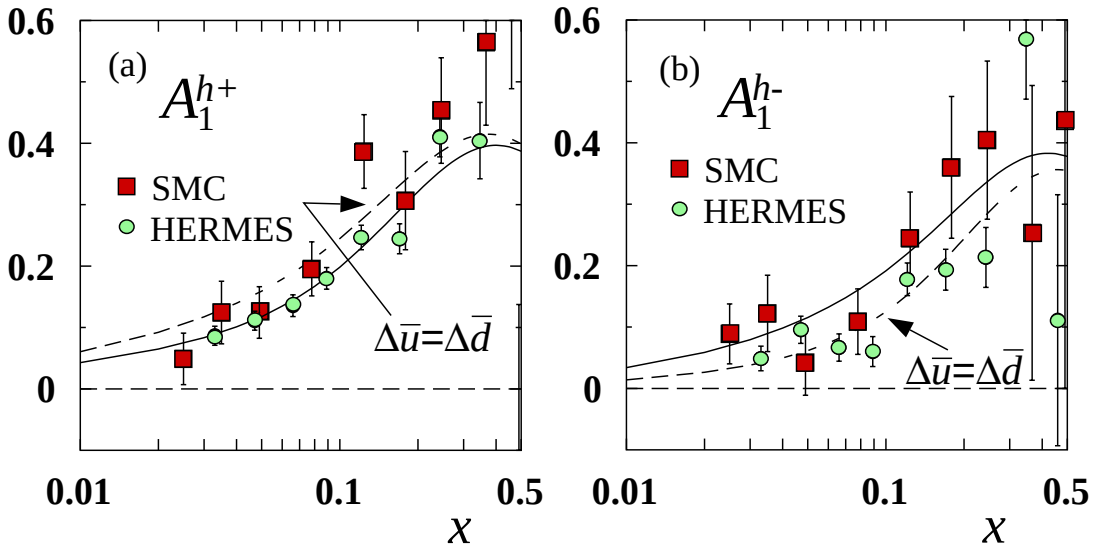
Symmetry of Polarized Sea?



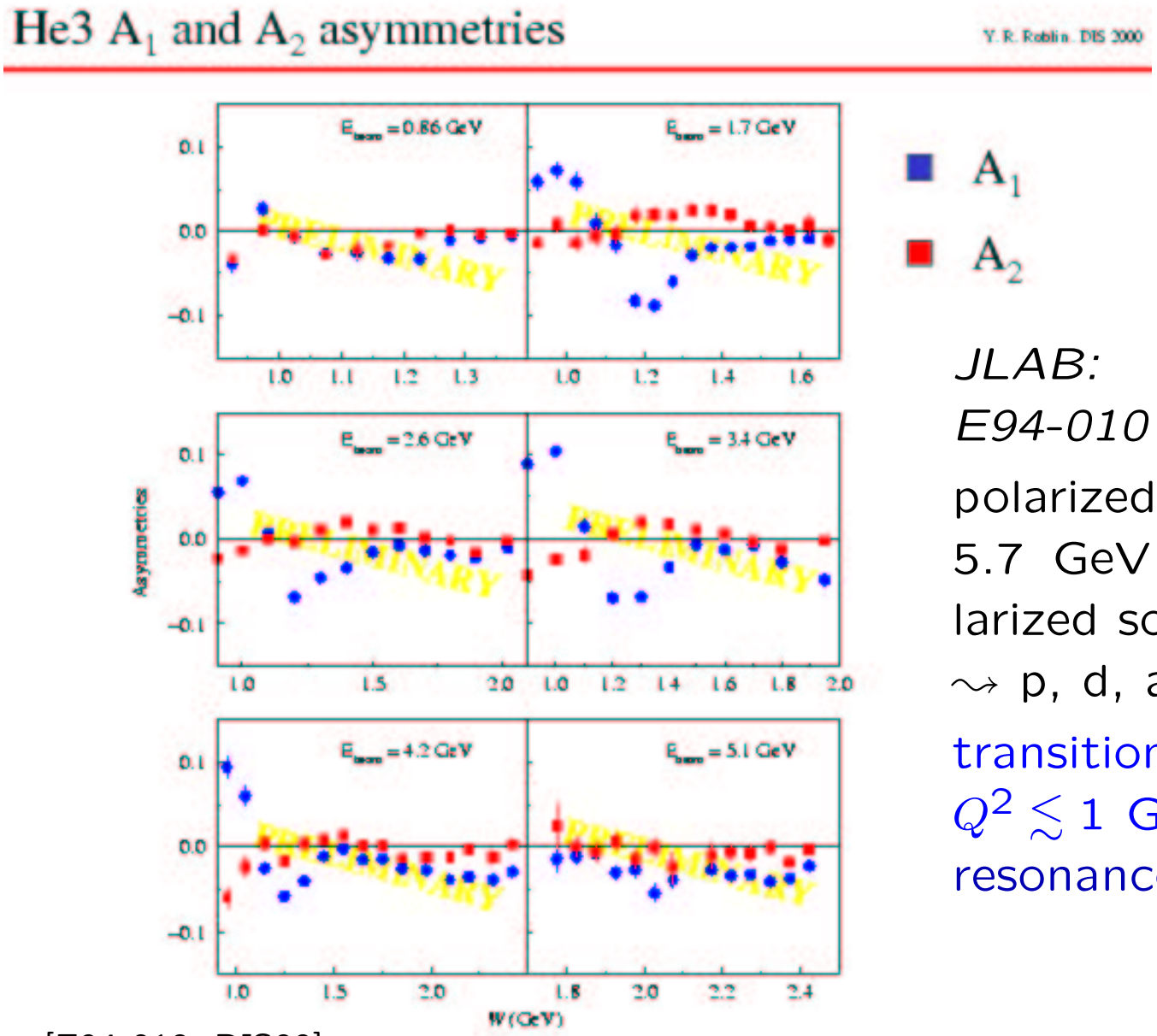
theoretical conjecture (e.g. chiral Quark-Soliton-Model) and recent pQCD fit including semi-inclusive data indicate $\Delta\bar{u} \neq \Delta\bar{d}$ as in unpolarized case

[Stratmann, Vogelsang, hep-ph/0107064]

$\rightsquigarrow$ high statistics deuteron data of HERMES being analyzed



Precision Measurements of A_1 and A_2 at Low W



[E94-010, DIS00]

JLAB: E91-023, E93-009, E94-010

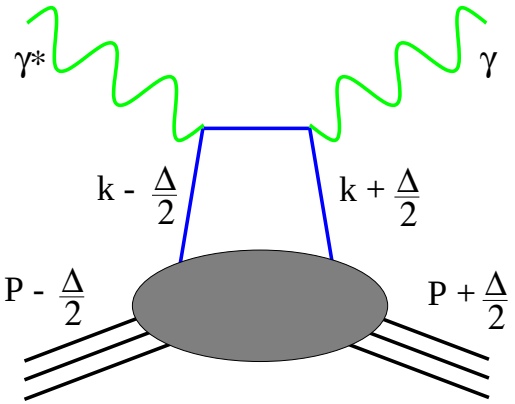
polarized electron beam 0.8-5.7 GeV ($P \sim 70\%$) and polarized solid targets

$\rightsquigarrow$ p, d, and n

transition from DIS to Low $Q^2 \lesssim 1$ GeV^2

resonance region $W \lesssim 2$ GeV

Generalized Parton Distributions and DVCS

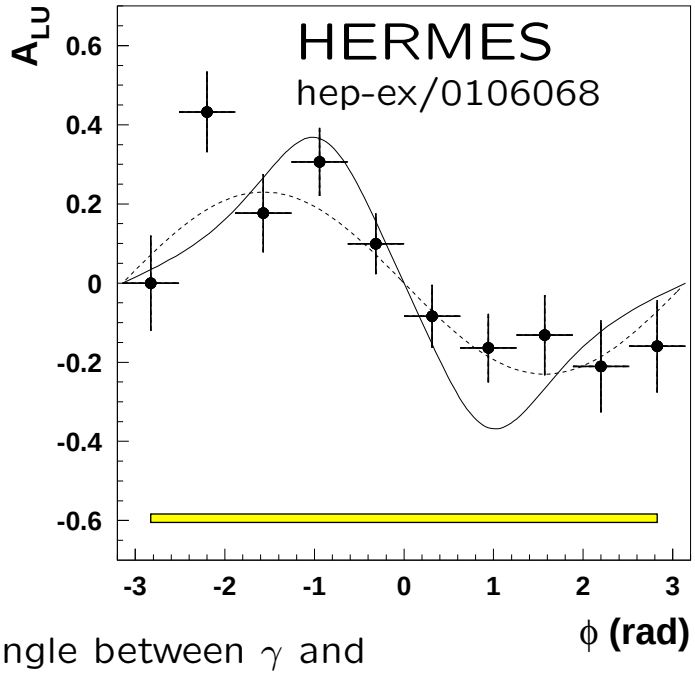


new observables in hard exclusive processes
Generalized Parton Distributions $(H, E, \tilde{H}, \tilde{E})$
related to DIS structure functions, elastic form factors and angular momentum
$J_q = \frac{1}{2}\Delta\Sigma + L_q = \frac{1}{2}\sum_q \int_{-1}^{1} x\,\mathrm{d}x(H^q + E^q)$ $[\Delta^2 = t = 0]$

reversal of beam helicity: $d\sigma_{\leftarrow} - d\sigma_{\rightarrow} \propto \mathrm{Im}(\mathrm{T_{DVCS}})\mathrm{T_{BH}}$

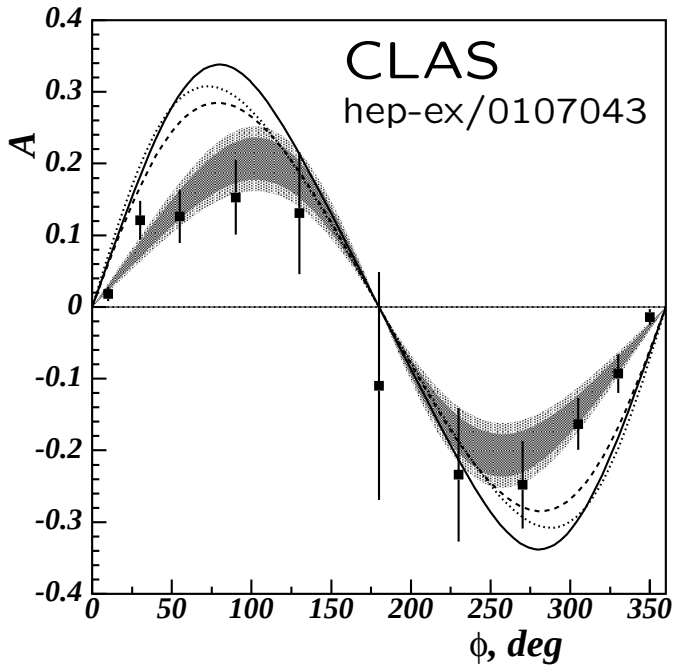
$\rightsquigarrow$ $\sin(\phi)$ dependence in LO leading twist: $A(\phi) = \alpha\,\mathrm{sign(e)}\,\sin(\phi)$

e^+: $\alpha = -0.23 \pm 0.04^{\mathrm{stat}} \pm 0.03^{\mathrm{sys}}$



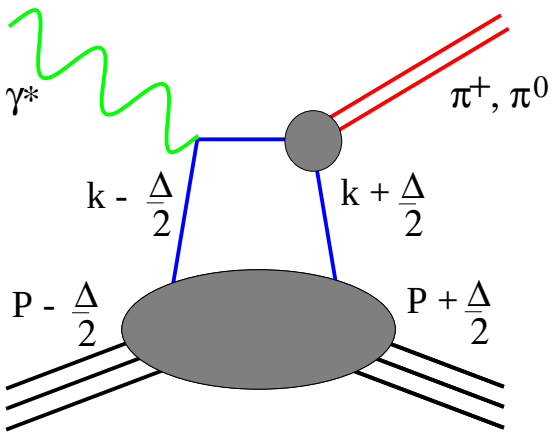
NEW

e^-: $\alpha = 0.202 \pm 0.021^{\mathrm{stat}} \pm 0.009^{\mathrm{sys}}$



ϕ: angle between γ and e scattering planes

Hard exclusive Pion Production



pseudoscalar mesons $\rightsquigarrow$ pol. GPD's $\tilde{E}$, $\tilde{H}$

reversal of transverse target spins:

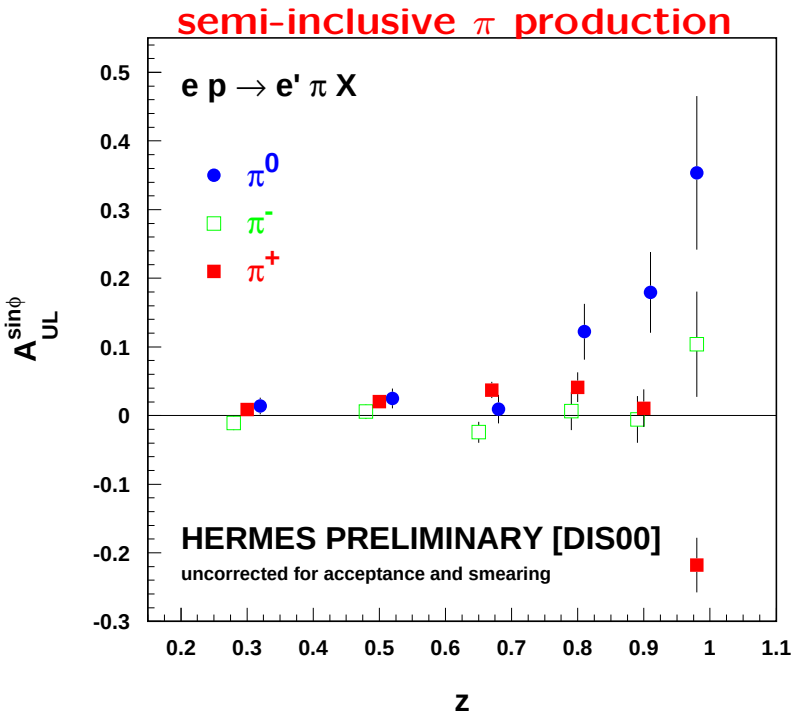
$d\sigma_{\Downarrow} - d\sigma_{\Uparrow} \sim \sin(\phi)\, \tilde{E}\, \tilde{H}$

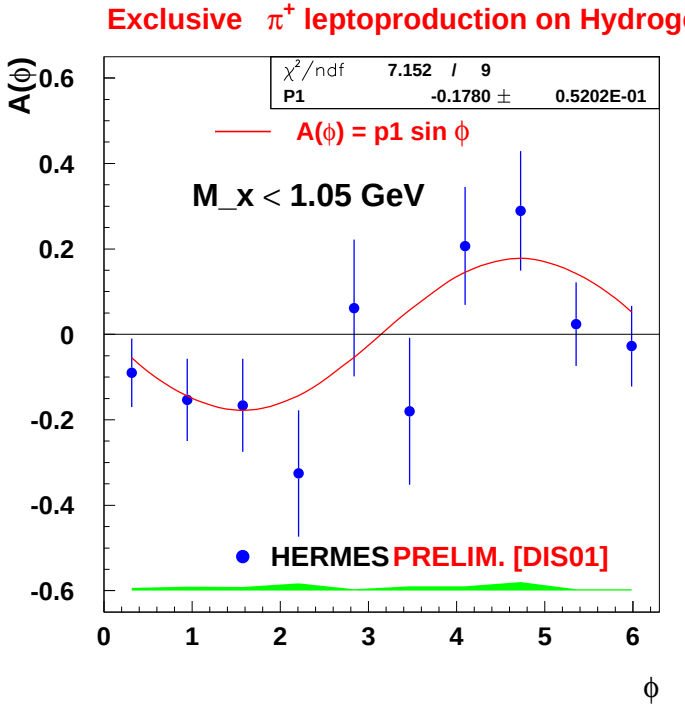
$\tilde{E}$: pion fragmentation function

$\tilde{H}$: $\rightarrow \Delta q$ in forward limit ($\Delta^2 = 0$)

$\rightsquigarrow$ large single-spin asymmetry

HERMES: long. target but transv. component w.r.t. γ^* about 20%





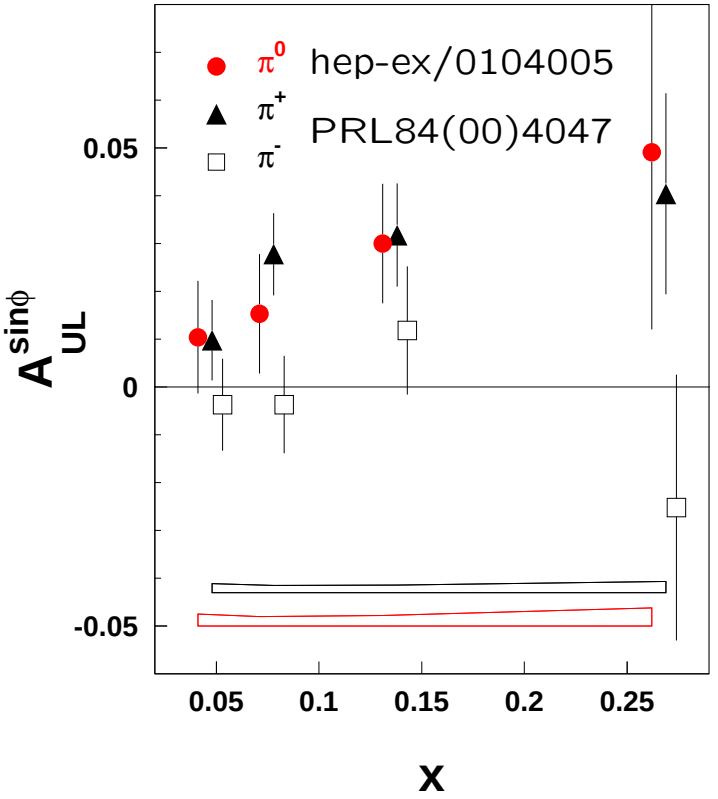
eN : HERMES RUN II $\geq$ 2001

focus: transversity distribution $h_1(x) \sim \delta q(x)$ unmeasured
first moment of $h_1(x)$ = tensor charge of nucleon
$h_1(x)$ chiral-odd: NOT accessible in inclusive DIS
BUT in processes involving another chiral-odd object
semi-inclusive DIS: fragmentation function H_1 chiral-odd

HERMES observation: single-spin azimuthal asymmetries in $e\overrightarrow{p} \rightarrow e'\pi X$ favour non-zero transversity and fragmentation functions, $A_{\rm UL}^{\sin\phi} \sim \sum_f e_f^2\, h_1^f\, H_1^f$

$\rightsquigarrow$ future measurements of δu, δd with transversely polarized targets ($H^\uparrow$, $D^\uparrow$)

furthermore:
improved measurements of ΔG, Δq, hard exclusive processes ...



μN : COMPASS $\geq$ 2001

100-200 GeV $\vec{\mu}^{\pm}$ on N$\vec{\text{H}}_3$ and $^6\vec{\text{Li}}\vec{\text{D}}$ targets, 2 fb^{-1}/y (5 $\times$ SMC)

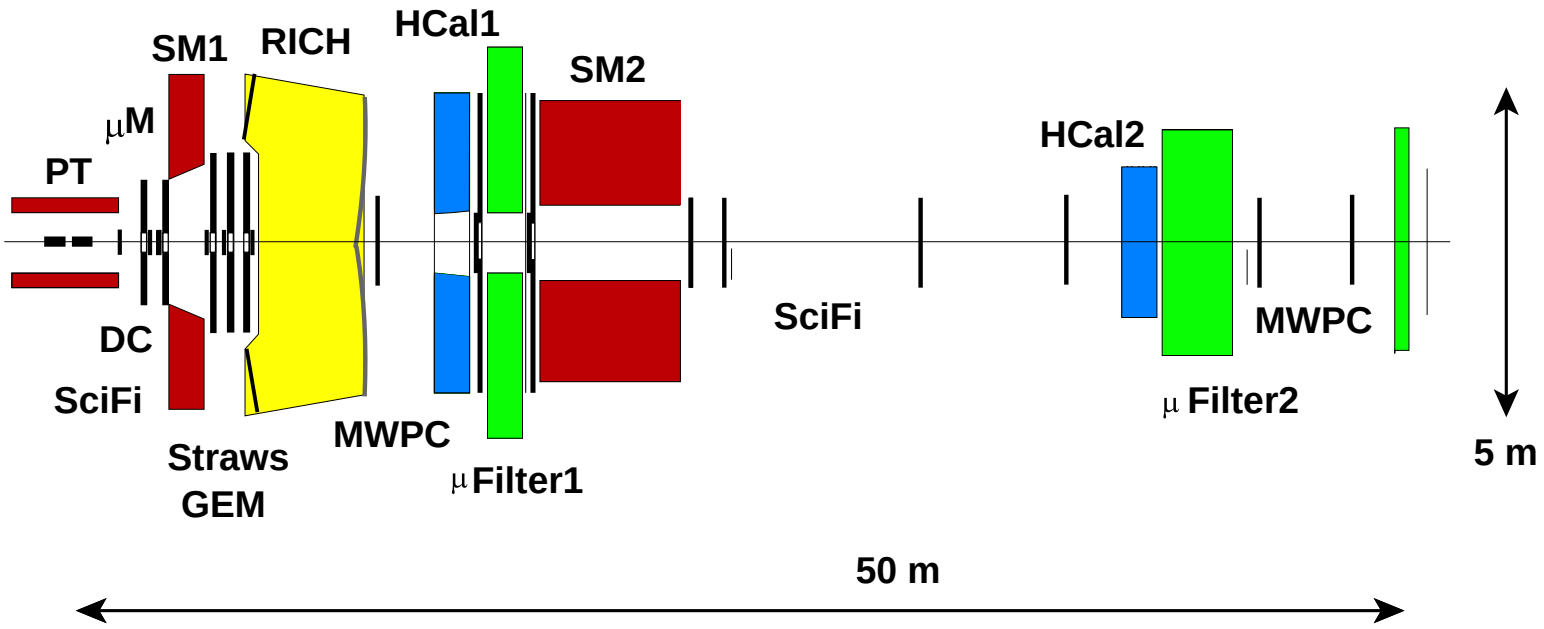
new magnetic spectrometer for hadron and spin physics

use of SMC solenoid currently limits acceptance

primary goal: $\Delta G/G$ with ~ 0.1 accuracy using

open charm or pairs of high-p_T hadrons: $0.04 < x_g < 0.3$

furthermore: measurements of Δq, g_1, h_1 ... at low x

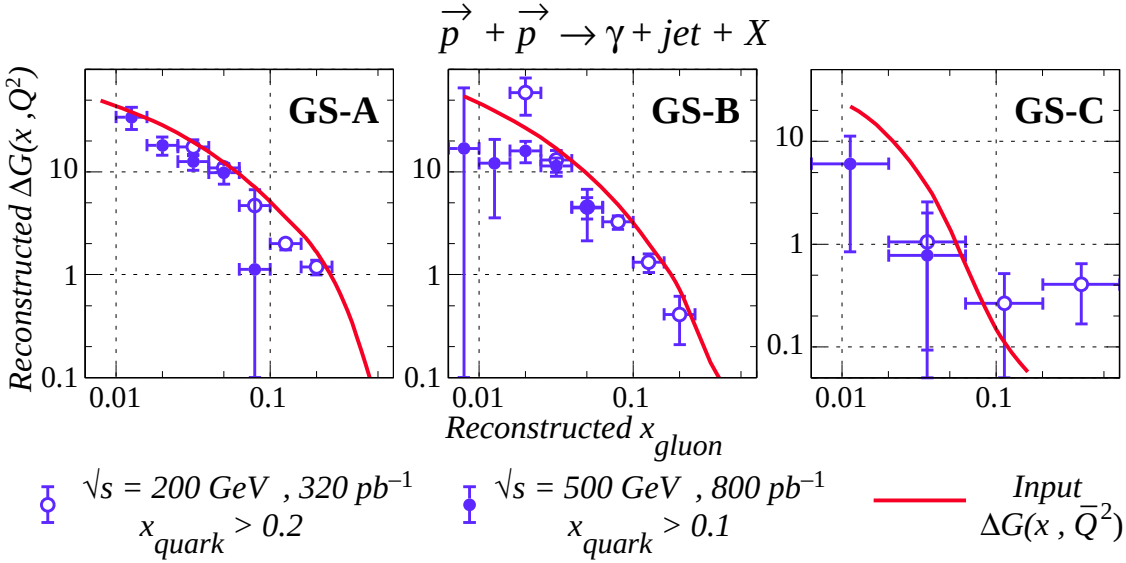


pp : STAR and PHENIX at RHIC $\geq$ 2001

$\sqrt{s} = 200$–500 GeV, luminosity $\simeq 0.3\,\mathrm{fb}^{-1}/\mathrm{y}$
polarization: 20% achieved in initial test (9/2000), design 70%

focus:

ΔG from direct photons
$qg \to \gamma q$: $0.02 < x_g < 0.3$



sea quark polarizations from $W\pm$ production asymmetries in $\vec{p}\,p$:

$u\bar{d} \to \mathrm{W}^+ \to l^+\nu$
$\sim \Delta u(x_1)/u(x_1)$
$\sim \Delta\bar{d}(x_1)/\bar{d}(x_1)$

$d\bar{u} \to \mathrm{W}^- \to l^-\nu$
$\sim \Delta d(x_1)/d(x_1)$ if $x_1 \gg x_2$
$\sim \Delta\bar{u}(x_1)/\bar{u}(x_1)$ if $x_1 \ll x_2$

Conclusion

- spin physics is an exciting and a rapidly developing field
- new data from DESY, JLAB, SLAC completes remarkably the QCD picture of the spin structure of the nucleon
  $\rightsquigarrow$ GPD's and hard exclusive processes open a window to access $L_{q,g}$ for the first time
- new and more precise data will be soon available
  $\Rightarrow$ Δq, $\Delta\bar{q}$, ΔG, δq, $\delta\bar{q}$, hard exclusive processes
  $\geq$ 2001 high luminosity experiments:
  COMPASS, HERMES, JLAB, RHIC-Spin, [SLAC-E161]
- future ($\geq$ 2006?)
  GPD's and hard exclusive processes $\leftrightarrow$ $L_{q,g}$:
  eN fixed target: *CEBAF@12 GeV, ELFE/TESLA-N*
  ΔG, Δq, g_5... at low x, high Q^2:
  eN collider: *eRHIC/EIC, pol. HERA*