Polarized Structure Functions and the Spin Structure of the Nucleon

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- Structure functions from inclusive measurements
- Polarized quark distributions: quark helicity and transversity
- Gluon polarization

CIPANP 2000, Quebec City

What elements contribute to the Spin Structure of the Nucleon?

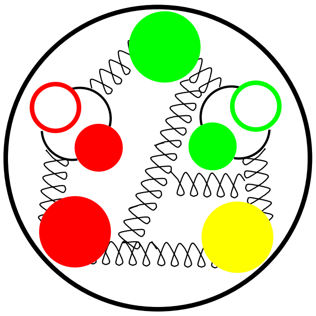
Early measurements of quark helicity:

Polarized Deep-Inelastic Scattering (DIS)

Σ quarks = 12 $\pm$ 17 %

Consistent with zero!

Nucleons have a rich structure



All partons can contribute:

Valence + sea +gluons + orb. ang. momentum = 1/2

Σ quarks $\approx$ 30% (naive rel. model $\approx$ 60%)

Discuss the status of

The Spin Structure of the Nucleon

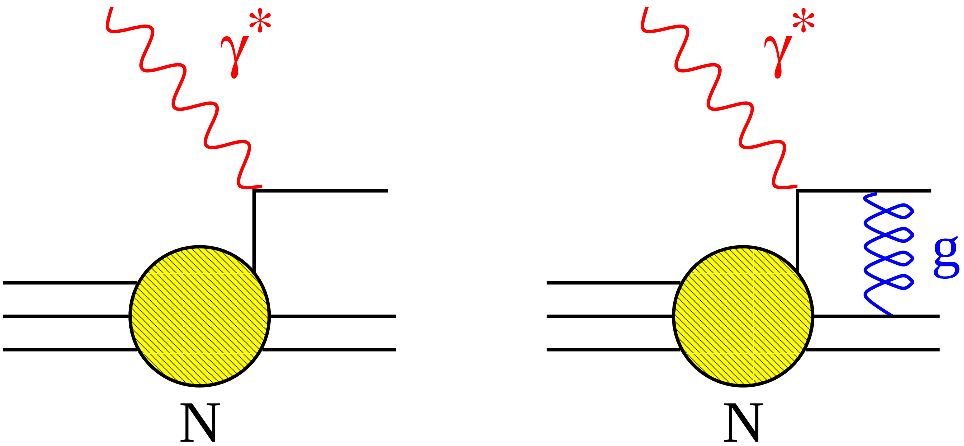
Partonic interpretation of structure

Possible to interpret nucleon structure functions using OPE

$\rightarrow$ express as a series of operators of increasing twist

$\rightarrow$ leading order in $1/Q$: twist-2

$\rightarrow$ higher twists suppressed by powers of $1/Q$



Leading twist   Higher twist

Integrating over all P_T, a quark inside the nucleon can be characterized by 3 twist-2 distributions

$$q(x), \quad \Delta q(x), \quad \delta q(x)$$

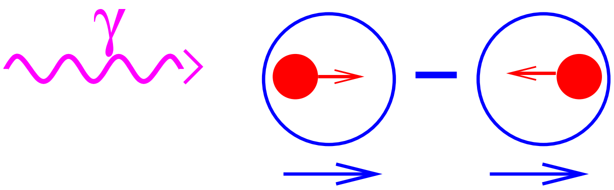
Twist-2 distributions

Quark number density: $q(x)$

$$F_1(x) = 1/2\, \Sigma_q\, e_q^2\, (q(x)+\bar{q}(x))$$

Quark helicity: $\Delta q(x)$

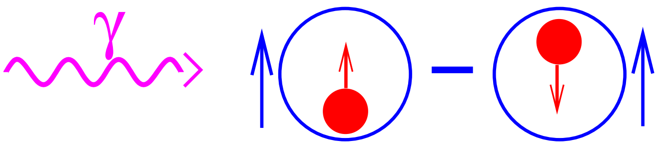
$$g_1(x) = 1/2\, \Sigma_q\, e_q^2 (\Delta q(x)+\Delta\bar{q}(x))$$



$$\Delta q(x)=(q^+(x)-q^-(x))$$

Quark transversity: $\delta q(x)$

$$h_1(x) = 1/2\, \Sigma_q\, e_q^2 (\delta q(x)+\delta\bar{q}(x))$$



NOTE:

- x is the fraction of the nucleon's momentum carried by the struck parton
- $\Delta q(x) \neq \delta q(x)$ due to relativistic and spin orbit effects
- $h_1(x)$ has never been measured (cannot be determined through inclusive DIS)

No simple QPM picture of higher-twist effects:
$\rightarrow$ sensitive to parton-parton correlations

The experiments

e/μ-N scattering

CERN: EMC, SMC

- SMC: precision low x information

SLAC: E142, E143, E154, E155, E155x

- high precision inclusive data

DESY: HERMES

- precision inclusive and semi-inclusive data

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

- test pQCD transition region

γ-N scattering

MAMI, ELSA: GDH Collaboration

- real photons

Future Experiments

e/μ-N scattering

CERN: COMPASS
- focus on ΔG

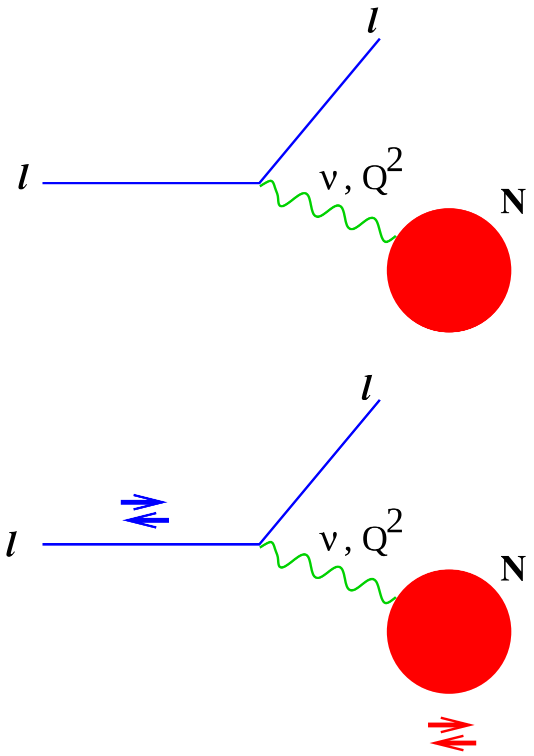
DESY: HERMES RUN2
- first measurements of transversity

JLAB: E97-103, E97-110
- test pQCD transition region

p-p Collider

RHIC: STAR, PHENIX
- probe polarized gluon and sea distributions

Inclusive lepton-nucleon scattering

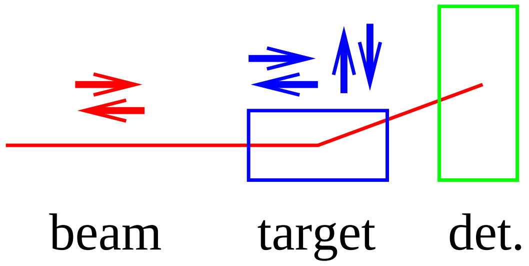


$$\frac{d\sigma}{dxdQ^2} = aF_1(x,Q^2) + bF_2(x,Q^2)$$

$$\frac{d\sigma}{dxdQ^2} = \alpha g_1(x,Q^2) + \beta g_2(x,Q^2)$$

- $\nu = \gamma^*$ energy
- $x =$Bjorken scaling variable
- $Q^2 =$ negative 4-momentum transfer squared
- $W =$ invariant mass of final hadronic system

$g_1(x)$ and $g_2(x)$ from DIS



construct σ asymmetries w.r.t. orientations of beam and target spins

Measured asymmetries:

$$A_{||} = \frac{\sigma^{\uparrow\downarrow} - \sigma^{\uparrow\uparrow}}{\sigma^{\uparrow\downarrow} + \sigma^{\uparrow\uparrow}} \quad A_{\perp} = \frac{\sigma^{\downarrow\rightarrow} - \sigma^{\uparrow\rightarrow}}{\sigma^{\downarrow\rightarrow} + \sigma^{\uparrow\rightarrow}}$$

Measured asymmetries related to the virtual photon-nucleon asymmetries: A_1 and A_2

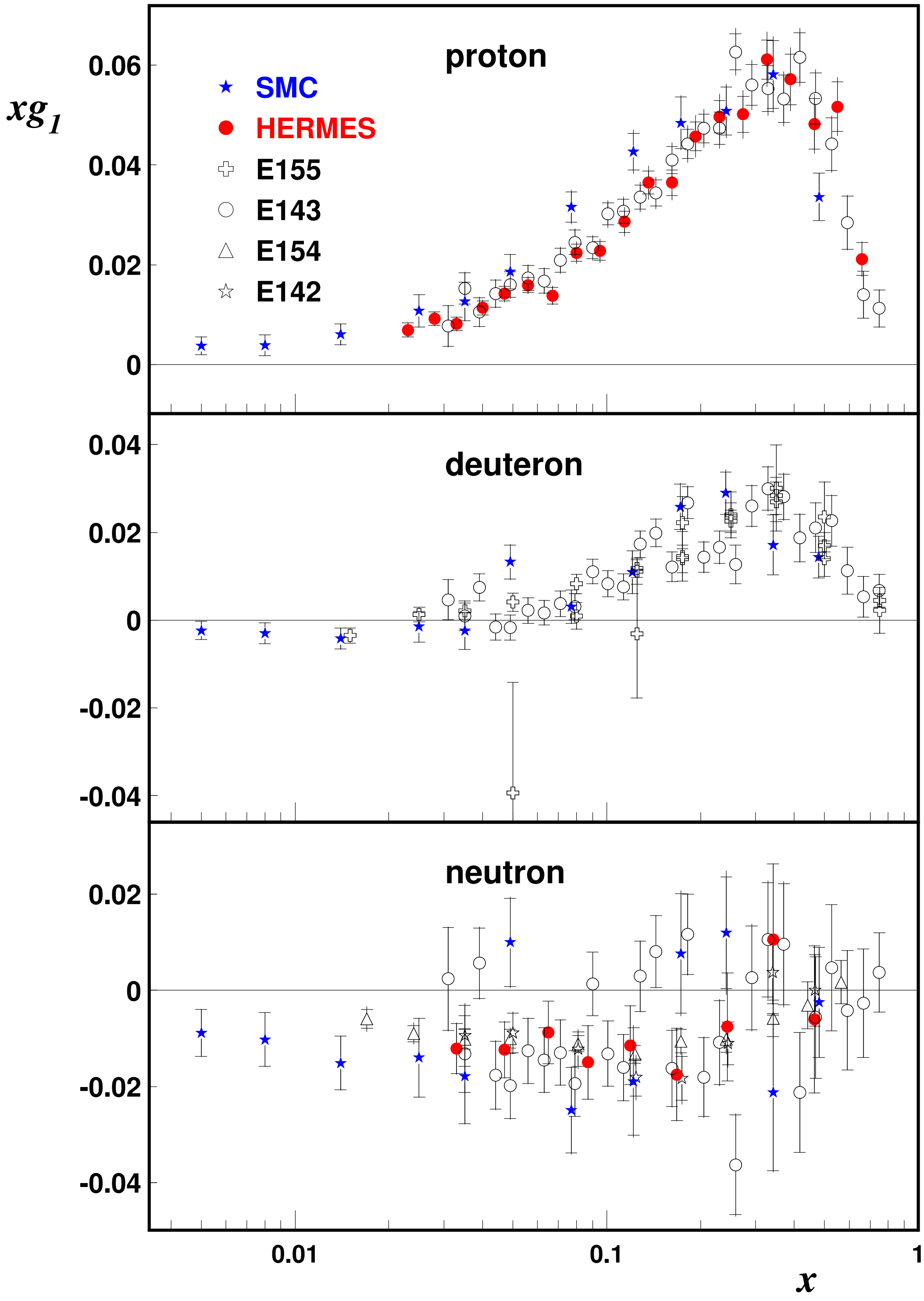
$$A_{||} = D(A_1 + \eta A_2) \quad A_{\perp} = d(\zeta A_1 + A_2)$$

η, ζ are kinematic factors
D, d are γ depolarization factors

These are related to the structure functions:

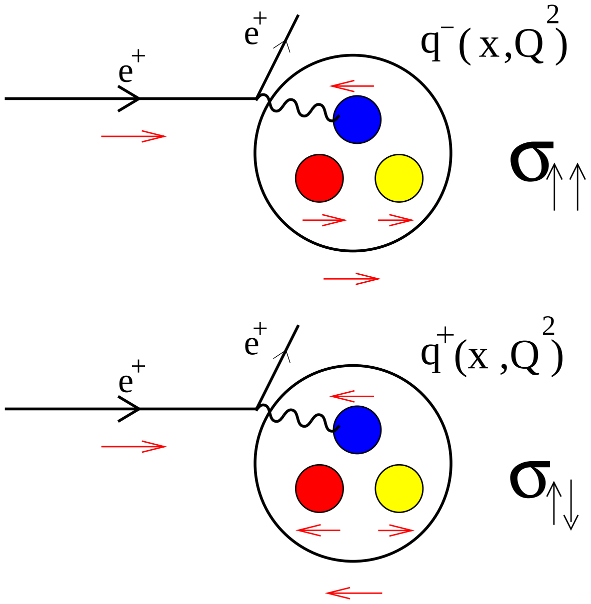
$$A_1 = \frac{(g_1 - \gamma^2 g_2)}{F_1} \quad A_2 = \frac{\gamma(g_1 + g_2)}{F_1}$$

World data on $xg_1(x)$



Given at experimental Q^2.

Partonic Interpretation



NLO QCD:

$$g_1(x,Q^2) = \frac{1}{2}\sum_q e_q^2 \Big[\Delta\Sigma \otimes (1+\frac{\alpha_s(Q^2)}{2\pi}\delta C_S)+$$
$$\Delta q_{\rm NS} \otimes (1+\frac{\alpha_s(Q^2)}{2\pi}\delta C_{NS}) + \Delta G \otimes (0+\frac{\alpha_s(Q^2)}{2\pi}\delta C_g)\Big]$$

$\Delta\Sigma = \sum_q \Delta q$, $\Delta q_{\rm NS} = \sum_q (e_q^2/\langle e^2\rangle - 1)\Delta q$
are the singlet and non-singlet quark dists.

In principle $\Delta\Sigma$, $\Delta q_{\rm NS}$, and $\Delta G(x,Q^2)$ can be uniquely determined in the DIS region due to their different Q^2 evolution.

At NLO, splitting functions, coefficient functions, and pdf's depend on normalization and factorization schemes.

- Two popular schemes: $\overline{MS}$, AB

$\longrightarrow$ main difference: whether or not axial anomaly contributes to the first moments

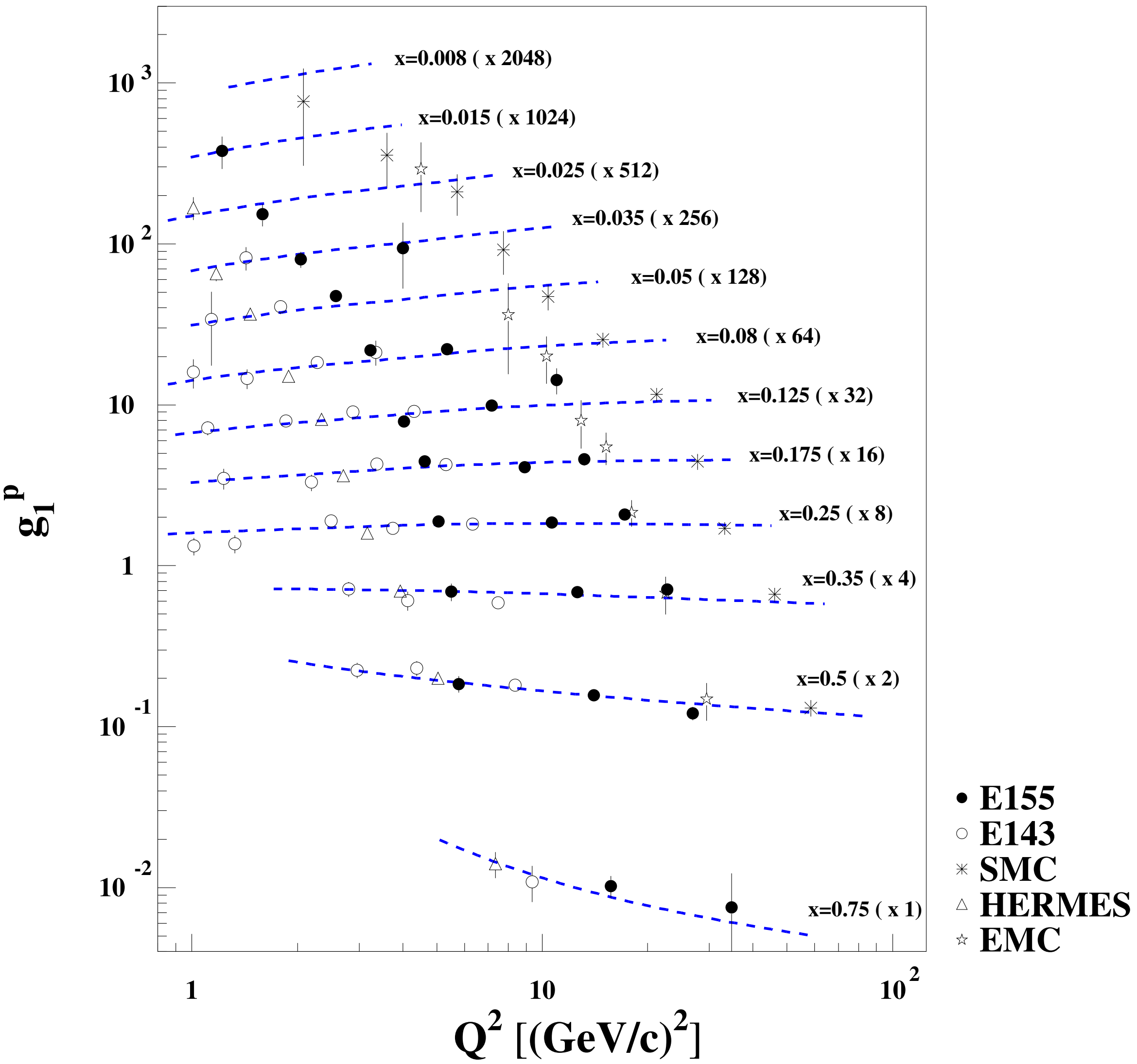
$$\Delta\Sigma_{AB} = \Delta\Sigma_{\overline{MS}}(Q^2) + N_f \frac{\alpha_s(Q^2)}{2\pi} \Delta G_{AB}(Q^2)$$

Note:
$\Delta\Sigma_{AB} = (\Delta u + \Delta\overline{u}) + (\Delta d + \Delta\overline{d}) + (\Delta s + \Delta\overline{s})$
is independent of $Q^2 \longrightarrow$ can interpret it as contribution of quark spins to the nucleon.

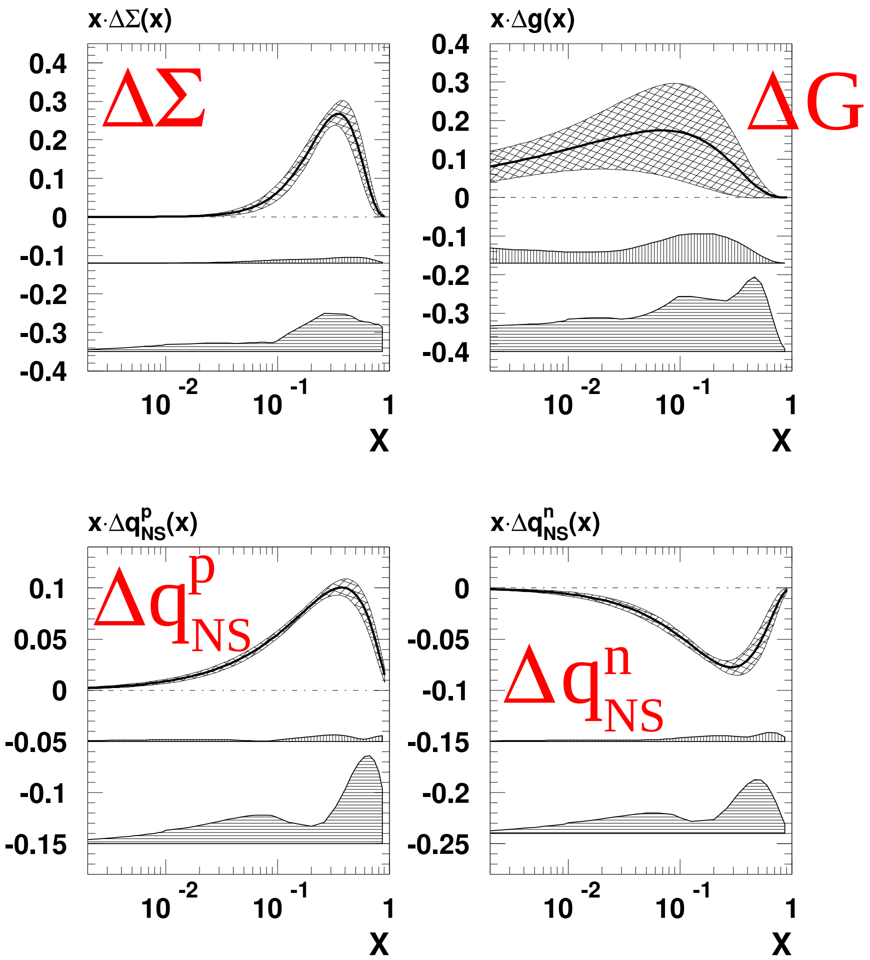
- Look at Q^2 dependence of world data on g_1

PRELIMINARY

World Data on $g_1^{\mathrm{p}}(x)$



In AB scheme



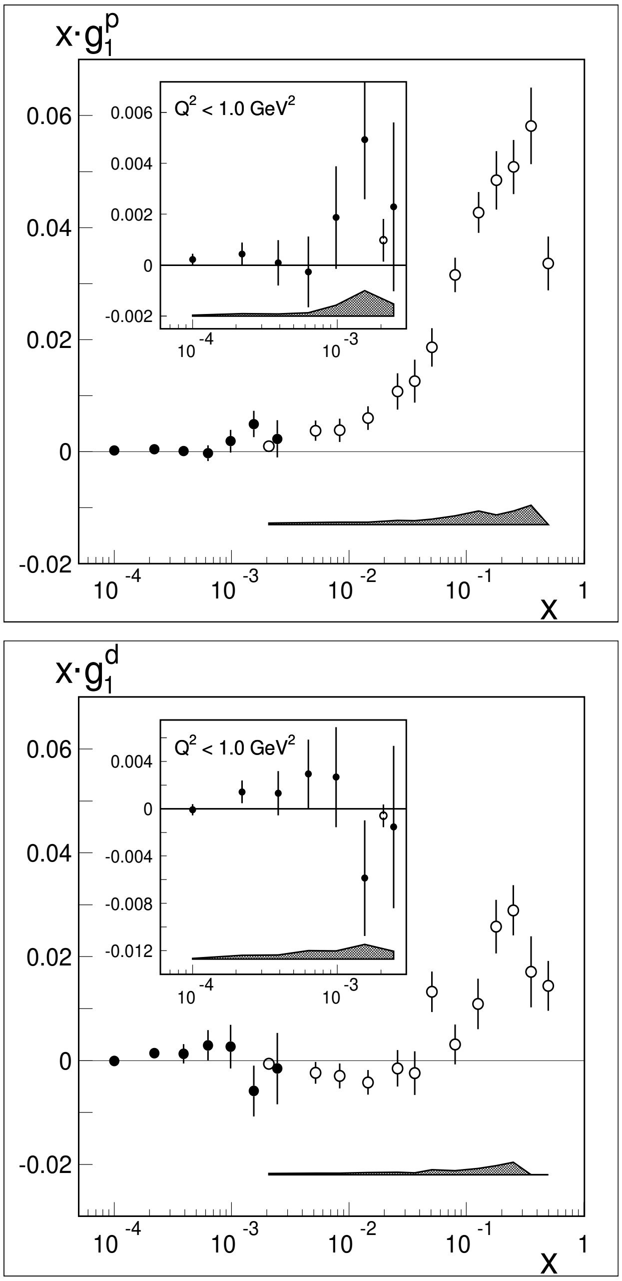
SMC, Phys.Rev.D58(1998)112002

- $\Delta\Sigma$, Δq_{NS} well determined from pQCD analysis while Δq and $\Delta\bar{q}$ separately and ΔG are not
- At $Q^2 = 1$ GeV^2:

$$\Delta G_{(AB)} = 0.99^{+1.17}_{-0.31}\,^{+0.42}_{-0.22}\,^{+1.43}_{-0.45}$$
$$\Delta\Sigma_{(AB)} = 0.38^{+0.03}_{-0.03}\,^{+0.03}_{-0.02}\,^{+0.03}_{-0.05}$$
$$\Delta\Sigma_{(\overline{MS})} = 0.19 \pm 0.05 \pm 0.04$$

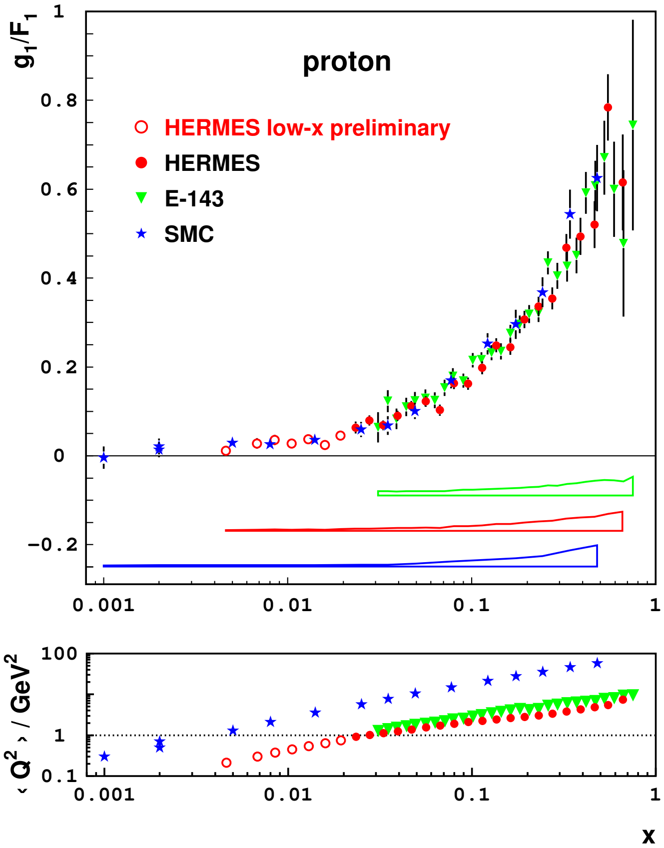
$xg_1(x)$ at low x and Q^2

SMC: $x>6\times10^{-5}$, $Q^2>0.01$ GeV^2



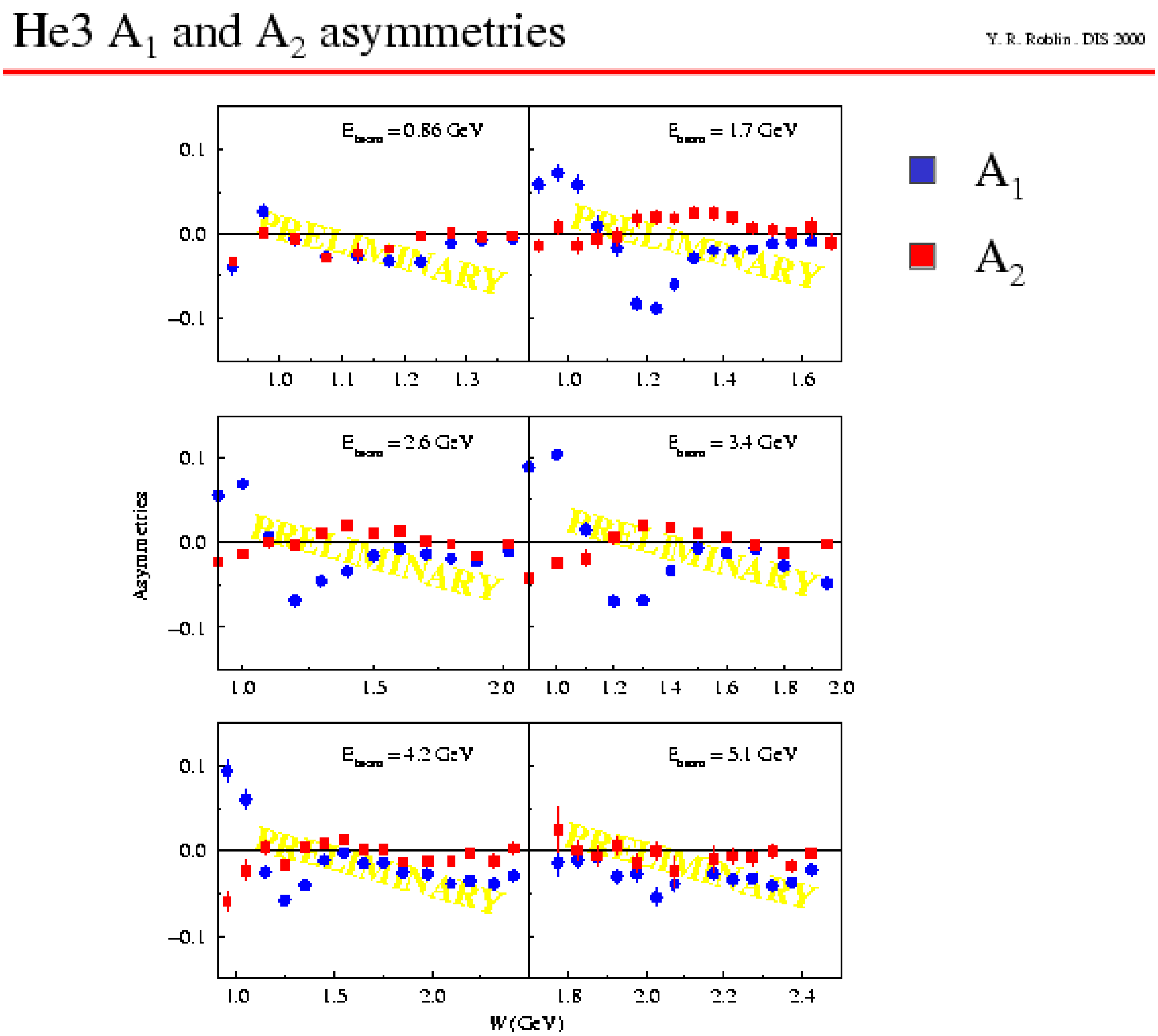
SMC, Phys.Rev.D60,072004

HERMES: $x>2\times10^{-3}$, $Q^2>0.1$ GeV^2



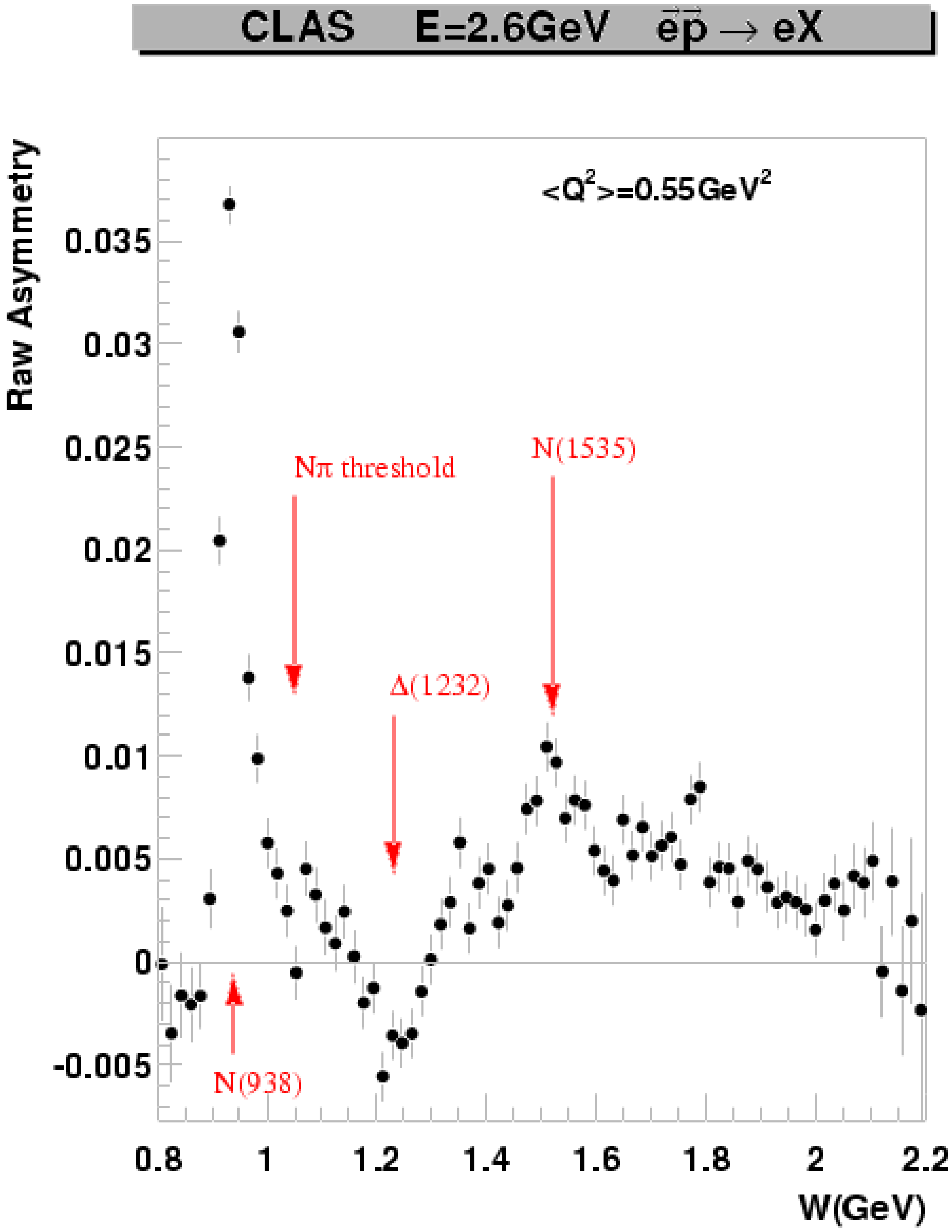
HERMES, DIS00

JLAB HALL A: resonance region



NOTE: more results on A_1 expected from JLAB within the next couple of years (at high x and also at low Q^2)

JLAB HALL B: resonance region



Gerasimov-Drell-Hearn Sum Rule

Relates anomalous contribution of the magnetic moment of the nucleon κ to helicity dependent total photoabsorption σ:

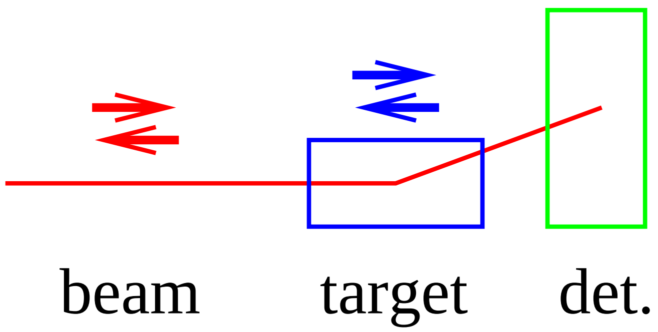
$$I = \int_{m_\pi}^{\infty} \frac{d\nu}{\nu} \left(\sigma_{3/2}(\nu) - \sigma_{1/2}(\nu)\right) = \frac{2\pi^2\alpha}{m^2}\kappa^2$$

Theoretical prediction:
$I^{proton} = 204\mu b$ $\quad$ $I^{neutron} = 233\mu b$

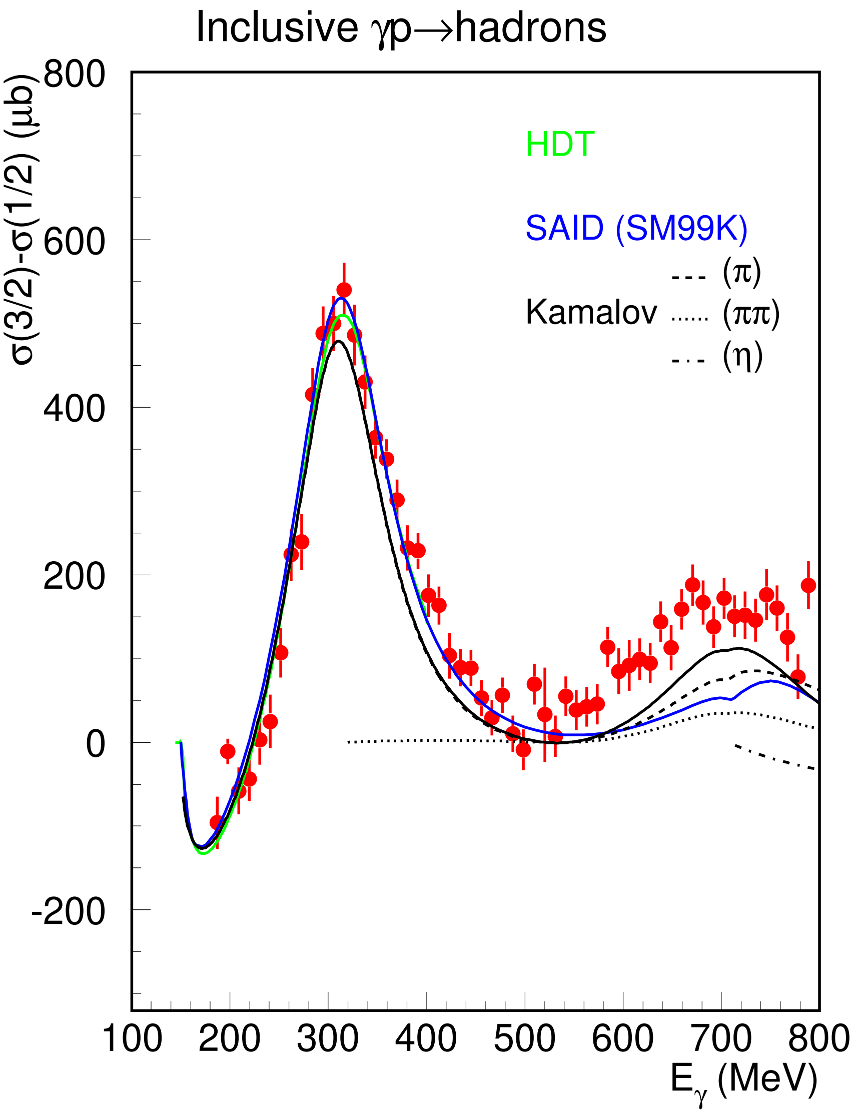
Not yet tested.

GDH Collaboration at MAMI:

- 200-800 MeV circularly pol. real γ



GDH Collaboration at MAMI



GDH Collab at MAMI, DIS00

Curves: Dispersion, Multipole (single π),

Kamalov: π, π-π, η (Phys.Rev.D59(1999)094021)

In measured region: $I^{proton} = 228 \pm 6 \mu b$

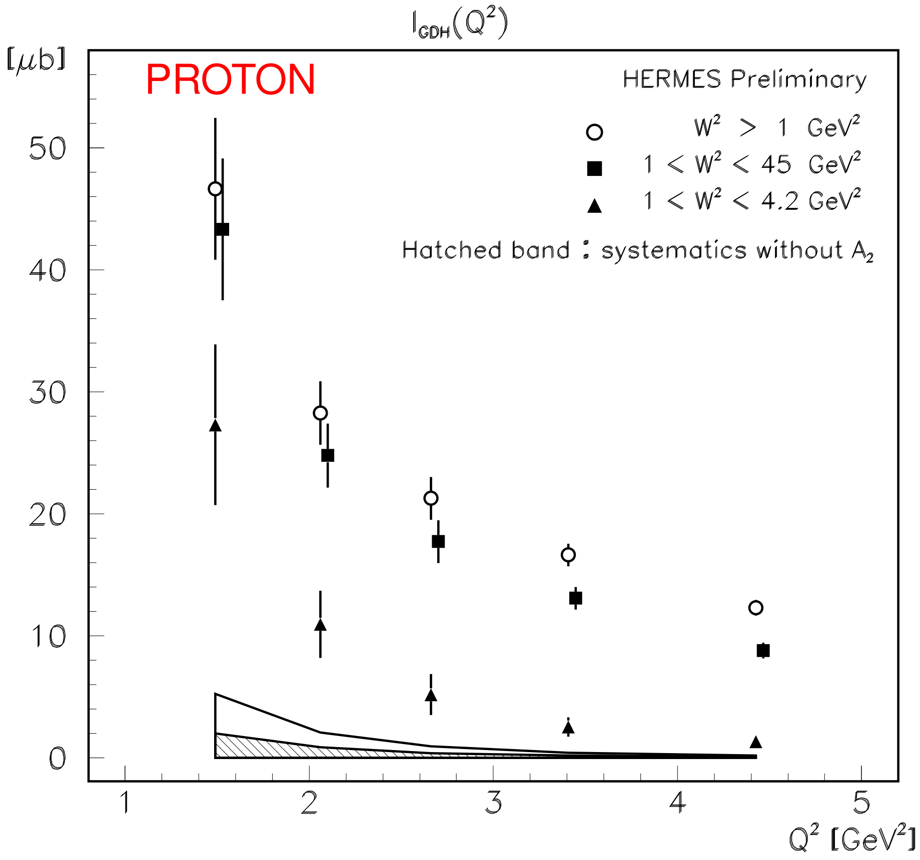
Next: Bonn accel. at ELSA E_γ=550-3400 MeV

Generalization of GDH Integral

Generalized to absorption of γ^* with ν and Q^2

$$I(Q^2) = \int_{m_\pi}^{\infty} \frac{d\nu}{\nu} \left(\sigma_{3/2}(\nu, Q^2) - \sigma_{1/2}(\nu, Q^2)\right)$$

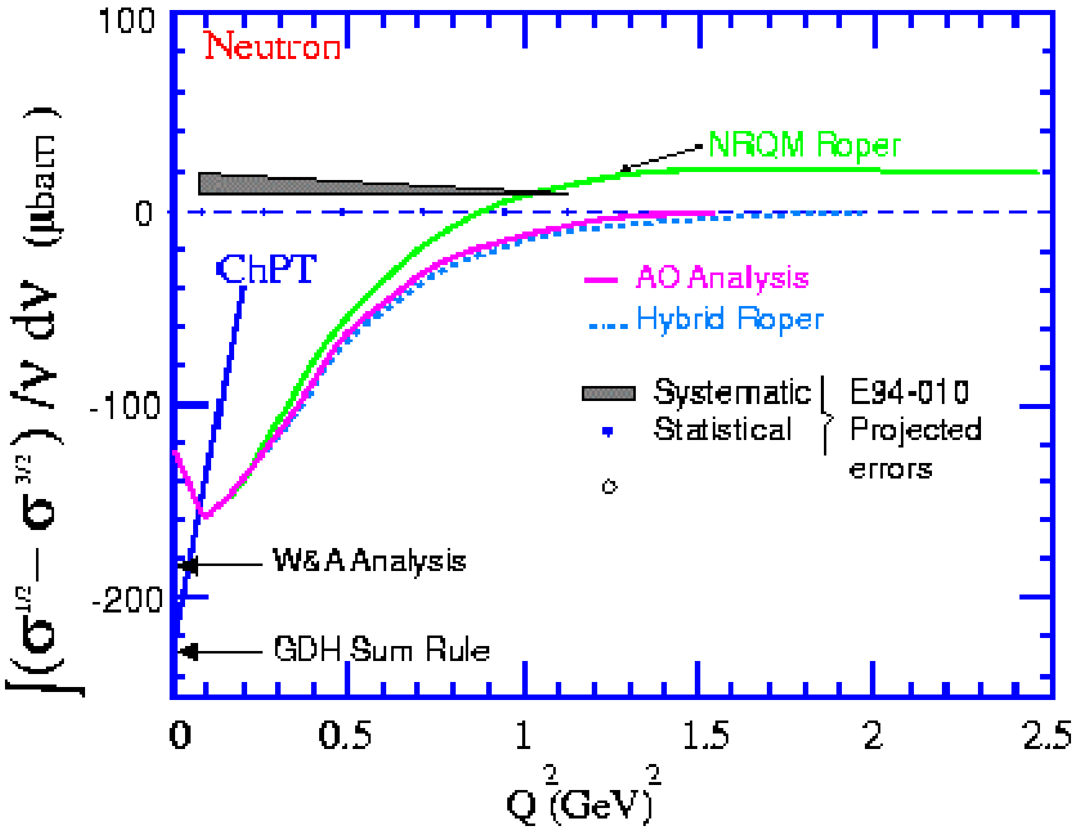
Q^2 dependence connects the static ground state properties of the nucleon with its helicity structure as measured in the resonance and DIS regions.



HERMES, DIS00

- sharp turn-over expected for $Q^2 < 1$ GeV^2

GDH in the Resonance Region

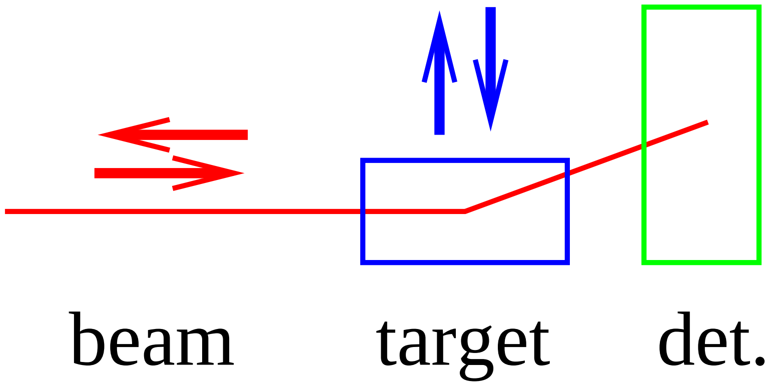


JLAB E94-010, DIS00

More data to come from JLAB: 2000-1
More data to come from HERMES: 2000

$\boxed{g_2(x,Q^2)}$

Longitudinally polarized beam on a transversely polarized target: $\vec{e}\vec{N} \to eX$



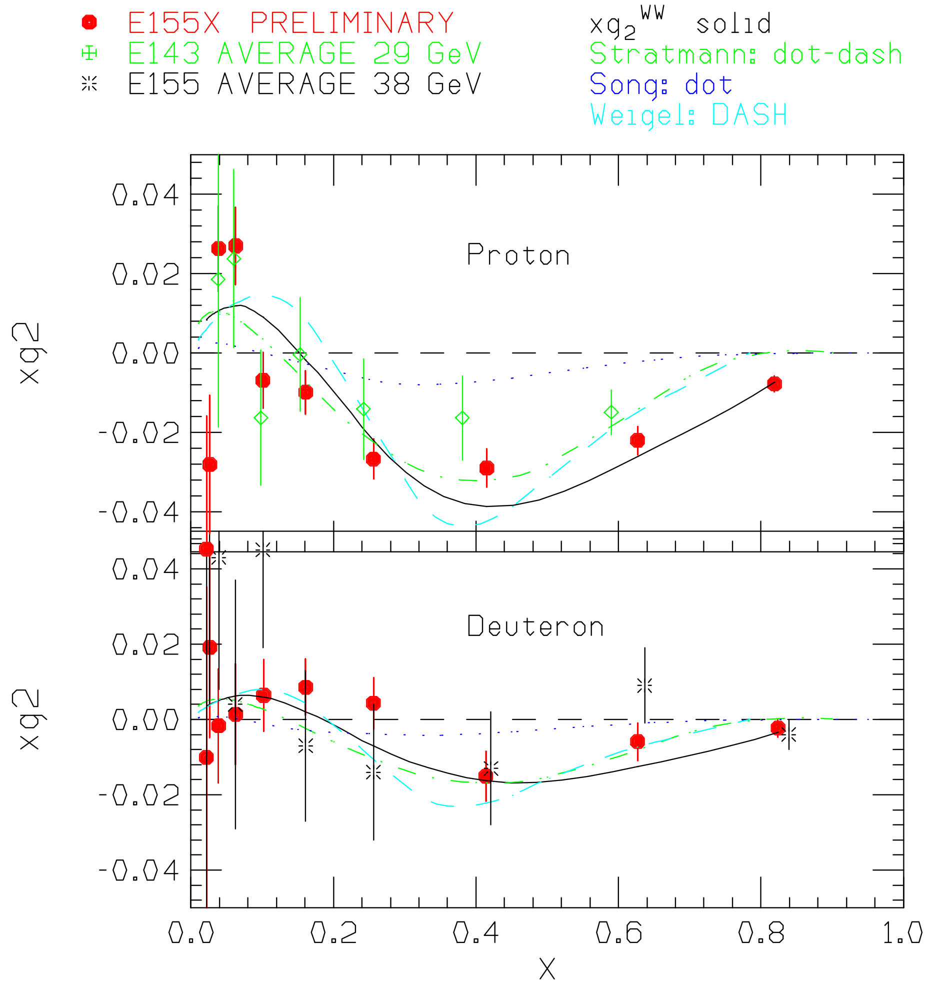
No simple QPM picture for g_2 but sensitive to higher twist effects

$$g_2(x,Q^2) = \underbrace{g_2^{WW}(x,Q^2)}_{\text{twist 2: } \propto g_1(x)} + \underbrace{\overline{g}_2(x,Q^2)}_{\text{mostly twist 3}}$$

Higher twist effects can be seen as deviations in $g_2(x,Q^2)$ from $g_2^{WW}(x,Q^2)$

RESULT: $g_2(x, Q^2)$ from SLAC E155x

E155x: 29 GeV, 32 GeV $\vec{e}$ on $\vec{p}, \vec{d}$



E155x, 1999 Europhysics Conference

- no evidence for higher twist effects
- no significant Q^2 dependence seen

Upcoming experiment:

- JLAB E97-103: (g_2^n) $0.14 < x < 0.22$ and $0.6 < Q^2 < 1.5$ GeV/c^2

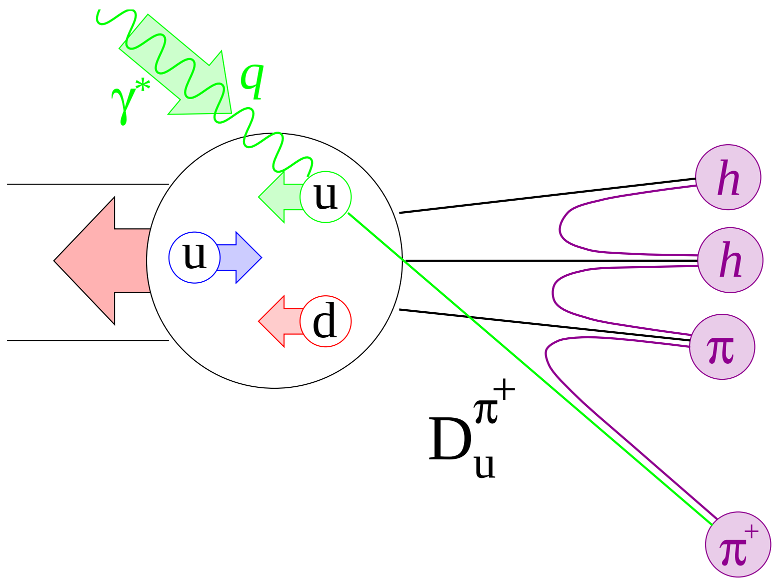
Polarized quark distributions: Δq, δq

Semi-inclusive DIS$\longrightarrow$ flavor separation of polarized quark distributions $\longrightarrow$ flavor tagging.

- lepton and nucleon pol: unpolarized (U), longitudinal (L), transverse (T)
- flavor of the leading hadron related to that of the struck quark via fragmentation functions

  - $D_q^h(z)$: unpolarized fragmentation function
  - $H_1^{\perp}(z)$: transverse polarization frag. func.

z is fraction of the γ's energy carried by h



$\boxed{\textbf{L on L} \rightarrow \Delta q(x), D_q^h(z)}$

Longitudinally polarized leptons on a longitudinally polarized target.

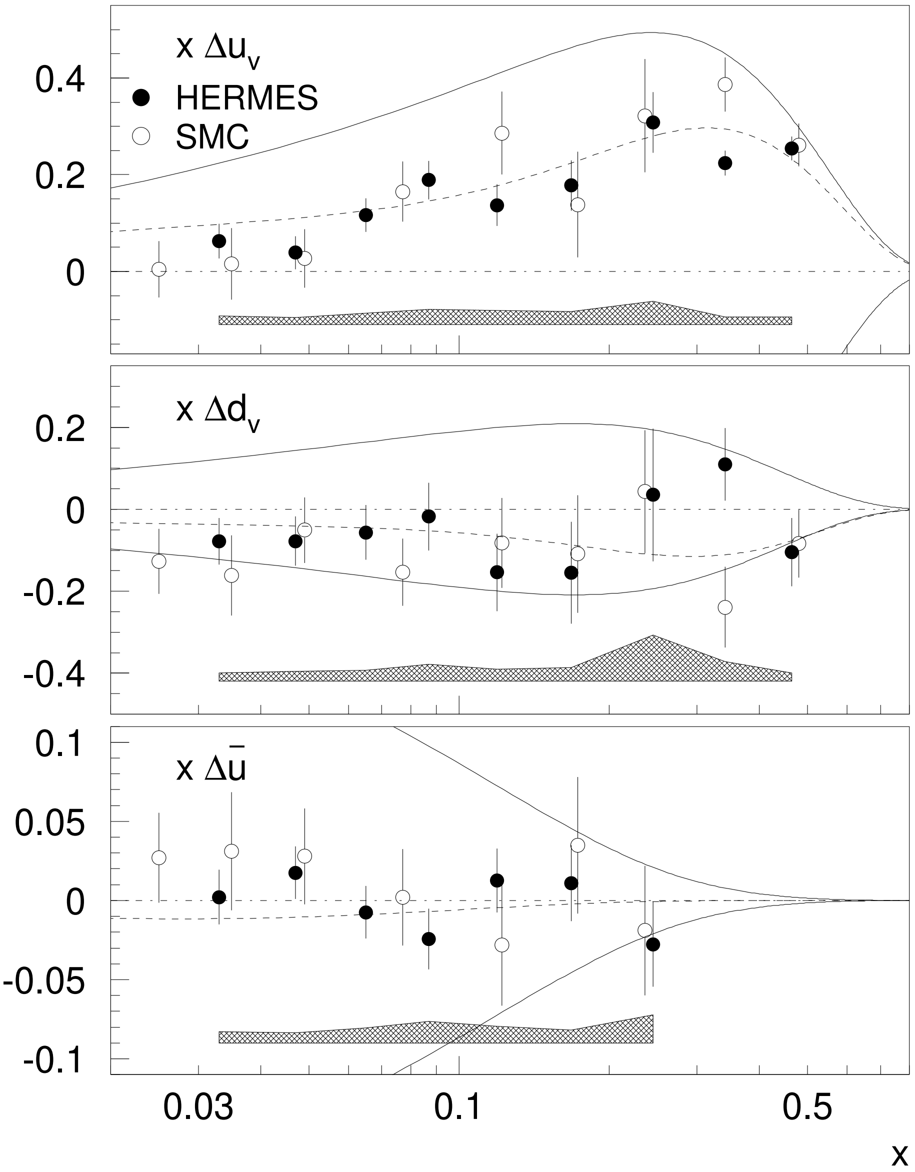
In LO QCD:

$$A_{||}^h = \frac{N^{\uparrow\downarrow} - N^{\uparrow\uparrow}}{N^{\uparrow\downarrow} + N^{\uparrow\uparrow}} \propto \frac{\sum_q e_q^2 \Delta q(x) D_q^h(z)}{\sum_q e_q^2 q(x) D_q^h(z)}$$

Asymmetry can be decomposed into

- unpolarized distributions $\left(D_q^h(z), q(x)\right)$
  $\rightarrow$ other experiments and Monte Carlo
- polarized distributions: $\Delta q(x)$

Results: HERMES and SMC on Δq



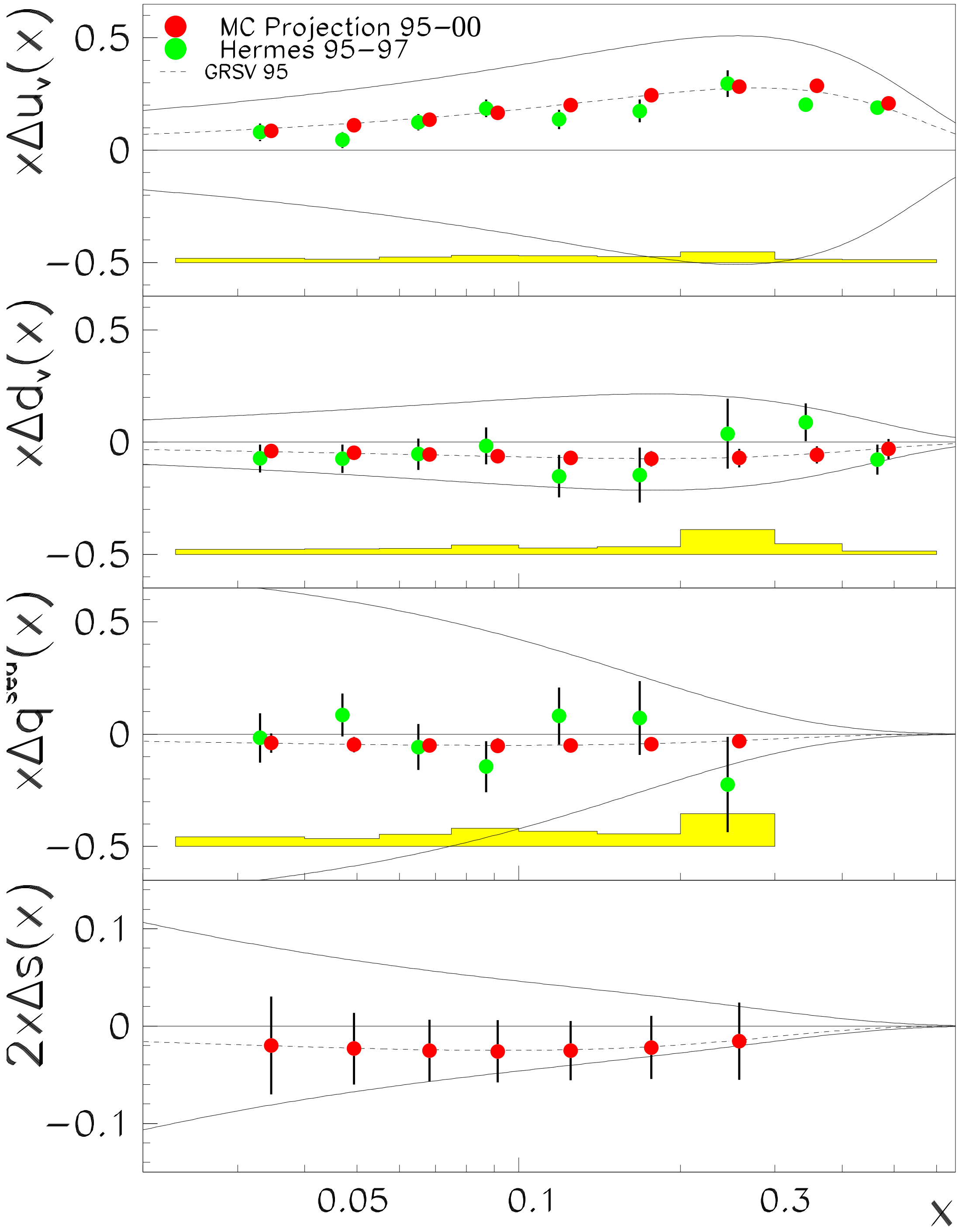
SMC, and HERMES, Phys.Lett.B464(1999),123

- The polarized quark sea is not yet constrained. Assumptions used:

HERMES: $\frac{\Delta u}{u} = \frac{\Delta d}{d} = \frac{\Delta s}{s} = \frac{\Delta \overline{u}}{\overline{u}} = \frac{\Delta \overline{d}}{\overline{d}} = \frac{\Delta \overline{s}}{\overline{s}}$

SMC: $\Delta u = \Delta d = \Delta s = \Delta \overline{u} = \Delta \overline{d} = \Delta \overline{s}$

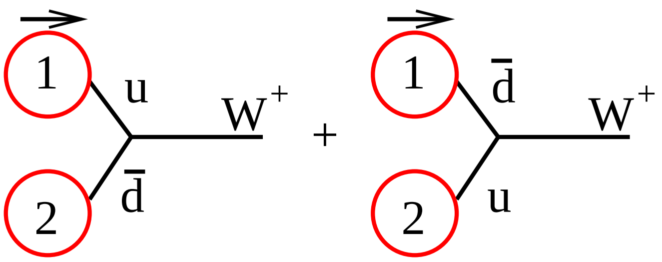
NOTE: HERMES new dataset (1998-2000) will better constrain the polarized sea:



HERMES RUN2 will add to this precision.

Polarized sea with RHIC-Spin: $p\vec{p} \rightarrow W^{\pm}$

Consider $\vec{p}_1 p_2 \rightarrow W^+$:



For $x_1 >> x_2$:

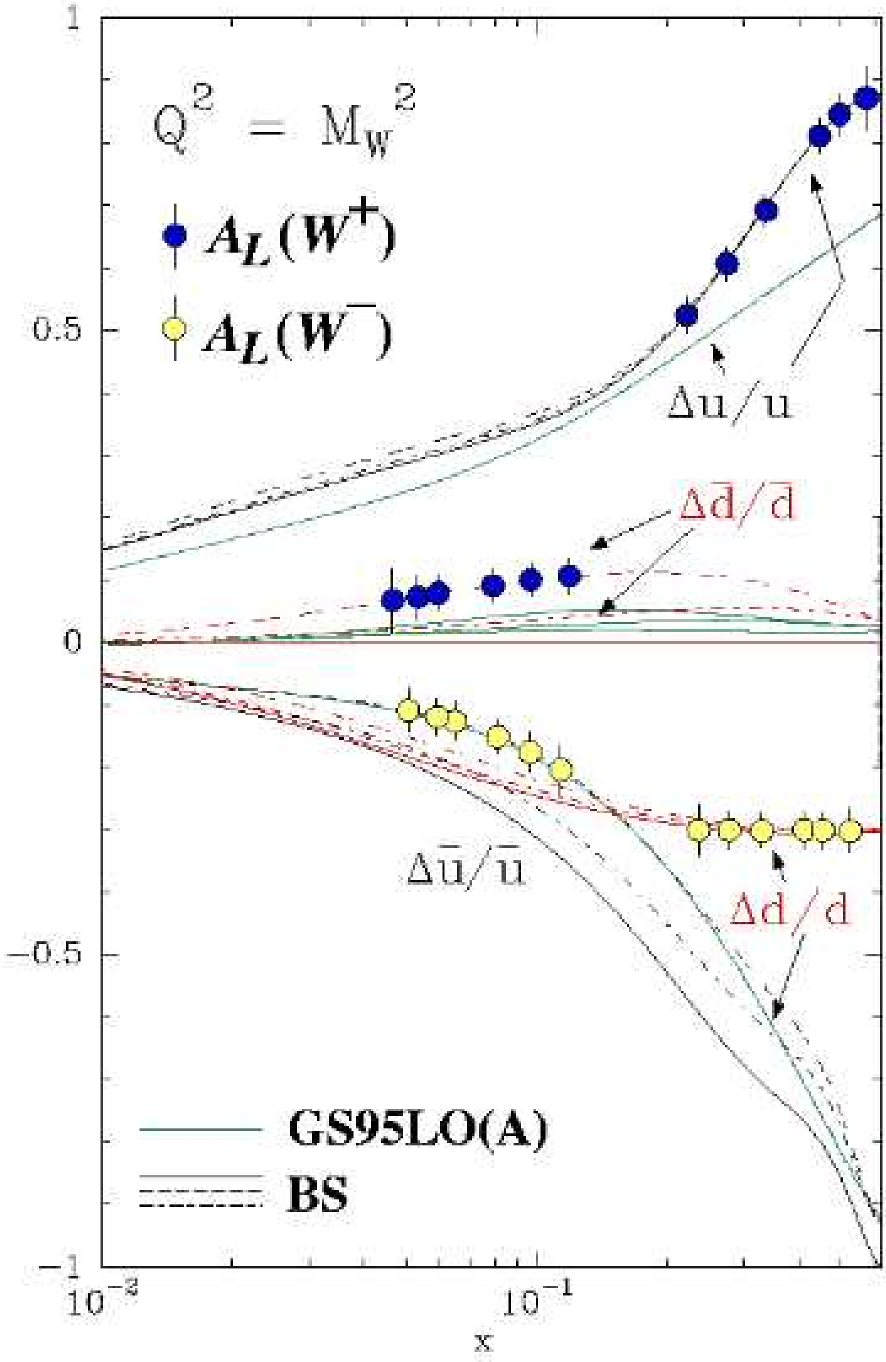
$\Delta\overline{d}(x_1) \approx 0$

$\rightarrow$ get$\Delta u(x_1)$

$$A_L^{W^+}(\vec{p}_1 p_2) \rightarrow \frac{\Delta u(x_1)}{u(x_1)},\ A_L^{W^+}(p_1 \vec{p}_2) \rightarrow \frac{\Delta\overline{d}(x_1)}{d(x_1)}$$
$$A_L^{W^-}(\vec{p}_1 p_2) \rightarrow \frac{\Delta d(x_1)}{d(x_1)},\ A_L^{W^-}(p_1 \vec{p}_2) \rightarrow \frac{\Delta\overline{u}(x_1)}{u(x_1)}$$

In practice, get linear combinations of quark distributions

PHENIX Sensitivity



STAR will have comparable sensitivity.

U on T $\rightarrow \delta q(x), H_1^{\perp}(z)$

Unpolarized leptons on a transversely polarized target

Transversity distributions $\delta q(x)$ can be accessed via the spin dependence of the azimuthal distribution of the leading pion (Collins' effect)

$$A_{\perp}^{h} \propto \frac{\langle \sin\phi_c (N^{\downarrow} - N^{\uparrow}) \rangle}{N^{\downarrow} + N^{\uparrow}} \propto \frac{\sum_q e_q^2 \delta q(x) H_1^{\perp(1),q}(z)}{\sum_q e_q^2 q(x) D_q^h(z)}$$

ϕ_c = Collins' angle = difference in the azimuthal angle of final hadron and final quark's spin.

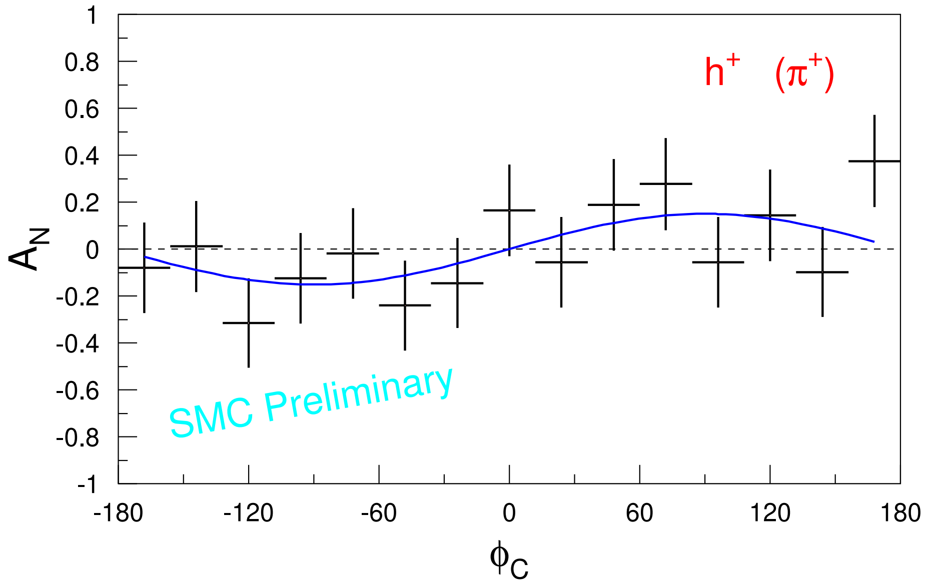
J. Collins, Nucl.Phys.B396(1993),161

RESULTS: SMC transversity

Tranversely polarized protons and deuterons

$$A_N = \frac{1}{P_t f D_n n} \frac{1}{< \sin\phi_c >} \left[\frac{N(\phi_c) - N(\phi_c + \pi)}{N(\phi_c) + N(\phi_c + \pi)} \right]$$

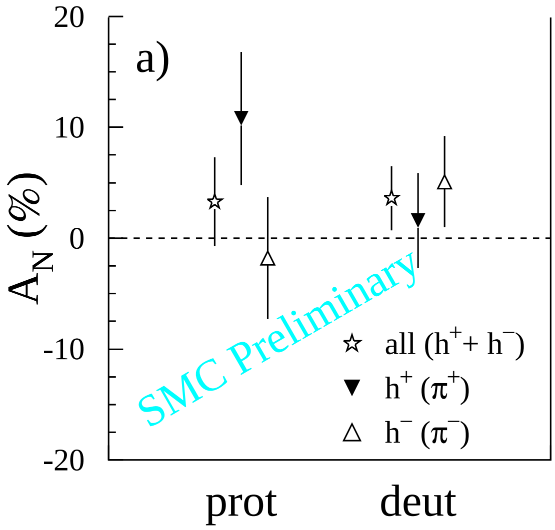
$$d\sigma \sim (1 + A_N \sin\phi_c) d\phi_c$$



$A_N^{\pi^+} = 0.11 \pm 0.06$

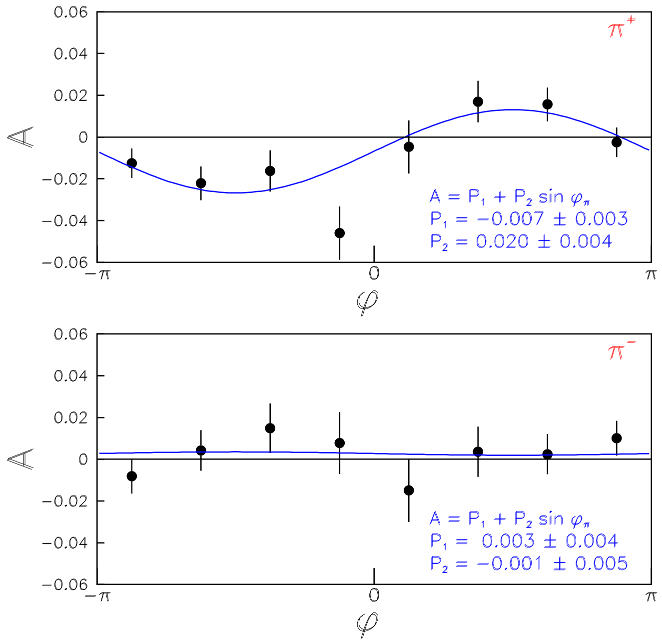
$A_N^{\pi^-} = -0.02 \pm 0.06$

SMC, DIS99

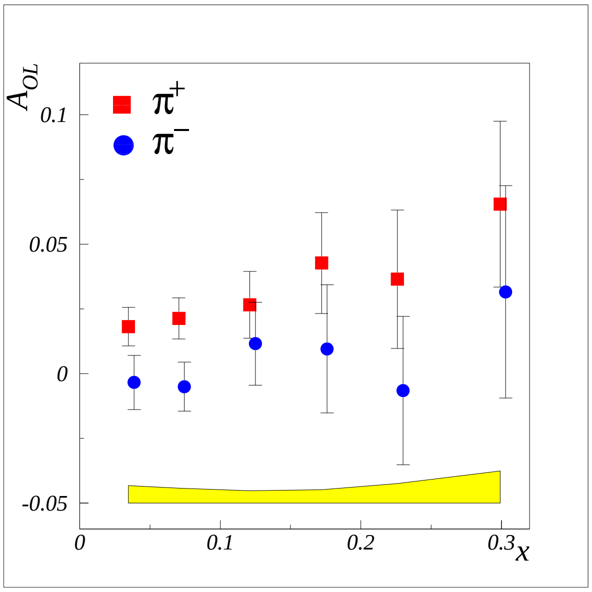


RESULTS: HERMES transversity

Single spin asymmetry with long. polarized target also sensitive to $\delta q(x) H_1^{\perp(1),q}(z)$



$\sin\phi$ moment of the asymmetry vs x:



- π^+, π^- diff. predicted by Collins
- sea quarks do not appear to play a significant role

HERMES, PRL84(2000)4047

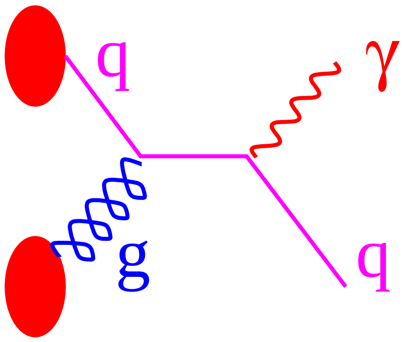
Future of transversity

- SIDIS with transverse targets
  - HERMES experiment at DESY
  - COMPASS experiment at CERN
- p-p collisions with transversely polarized beams
  - RHIC-Spin (STAR, PHENIX) at BNL:

$$A_{TT}^{DY} \propto \frac{\sum e_q^2 \delta q(x_1)\delta q(x_2) + (2 \leftrightarrow 1)}{\sum e_q^2 q(x_1) q(x_2) + (2 \leftrightarrow 1)}$$

ΔG via direct γ production: RHIC

$$\vec{p}\vec{p} \rightarrow \gamma + jet + X$$



Long. pol. p, p: $P_b = 70\%$

$\sqrt{s} = 200, 500$ GeV

- identify isolated large P_T γ + away-side jet: enables initial state partonic kinematics to be reconstructed

If qg compton dominates:

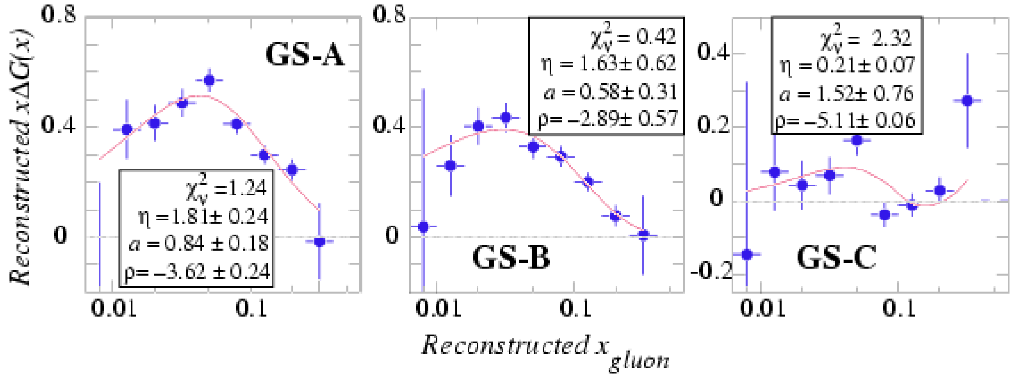
$$A^{qg \rightarrow \gamma q} \propto \frac{\Delta G(x_g, Q^2)}{G(x_g, Q^2)} A_1^p(x_q, Q^2)$$

Note: large background from $\pi^o \rightarrow \gamma\gamma$

Projections: RHIC ΔG

STAR sensitivity to ΔG based on 20 weeks:

$$\vec{p} + \vec{p} \rightarrow \gamma + jet + X \quad \begin{cases} \sqrt{s} = 200 \text{ GeV}, \ 320 \text{ pb}^{-1} \\ \sqrt{s} = 500 \text{ GeV}, \ 800 \text{ pb}^{-1} \end{cases}$$



GS-A,B,C models of $x\Delta G(x)$ from Gehrmann and Stirling, PR **D53**, 6100 (1996).

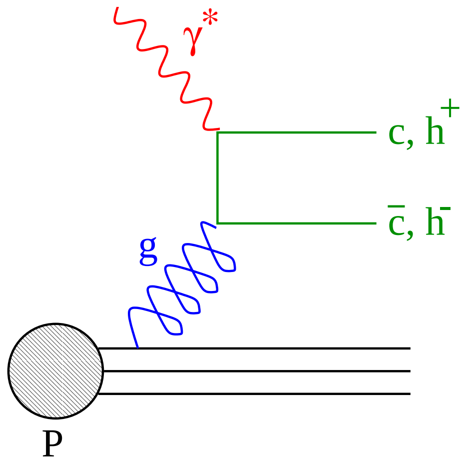
Fit $x\Delta G(x) = \eta A\, x^a\, (1-x)^b\, [1 + \rho x^{1/2} + \gamma x]$, *with*
b and γ *fixed to determine integral* ΔG (η).

L. Bland, Proceedings, Circum-Pan Pacific RIKEN, Nov. 99

- need both $\sqrt{s} = 200$ GeV and $\sqrt{s} = 500$ GeV to cover this x range
- large x behavior of ΔG still not constrained.

ΔG via $\gamma - g$ Fusion: COMPASS

The photon-gluon fusion mechanism (PGF) producing two hadrons:



If only photon-gluon fusion exists:

<u>OPEN CHARM</u>

- reconstruct D^o, D^+

$$A = \frac{N^{\uparrow\downarrow}_{c\bar{c}} - N^{\uparrow\uparrow}_{c\bar{c}}}{N^{\uparrow\downarrow}_{c\bar{c}} + N^{\uparrow\uparrow}_{c\bar{c}}}$$

$$A^{\gamma p \to c\bar{c}} \propto \Delta G/G$$

<u>HIGH-P$_T$ Hadron Pairs</u>

- ID 2 high-P$_T$ hadron pairs

$$A = \frac{N^{\uparrow\downarrow}_{h^\pm} - N^{\uparrow\uparrow}_{h^\pm}}{N^{\uparrow\downarrow}_{h^\pm} + N^{\uparrow\uparrow}_{h^\pm}}$$

$$A^{\gamma p \to h^\pm} \propto \Delta G/G$$

Projections: COMPASS ΔG

OPEN CHARM:
2.5 years (1.5 with ^6LiD and 1 with NH_3)

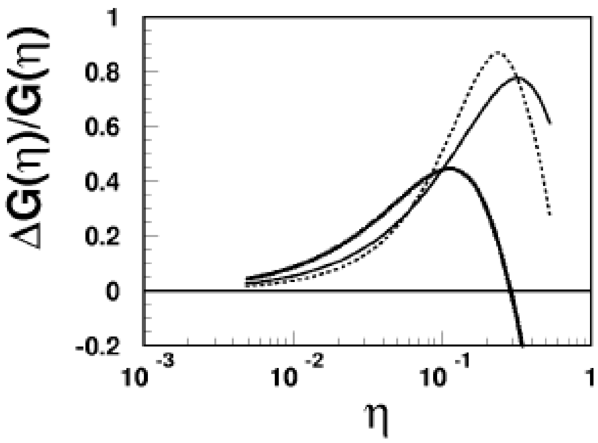
$$\delta\left(\Delta G/G\right) \approx 0.11$$

in the accessible η, gluon momentum fraction, region.

Solid: GS-A

Dashed: GS-B

Thick: GS-C



F. Bradamante, Proceedings, Erice Sept. 1999

HIGH P$_T$ HADRON PAIRS:
1 year of running with ^6LiD

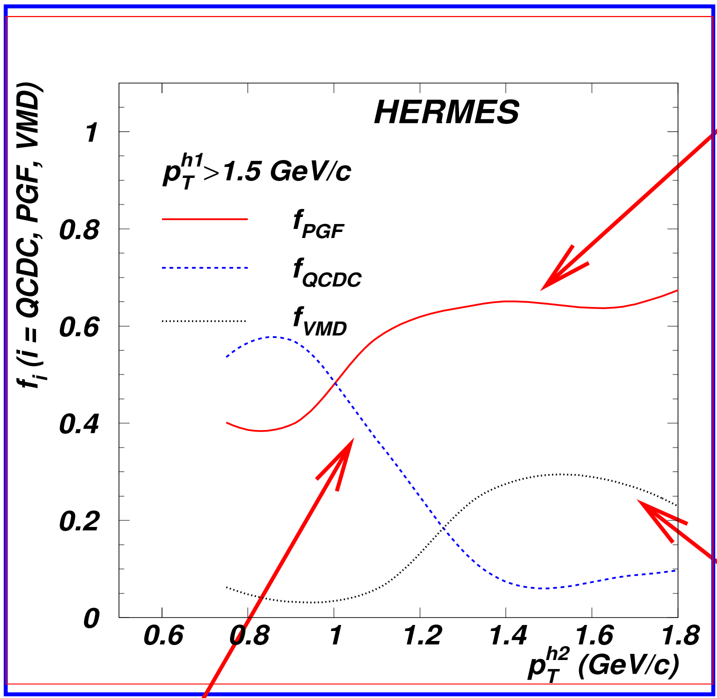
$$\delta\left(\Delta G/G\right) \approx 0.05$$

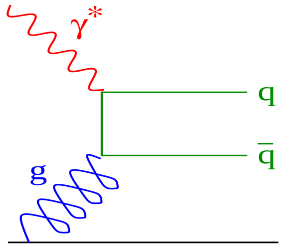
A.Bravar *et al.*, Phys.Lett.B421 (1998) 349

ΔG via γ-g Fusion: HERMES

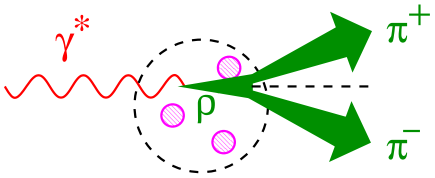
HIGH P$_T$ HADRON PAIRS: $\vec{\gamma}\vec{p} \rightarrow h^+h^-X$

PYTHIA

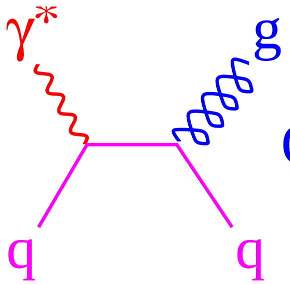




PGF: $A \sim -\frac{\Delta G}{G}$

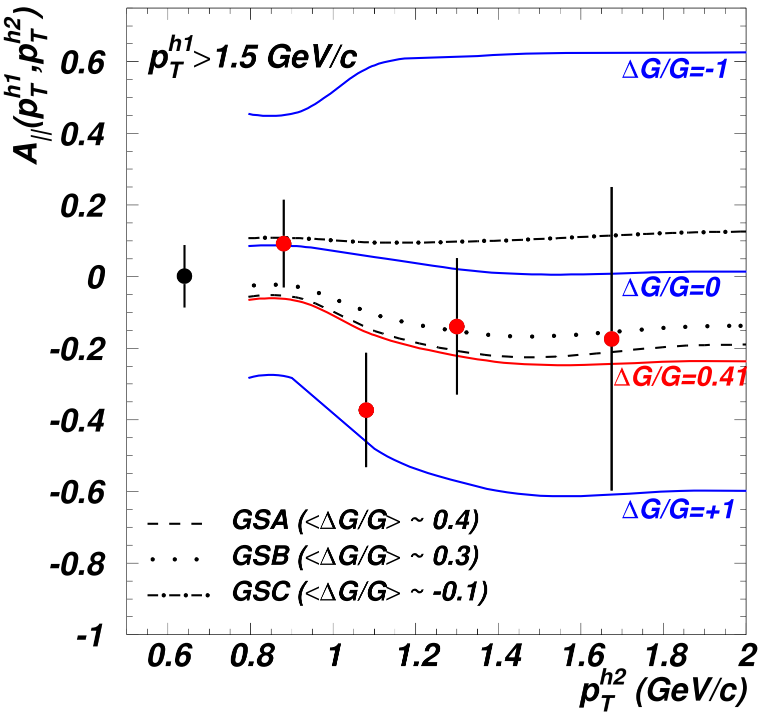


VDM: $A \sim 0$



QCDC: $A \sim 0.5\frac{\Delta q}{q}$

Results: HERMES ΔG from PYTHIA



$$\frac{\Delta G}{G} = 0.41 \pm 0.18(stat) \pm 0.03(sys)$$

for $p_T^{h_1} > 1.5$ GeV and $p_T^{h_2} > 0.8$ GeV

- $\langle x_G \rangle = 0.17$
- $\langle Q^2 \rangle = 0.06$ GeV^2

HERMES, Phys.Rev.Lett.84(2000)2584

Note: much more data expected from current HERMES run.

Conclusions

The Present

- precise polarized structure functions
  $\longrightarrow$ still lack kinematic range for definitive pQCD analyses
- polarized valence quark distributions are becoming increasingly well constrained
  $\longrightarrow$ polarized gluon and polarized sea distributions are not! Need more semi-inclusive data on $\Delta\overline{q}$.

The Future

Attention now on transversity and ΔG

- HERMES RUN2 (2001): first measurements of transversity
- HERMES 1998-2000 run: significant improvement in ΔG from high P_T $h^{\pm}$
- COMPASS (2001): ΔG from PGF
- RHIC-Spin (2001): $\longrightarrow$ will map out the x dependence of ΔG

ΔG $\longrightarrow$ one of the final pieces of the

"Spin Puzzle"

Δvalence ***+ Δsea*** ***+ Δgluons*** ***+ Δorb. ang. mom*** ***= 1/2***