Phenomenology at low Q^2

Lecture IV

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HUGS @ JLAB
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Outline

1. High energy DIS spin experiments
   - Acceptance
   - Status of g_1 measurements
2. Regge model predictions for g_1
3. Low x implications from the pQCD
4. $\mathrm{Ln}^2(1/x)$ corrections to $g_1(x, Q^2)$
   - General
   - Predictions for g_1^{ns}
   - Low Q^2 extrapolation of g_1^{ns}
   - Predictions for g_1
   - Low x contributions to g_1 moments
5. Nonperturbative effects in g_1
   - g_1 at low Q^2, method I
   - g_1 at low Q^2, method II
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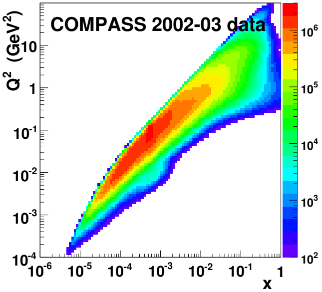
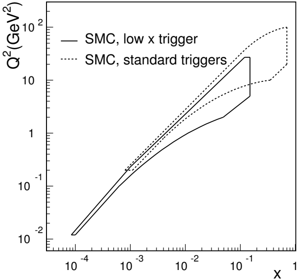
1. E142, E143, E154, E155, E155X at SLAC; electrons of < 50 GeV, targets: protons, deuterons, helium-3;
2. EMC, SMC, COMPASS at CERN; muons of 90 – 280 GeV, targets: protons, deuterons;
3. HERMES at DESY; electrons of 30 GeV, targets: protons, deuterons, (helium-3);
4. STAR, PHENIX at BNL; *pp* collider, $\sqrt{s}$ = 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 2, 3 – identified if momenta larger than 1 and 2.5 GeV respectively;
6. background due to μe scattering (at $x = 0.000545$) in 2, 3;





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High energy DIS spin experiments...cont'd

Status of g_1 measurements

Spin-dependent cross sections are a small part of the DIS cross section $\Longrightarrow$ c.s. asymmetries $\Longrightarrow$ getting $A_{||}$ then A_1 then (using F_2 and R) g_1. Practical matters in: R. Windmolders, in "Spin in physics", X Séminaire Rhodanien de Physique, eds Anselmino, Mila, Soffer, Frontier Group, 2002.

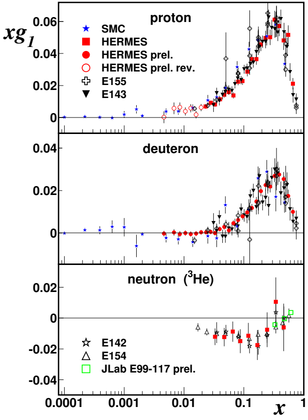


Figure from Stösslein, Acta Phys. Pol. B33 (2002) 2813

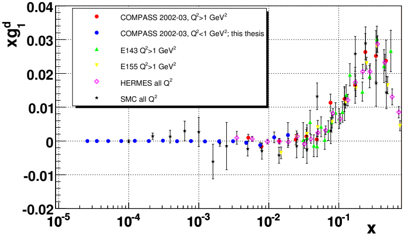


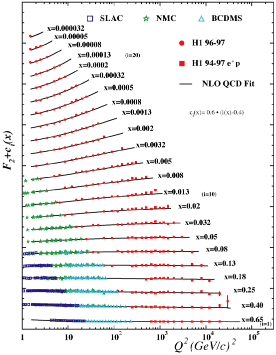
Figure comes from M.Stolarski, PhD, Warsaw University, 2006

All data at their quoted mean Q^2; errors are total;
New precise results from COMPASS on g_1^d,
for $x >$few $\times 10^{-6}$;
Lowest x for g_1^p from SMC, $x > 0.00006$;
Direct measurements on neutron for $x \gtrsim 0.02$.
No significant spin effects seen at lowest x!

High energy DIS spin experiments...cont'd

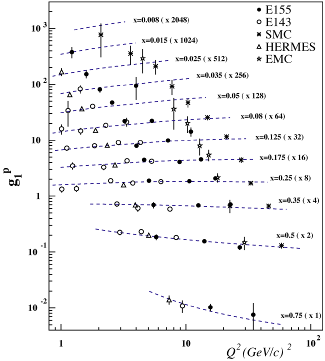
Status of g_1 measurements...cont'd

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.

Outline

Regge model predictions for g_1

- Remember: $s \equiv W^2 = M^2 + Q^2(1/x - 1)$; thus low x behaviour of a structure function (F_2, g_1, ...) reflects the high energy behaviour of the virtual Compton scattering cross section with the cms energy squared, s. This is the Regge limit of DIS.
- Regge gives for $x \to 0$ (i.e. $Q^2 \ll W^2$):

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

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 $\sim \ln x$;
  - 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 $x \to 0$ extrapolation of g_1 to extract g_1 moments is not correct! Evolve g_1 to a common Q^2 before extrapolation!

Outline

Low x implications from the pQCD

In the DGLAP the singular small x behaviour of the gluon and sea quark distributions (implied by the data) may originate from

- parametrization of the starting distributions at moderate Q_0^2 (equal to about 4 GeV^2 or so);
- evolution starting from non-singular "valence-like" parton distributions at a very low scale, $\mu_0 \sim 0.35$ GeV^2. Glück, Reya, Vogt, Eur. Phys.J.C5 (1998) 461

Then

$$g_1(x, Q^2) \sim exp\left[A\sqrt{\xi(Q^2)\ln(1/x)}\right] \tag{2}$$

where

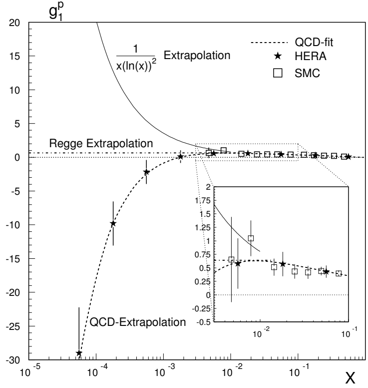
$$\xi(Q^2) = \int_{\mu_0^2}^{Q^2} \frac{\mathrm{d}q^2}{q^2} \frac{\alpha_s(q^2)}{2\pi} \tag{3}$$

and A is different for the singlet and non-singlet case.

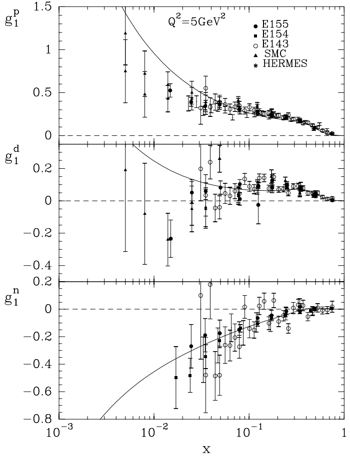
Low x implications from the pQCD

World data on g_1^p and g_1^d were NLO QCD analysed but at low x neither measurements nor reliable calculations exist.

De Roeck et al., Eur. Phys. J. C6 (1999)121



Bourrely, Soffer, Buccella, Eur. Phys. J. C23(2002) 487.



Outline

- Low x $\equiv$ large parton densities $\Longrightarrow$ new dynamics?
- 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.
- 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

$$p(x, Q^2) = \int^{Q^2} \frac{\mathrm{d}k^2}{k^2} f(x, k^2) \tag{4}$$

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

Outline

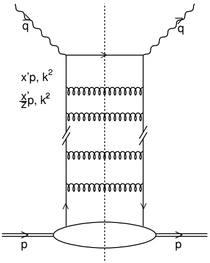
- $\mathrm{Ln}^2(1/x)$ corrections to g_1^{ns} are generated by ladder diagrams $\Longrightarrow$ or mathematically by an equation:

$$f(x',k) = f^{(0)}(x',k) + \bar{\alpha}_s(k^2)\int_{x'}^{1}\frac{\mathrm{d}z}{z}\int_{k_0^2}^{k^2/z}\frac{\mathrm{d}k'^2}{k'^2} f\left(\frac{x'}{z},k'^2\right)$$

and

$$g_1^{ns}(x,Q^2) = g_1^{(0)}(x) + \int_{k_0^2}^{W^2}\frac{\mathrm{d}k^2}{k^2} f\left(x' = x\left(1+\frac{k^2}{Q^2}\right),k^2\right)$$

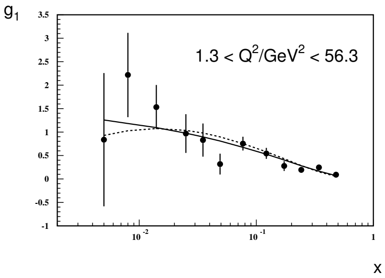
where $\bar{\alpha}_s(k^2) = 2\alpha_s(k^2)/3\pi$ and $g_1^{(0)}(x)$ is a nonperturbative part, corresponding to $k^2 < k_0^2$.



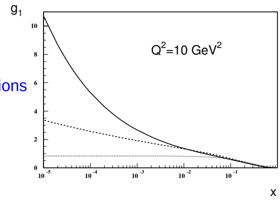
- $\mathrm{Ln}^2(1/x)$ terms originate from the z-dependent limit of the $\int \mathrm{d}k'^2/k'^2$ and x-dependent limit in $W^2(x)$.
- They create a leading small x behaviour of g_1^{ns} if $g_1^{ns(0)}$ and $f^{(0)}$ are non-singular at $x \to 0$.
- DGLAP evolution is incomplete at low x; only $\ln(1/x)$ terms are present, originating from $\int_{k_0^2}^{k^2} \mathrm{d}k'^2/k'^2$.
- For fixed (i.e. non-running) $\bar{\alpha}_s(k^2) \to \tilde{\alpha}_s$, small x behaviour is $g_1^{ns}(x,Q^2) \sim x^{-\lambda}$ where $\lambda = 2\sqrt{\tilde{\alpha}_s}$

Predictions for g_1^{ns}...cont'd

- A unified equation which incorporates the complete LO DGLAP at finite x and $\ln^2(1/x)$ effects at $x \to 0$ was formulated.
- Potentially large $\ln Q^2$ and $\ln(1/x)$ treated on equal footing.
- For the numerical results it was assumed that $g_1^{ns(0)} = 2g_A(1-x)^3/3$ where g_A = 1.257 (axial vector coupling). At $x \to 0$, $g_1^{ns(0)}$ →const, in agreement with the Regge expectation.
- The $g_1^{ns(0)}$ satisfies the Bjorken sum rule at LO: $\int_0^1 \mathrm{d}x g_1^{ns(0)}(x) = g_A/6$.
- Parameter k_0^2=1 GeV^2.
- To compare the g_1^{ns} to the (SMC) data it was assumed:
  $g_1^{ns} \equiv g_1^p - g_1^n = 2\left[g_1^p - g_1^d/(1-\omega_D/3)\right]$; ω_D =0.05 (D-state probability in the deuteron).



g_1^{ns} vs x
continuous – full calculations
broken – LO DGLAP



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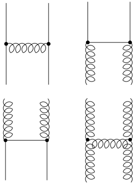
Low Q^2 extrapolation of g_1^{ns}

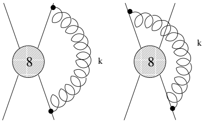
Badelek, Kwiecinski, Phys. Lett. B418 (1998) 229

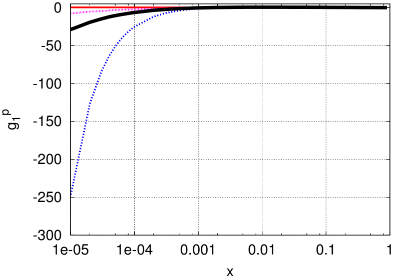
- For $Q^2 \to 0$ (for fixed W^2), g_1 should be a finite function of W^2, free from kinematical singularities or zeroes at $Q^2 = 0$.
- g_1^{ns} from the above formalism and the above $g_1^{ns(0)}$ fulfill this.
- If $g_1^{ns(0)}(x)$ has a singularity then it should be replaced by $g_1^{ns(0)}(\bar{x})$ where $\bar{x} = x(1 + k_0^2/Q^2)$. Remaining parts left unchanged.
- Then g_1^{ns} can be extrapolated to the low Q^2 for fixed $2M\nu = Q^2/x$ including $Q^2 = 0$. Observe! That is just the partonic contribution to the low Q^2 region; it may not be the only one there.

Outline

Results of full $g_1(x, Q^2)$ calculations at $Q^2 = 10$ GeV^2. At low x, the singlet part, g_1^s dominates g_1^{ns}. Apart of the “standard” ladder diagram, the following ones were taken into account for $g_1^{ns}(x, Q^2)$:







$\Longleftarrow g_1^p(x, Q^2)$ vs x at $Q^2 = 10$ GeV^2

red – nonperturbative input, $g_1^{(0)}$

pink – only LO DGLAP

thick black – full g_1

blue – LO DGLAP + ladder $\ln^2(1/x)$

At low x, $g_1 \to x^{-\lambda}$ with $\lambda \sim 0.4$ for g_1^{ns} and $\lambda \sim 0.8$ for g_1^s.

More singular than Regge expectations!

Outline

$\ln^2(1/x)$ corrections to $g_1(x, Q^2)$...cont'd

Low x contributions to g_1 moments

- Fundamental tools: sum rules (Ellis–Jaffe, Bjorken, DHG, ...) which involve first moments of g_1, i.e. integrations over dx from 0 to 1, e.g. $\Gamma_1 = \int_0^1 g_1 dx$.
- Unmeasured regions: [0,x_{min}], [x_{max},1].
- The [x_{max},1] not critical but [0,x_{min}] is very important.
- x_{min} depends on ν_{max} accessed in experiments at a given Q_0^2, e.g.

  SMC at 200 GeV and Q_0^2= 1 GeV^2 $\Longrightarrow x_{min} \approx 0.003$;

  COMPASS at 160 GeV and Q_0^2= 1 GeV^2 $\Longrightarrow x_{min} \approx 0.002$.
- Contribution to moments from the $0 \leq x \lesssim 0.003$ has to be estimated phenomenologically.
- LO DGLAP + $\ln^2(1/x)$ resummation used to extrapolate polarised parton distributions and structure functions down to $x \sim 10^{-5}$ to calculate contributions to moments from $10^{-5} < x < 10^{-3}$. In $2 < Q^2 < 15$ GeV^2 interval, contributions to Γ_1^p was 2% and 8% for Γ_1^n (however calculations of Γ_1^n were below the data in the overlap region). Contributions $\nearrow$ with Q^2 $\nearrow$. Also estimated that $10^{-5} < x < 10^{-3}$ interval contributes 1% and 2% to the Bjorken and Ellis–Jaffe s.r.
- Same formalism gave a contribution of 0.0080 to the Bjorken integral from the unmeasured region, $0 \leq x < 0.003$ at Q^2 = 10 GeV^2 (LO DGLAP only gave 0.0057 and assuming g_1 = const resulted in 0.004). Kwiecinski, Ziaja, Phys. Rev.,60 (1999)054004
- Extrapolation of the NLO DGLAP fits to the world data: in $0 \leq x < 0.003$ is 10% of Γ_1^p. NLO DGLAP for the SMC data at Q^2 = 10 GeV^2 gave 10% contribution to the Bjorken integral. SMC, Phys. Rev., D58 (1998) 112002 (obs! assumptions!).

Nonperturbative effects in g_1

- Data on $g_1(x, Q^2)$ extend to low $Q^2 \sim 0.0001$ GeV^2.
- Nonperturbative mechanisms dominate the particle dynamics there; transition from “soft” to “hard” physics may be studied.
- Partonic contribution to g_1 has to be suitably extrapolated to low Q^2 and complemented by a nonperturbative component.
- Low Q^2, spin-independent electroproduction well described by the GVMD $\Longrightarrow$ GVMD should be used to describe the g_1.
- Two attempts tried to extract from the data a contribution of nonperturbative effects at low x, low Q^2.

Outline

g_1 at low Q^2, method I

Badelek, Kiryluk, Kwiecinski, Phys. Rev. D61 (2000) 014009

The following representation of g_1 was assumed:

$$g_1(x,Q^2) = g_1^{VMD}(x,Q^2) + g_1^{part}(x,Q^2) \qquad (5)$$

g_1^{part} at low x is controlled by the $\ln^2(1/x)$ terms; it was parametrised as discussed in Kwiecinski, Ziaja, Phys. Rev. D60 (1999) 054004. $g_1^{VMD}(x,Q^2)$ was represented as:

$$g_1^{VMD}(x,Q^2) = \frac{M\nu}{4\pi} \sum_{V=\rho,\omega,\phi} \frac{M_V^4 \Delta\sigma_V(W^2)}{\gamma_V^2 (Q^2+M_V^2)^2} \qquad (6)$$

The unknown cross sections $\Delta\sigma_V(W^2)$ are combinations of the total cross sections for the scattering of polarised vector mesons and nucleons. At high W^2: $\Delta\sigma_V = (\sigma_{1/2} - \sigma_{3/2})/2$
Assume:

$$\frac{M\nu}{4\pi} \sum_{V=\rho,\omega} \frac{M_V^4 \Delta\sigma_V}{\gamma_V^2 (Q^2+M_V^2)^2} =$$

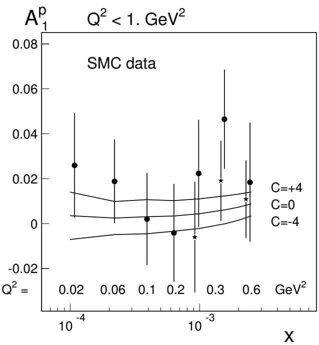
$$C\left[\frac{4}{9}\left(\Delta u_{val}^0(x) + 2\Delta\bar{u}^0(x)\right) + \frac{1}{9}\left(\Delta d_{val}^0(x) + 2\Delta\bar{d}^0(x)\right)\right] \frac{M_\rho^4}{(Q^2+M_\rho^2)^2}, \qquad (7)$$

$$\frac{M\nu}{4\pi} \frac{M_\phi^4 \Delta\sigma_{\phi p}}{\gamma_\phi^2 (Q^2+M_\phi^2)^2} = C\,\frac{2}{9}\Delta\bar{s}^0(x)\frac{M_\phi^4}{(Q^2+M_\phi^2)^2}, \qquad (8)$$

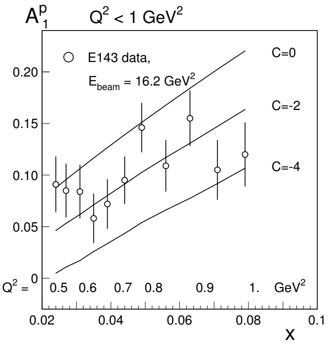
Each $\Delta p_j^0(x) \to x^0$ for $x \to 0$. Thus $\Delta\sigma_V \to 1/W^2$ at large W^2, i.e. zero intercept of the appropriate Regge trajectories.

Results for the spin asymmetry, $A_1 = g_1/F_1$, for the proton, and for different C:

C ??



$C < 0$?



Outline

Nonperturbative effects in g_1...cont'd

g_1 at low Q^2, method II

Badelek, Kwiecinski, Ziaja, Eur. Phys. J. C26 (2002) 45

The following representation of g_1 was assumed, valid for fixed $W^2 \gg Q^2$, i.e. small $x = Q^2/(Q^2 + W^2 - M^2)$:

$$g_1(x, Q^2) = g_1^L(x, Q^2) + g_1^H(x, Q^2) = \frac{M\nu}{4\pi} \sum_V \frac{M_V^4 \Delta\sigma_V(W^2)}{\gamma_V^2 (Q^2 + M_V^2)^2} + g_1^{AS}(\bar{x}, Q^2 + Q_0^2). \quad (9)$$

The first term sums up contributions from light vector mesons, $M_V < Q_0$, $Q_0^2 \sim 1$ GeV^2. The unknown $\Delta\sigma_V$ are expressed through the combinations of nonperturbative parton distributions, evaluated at fixed Q_0^2, similar to method I.

The second term, $g_1^H(x, Q^2)$, represents the contribution of heavy ($M_V > Q_0$) vector mesons to $g_1(x, Q^2)$ can also be treated as an extrapolation of the QCD improved parton model structure function, $g_1^{AS}(x, Q^2)$, to arbitrary values of Q^2: $g_1^H(x, Q^2) = g_1^{AS}(\bar{x}, Q^2 + Q_0^2)$. The scaling variable x is replaced by $\bar{x} = (Q^2 + Q_0^2)/(Q^2 + Q_0^2 + W^2 - M^2)$. It follows that at large Q^2, $g_1^H(x, Q^2) \to g_1^{AS}(x, Q^2)$. Thus:

$$\begin{aligned} g_1(x, Q^2) \quad &= \quad C \left[\frac{4}{9} (\Delta u_{val}^0(x) + 2\Delta\bar{u}^0(x)) + \frac{1}{9} (\Delta d_{val}^0(x) + 2\Delta\bar{d}^0(x)) \right] \frac{M_\rho^4}{(Q^2 + M_\rho^2)^2} \\ &+ \quad C \left[\frac{1}{9} (2\Delta\bar{s}^0(x)) \right] \frac{M_\phi^4}{(Q^2 + M_\phi^2)^2} + g_1^{AS}(\bar{x}, Q^2 + Q_0^2). \quad (10) \end{aligned}$$

Nonperturbative effects in g_1...cont'd

g_1 at low Q^2, method II...cont'd

Now fixing C in the photoproduction limit via the DHGHY sum rule.

Digression: the DHGHY sum rule

The $\gamma^* p$ scattering amplitude fulfills the dispersion relation:

$$S_1(\nu, q^2) = 4 \int_{-q^2/2M}^{\infty} \nu' \mathrm{d}\nu' \frac{G_1(\nu', q^2)}{(\nu')^2 - \nu^2} \tag{11}$$

where

$$G_1(\nu, q^2) = \frac{M}{\nu} g_1(x, Q^2) \tag{12}$$

in the $Q^2, \nu \to \infty$ limit. As a result of Low's theorem: $S_1(0,0) = -\kappa^2_{p(n)}$, G_1 in the $Q^2 \to 0$ limit fulfills the DHGHY sum rule:

$$\int_0^{\infty} \frac{\mathrm{d}\nu}{\nu} G_1(\nu, 0) = -\frac{1}{4} \kappa^2_{p(n)}. \tag{13}$$

End of digression

Nonperturbative effects in g_1...cont'd

g_1 at low Q^2, method II...cont'd

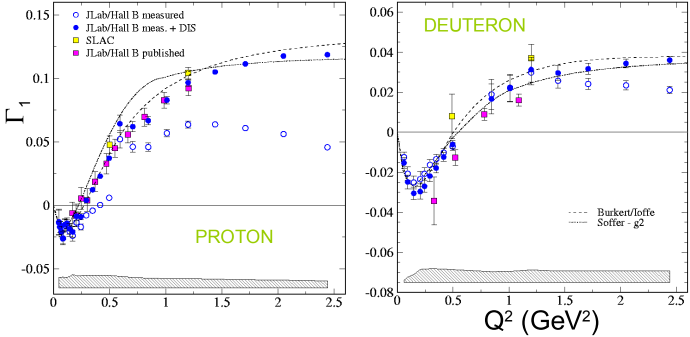
First moment Γ_1 for the proton and deuteron

$$\Gamma_1 = \underbrace{\int_{x=0.001}^{x_{min}} g_1 dx}_{\text{DIS (unmeasured)}} + \underbrace{\int_{x_{min}}^{x(W=1.07)} g_1 dx}_{\text{without elastic}}$$

DIS (unmeasured) Parameterization of world data

without elastic contribution

- Phenomenological Models
  - Burkert/Ioffe
    Resonance contribution pion electroproduction analysis
  - Soffer/Teryaev
    Interpolation of the integral $\int (g_1+g_2)dx$



V. Dharmawardane, DIS2006

At $\nu \rightarrow 0$, eq.(11) is:

$$S_1(0, q^2) = 4M \int_{Q^2/2M}^{\infty} \frac{\mathrm{d}\nu}{\nu^2} g_1(x(\nu), Q^2). \tag{14}$$

Now we define the DHGHY moment, $I(Q^2)$ as:

$$I(Q^2) = S_1(0, q^2)/4 = M \int_{Q^2/2M}^{\infty} \frac{\mathrm{d}\nu}{\nu^2} g_1(x(\nu), Q^2). \tag{15}$$

Before taking the $Q^2 \rightarrow 0$ limit of (14), observe that it is valid only down to some threshold value of W, $W_{th} \lesssim 2$ GeV (above resonances). Requirement $W > W_{th}$ gives the lower limit for integration over ν in (14), where $\nu_t(Q^2) = (W_t^2 + Q^2 - M^2)/2M$:

$$I(Q^2) = I_{res}(Q^2) + M \int_{\nu_t(Q^2)}^{\infty} \frac{d\nu}{\nu^2} g_1 \left(x(\nu), Q^2 \right). \tag{16}$$

Here I_{res} = contribution of resonances. The DHGHY sum rule now implies:

$$I(0) = I_{res}(0) + M \int_{\nu_t(0)}^{\infty} \frac{d\nu}{\nu^2} g_1 \left(x(\nu), 0\right) = -\kappa^2_{p(n)}/4. \tag{17}$$

Thus action plan for extracting C in eq.(10):

- take $g_1(x(\nu), 0)$, eq.(10); C is the only free parameter,
- put it into eq.(17),
- get $I_{res}(0)$ from measurements,
- extract C from (17).

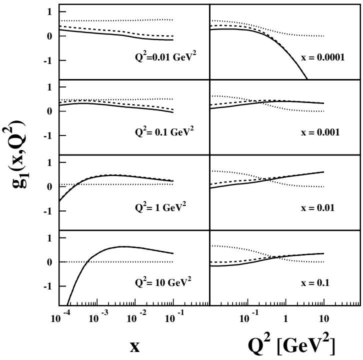
Taking:

- $I_{res}(0)$ from photoproduction, W_t=1.8 GeV GDH, Nucl. Phys. 105 (2002) 113,
- g_1^{AS} prametrized by NLO GRSV2000 Phys.Rev. D63 (2001) 094005
- nonperturbative $\Delta p_j^{(0)}(x)$ at $Q^2 = Q_0^2 = 1.2$ GeV^2 from
  1. GRSV2000 $\Longrightarrow C = -0.30$
  2. "flat" $\Delta p_j^{(0)}(x) = N_i(1-x)^{\eta_i}$ $\Longrightarrow C = -0.24$.

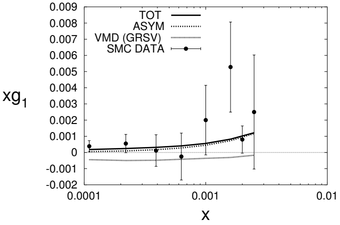
Nonperturbative effects in g_1...cont'd

g_1 at low Q^2, method II...cont'd

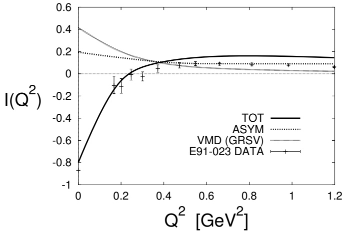
Byproducts: g_1 from eq.(10) and the DHGHY moment, $I(Q^2)$, eq.(15). Results for the proton:



broken lines – g_1^{AS}, dotted – g_1^L, continuous – total g_1



data at $Q^2 < 1$ GeV^2



points mark resonances at $W < W_t(Q^2)$

Figures from: Badelek, Kwiecinski, Ziaja, Eur. Phys. J. C26 (2002)45.

Outline

Summary

- At high energies, low Q^2 region correlated with low x.
- Very important for understanding the nucleon structure is the transition from photoproduction to DIS; also for practical purposes.
- Several theoretical concepts relevant there.

Both perturbative and nonperturbative contributions to the nucleon structure are present everywhere in Q^2