Spin Structure of the Nucleon

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The Nucleon spin puzzle

- Nucleon spin:

$$\boxed{\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta g + \langle L_z \rangle}$$

$$\Delta q = q^{\uparrow} - q^{\downarrow} + \bar{q}^{\uparrow} - \bar{q}^{\downarrow}$$

- quarks spins: $\Delta\Sigma = \Delta u + \Delta d + \Delta s$
- gluons spins: Δg
- orbital angular momentum of q & g: L_z
- Naïve: $\Delta\Sigma = 1$

EMC 1987:

$$\boxed{\Delta\Sigma = 0.12 \pm 0.17}$$

$$\Delta s = -0.19 \pm 0.06$$

Spin structure functions

- DIS with polarised beam and target

$$\boxed{\sigma = \bar{\sigma} \pm \frac{1}{2}\Delta\sigma}$$

  - longitudinal pol. $\Delta\sigma_{\parallel} = \sigma^{\Uparrow\downarrow} - \sigma^{\Uparrow\uparrow}$
  - transverse pol. $\Delta\sigma_{\perp} = \sigma^{\Uparrow\rightarrow} - \sigma^{\Uparrow\leftarrow}$

- Structure functions

$$\begin{aligned} \bar{\sigma} &= aF_1(x,Q^2) + bF_2(x,Q^2) \\ \Delta\sigma &= \alpha g_1(x,Q^2) + \beta g_2(x,Q^2) \end{aligned}$$

- QPM

$$\begin{aligned} g_1(x,Q^2) &= \frac{1}{2}\sum e_f^2 \Delta q_f(x,Q^2) \\ F_1(x,Q^2) &= \frac{1}{2}\sum e_f^2 \;\; q_f(x,Q^2) \end{aligned}$$

Experimental technique

- Double spin asymmetries

$$A = \frac{\Delta\sigma}{2\bar{\sigma}} = \frac{A_{meas}}{P_t P_b f}$$

- target & beam polarisations: P_t, P_b
  dilution factor: f, fraction of polarisable nucleons

- depolarisation of virtual photon: D

$$\begin{aligned} g_1 &\simeq \frac{A_\parallel}{D} F_1 \\ g_2 &\simeq \frac{A_\perp}{d}\frac{F_1}{\gamma} - \frac{y}{2} g_1; \qquad \gamma = \frac{4x^2M^2}{Q^2} \end{aligned}$$

- virtual photon asymmetry

$$\begin{aligned} A_1 &= \frac{\sigma^{1/2} - \sigma^{3/2}}{\sigma^{1/2} + \sigma^{3/2}} \simeq \frac{g_1}{F_1} \\ A_2 &= \frac{\sigma_{LT}}{\sigma^{1/2} + \sigma^{3/2}} \simeq \frac{\gamma}{F_1}(g_1 + g_2) \end{aligned}$$

$$0 \leq A_1 \leq 1; \qquad |A_2| \leq \sqrt{R}$$

THE PLAYERS

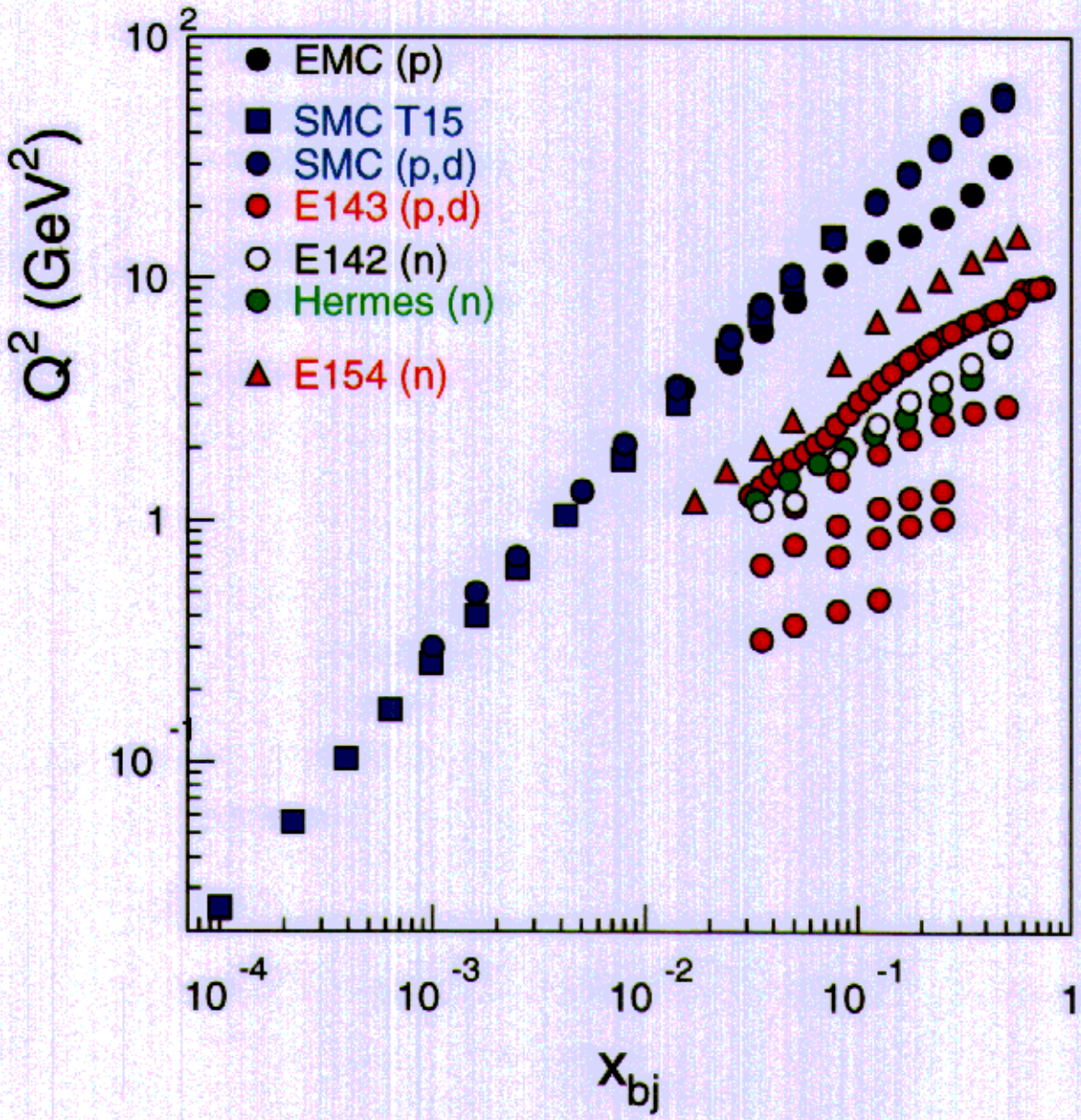
All started 1972 at SLAC with E80 and E130!

SMC 1992–1996
CERN μ^+ beam: 100–190 GeV
targets: butanol, ammonia
twin target

SLAC 1992–1999, E142, E143, E154, E155, E155x
SLAC e^-: 28–48 GeV
targets: ^{3}He, butanol, ammonia, ^{6}LiD
rapid change of beam polarisation

Hermes 1995–
Desy $e^\pm$: 27 GeV
targets: ^{3}He, H, D; internal gas storage cell
rapid change of target polarisation

KINEMATIC RANGES



- new low Q^2 data from SMC

Present status of A_1 and g_1

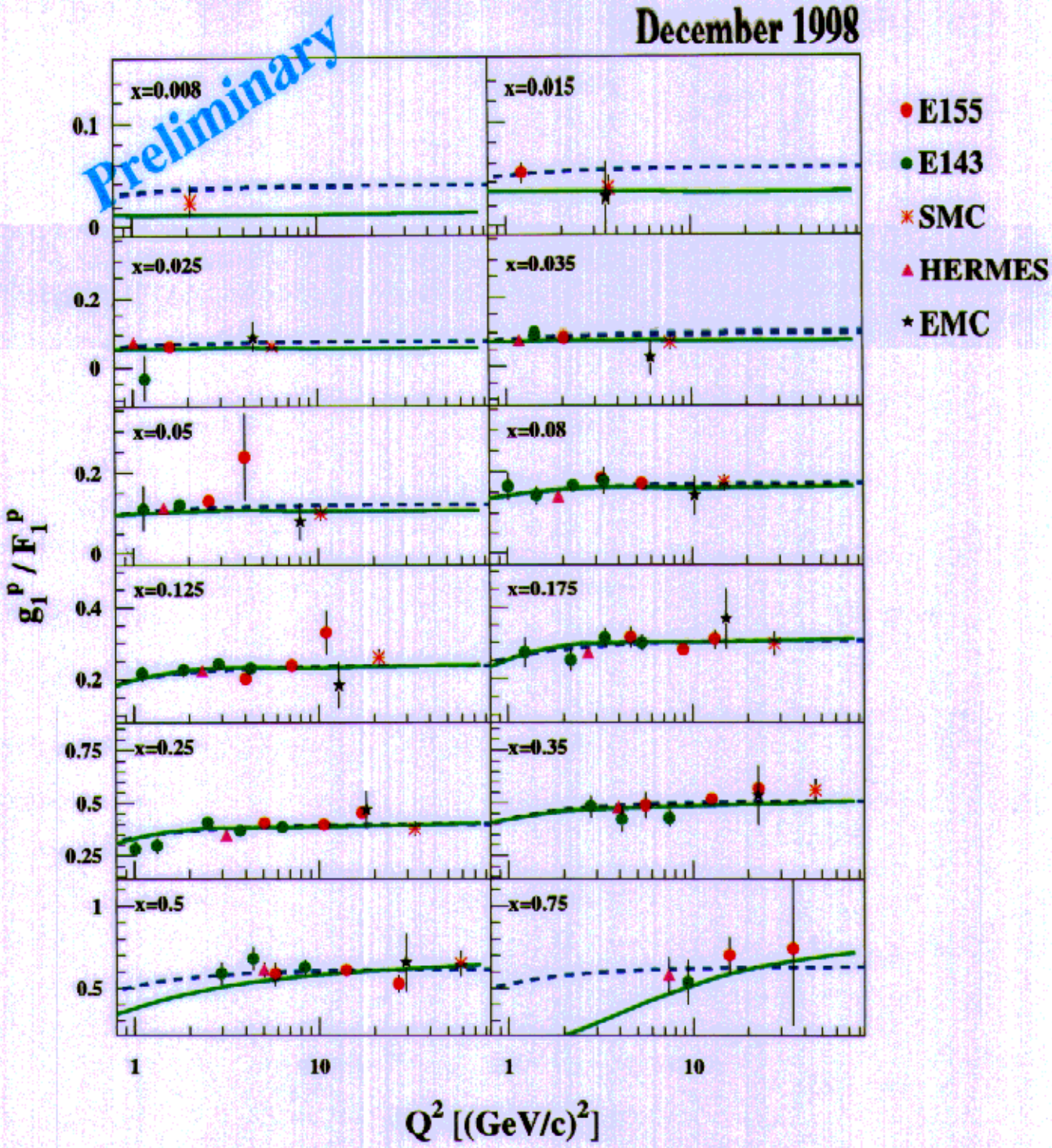
- New data:

E155 $0.015 < x < 0.75$
g_1^{p} preliminary
g_1^{d} published
most precise data

Hermes $0.02 < x < 0.8$
g_1^{p} 1997 data published
good agreement with E143,
same kinematics (27 GeV vs. 29 GeV)

SMC $6 \cdot 10^{-5} < x < 8 \cdot 10^{-4}$
g_1^{p}, g_1^{d} published
low x, low Q^2 data
no surprise

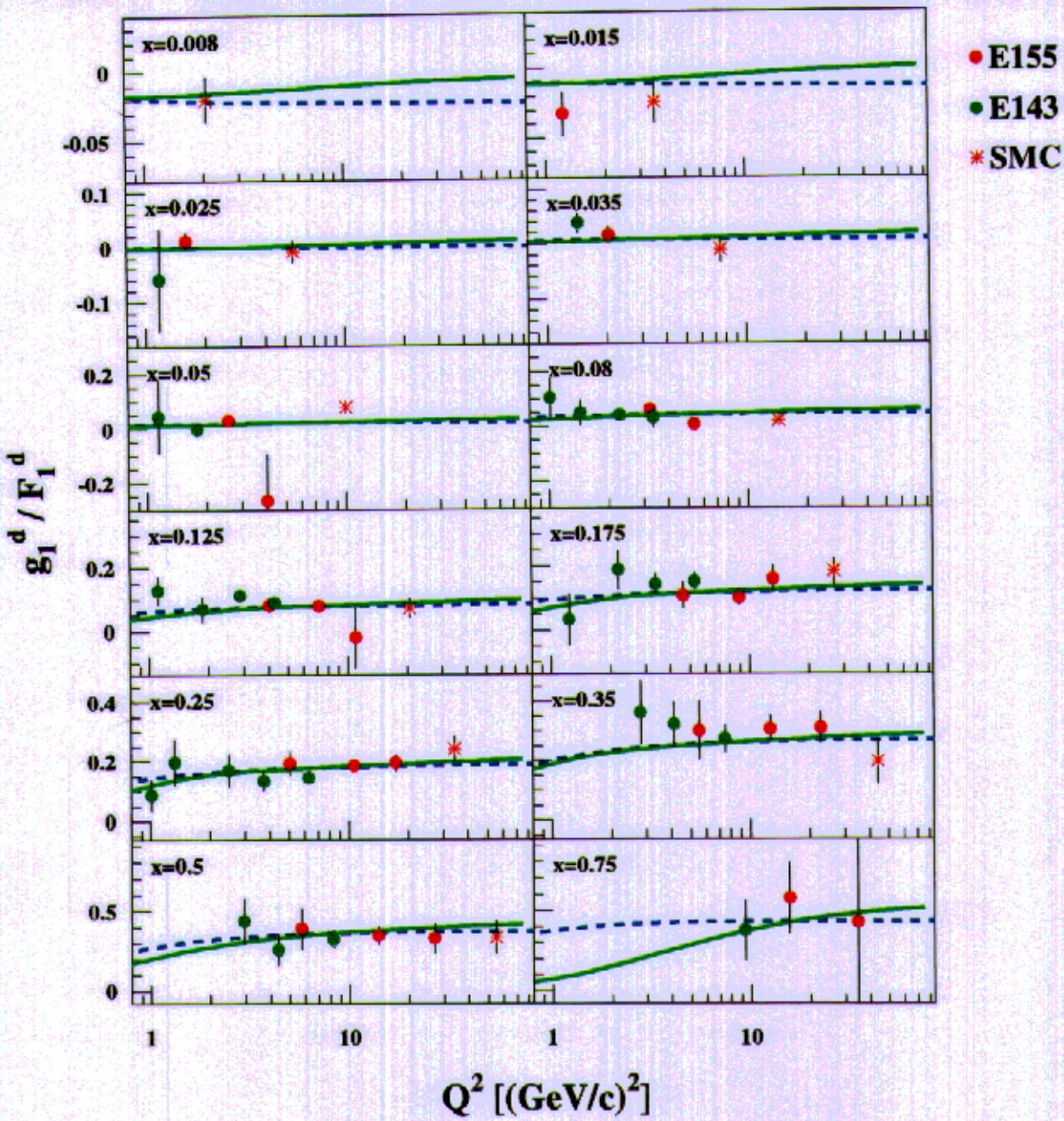
Proton Asymmetry



phenomenological fit

E154 NLO fit

Deuteron Asymmetry

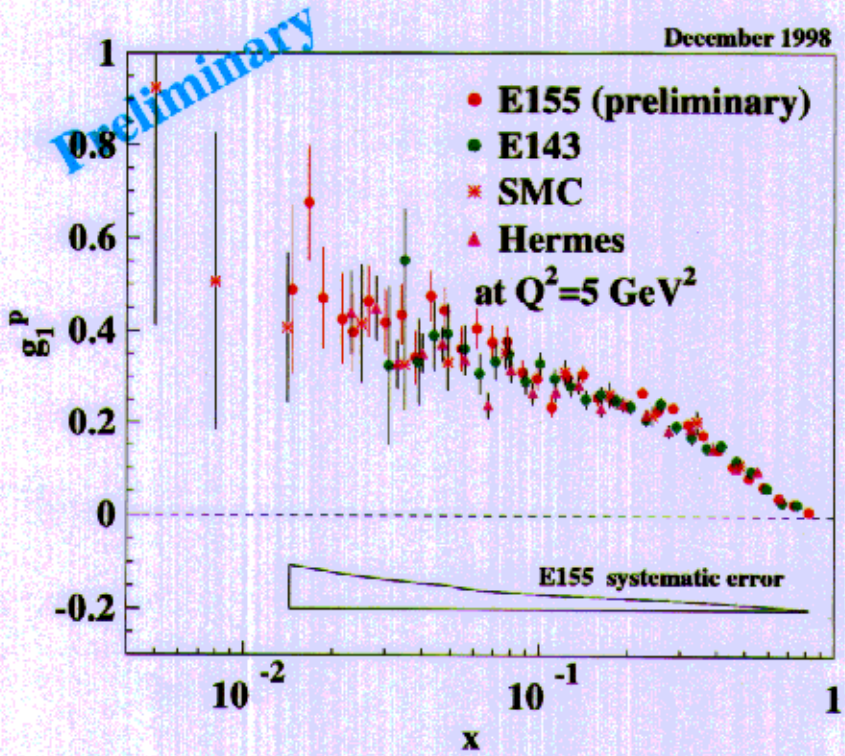


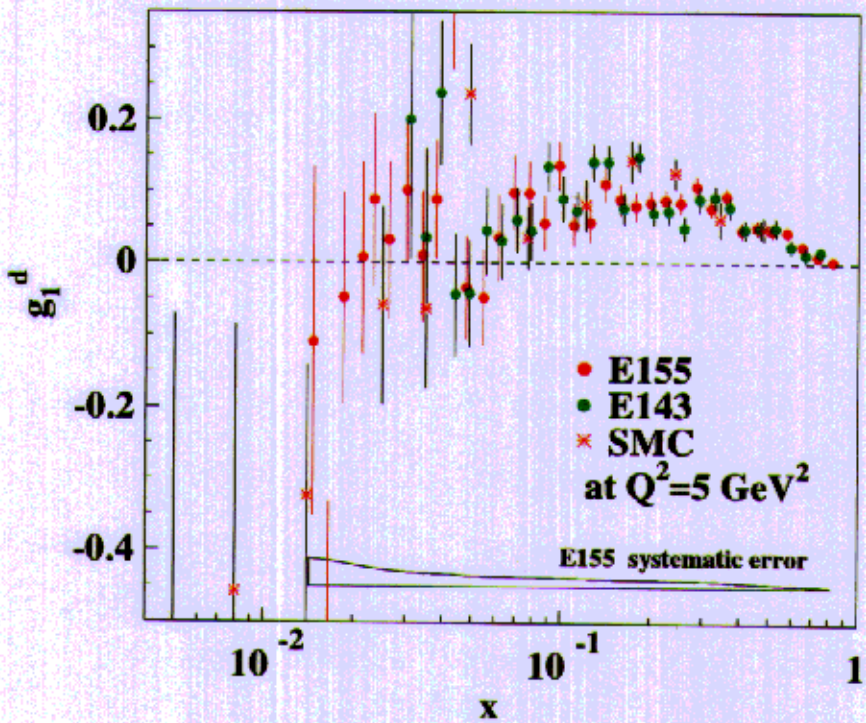
phenomenological fit

E154 NLO fit

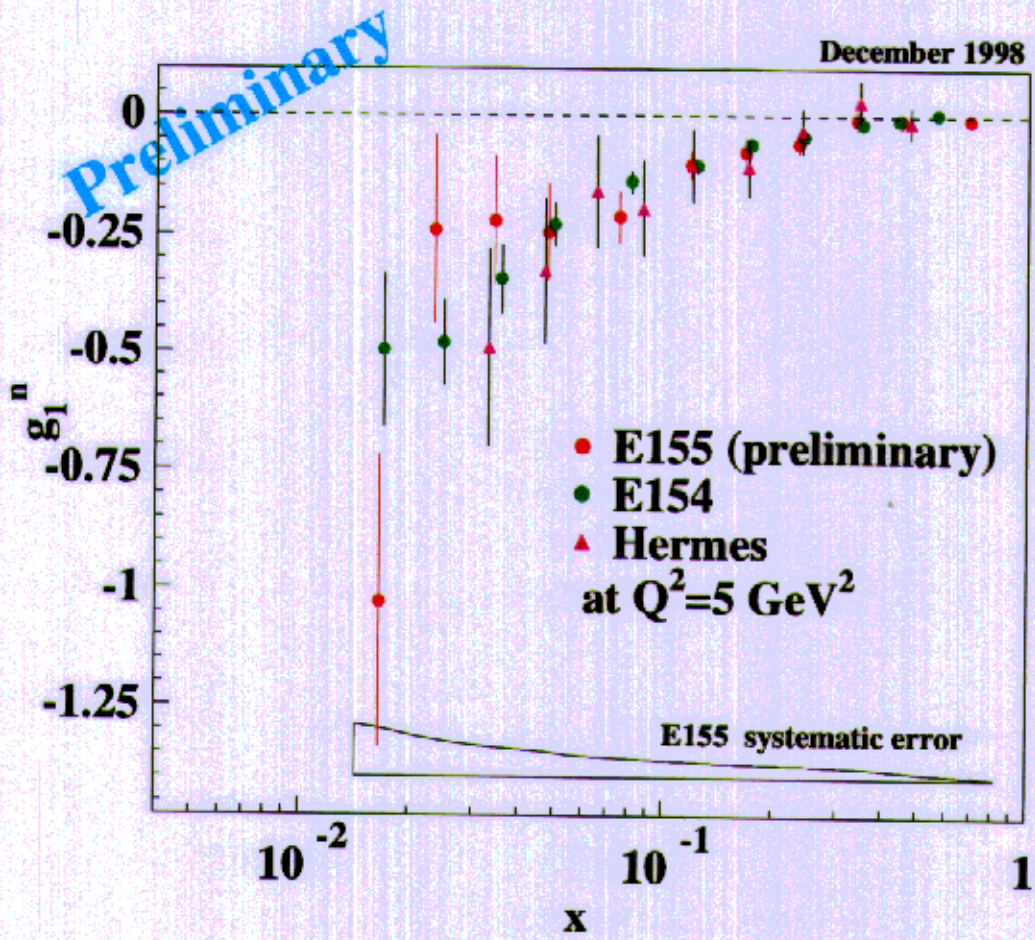
hep-ex/9904002

$g_1(x,\ 5\ \mathrm{GeV}^2)$



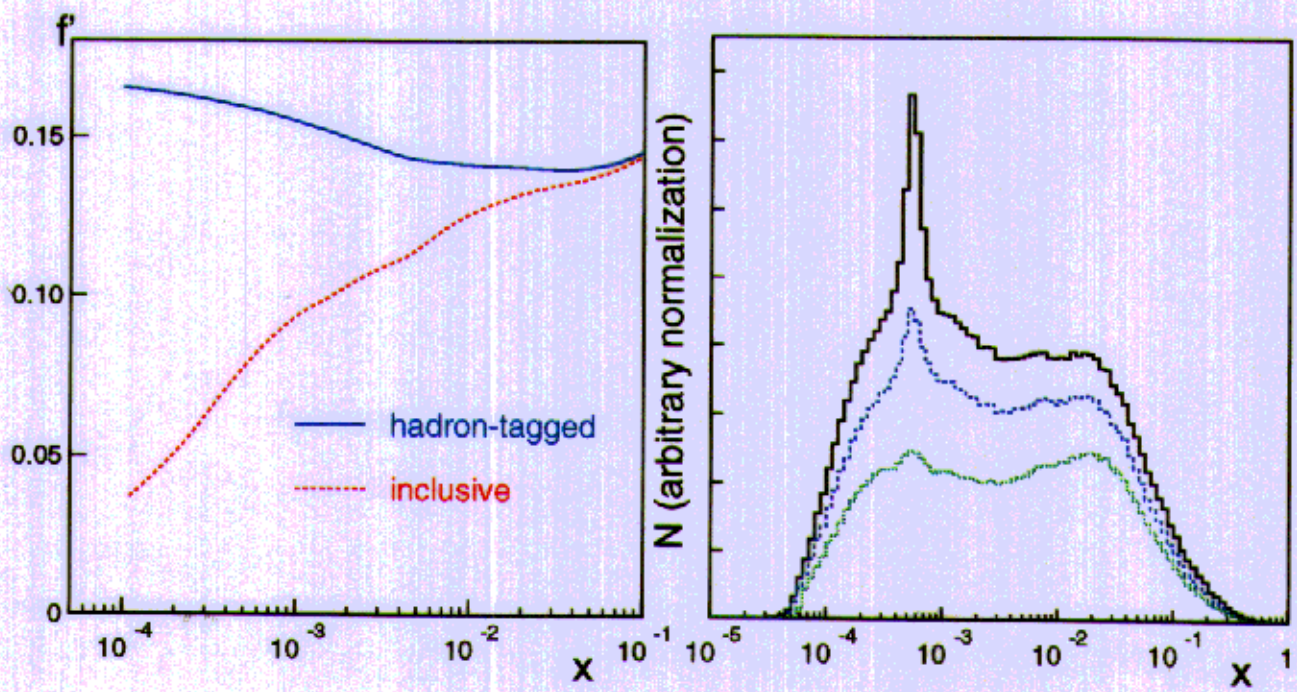


NEUTRON $g_1(x,\ 5\ \mathrm{GeV}^2)$

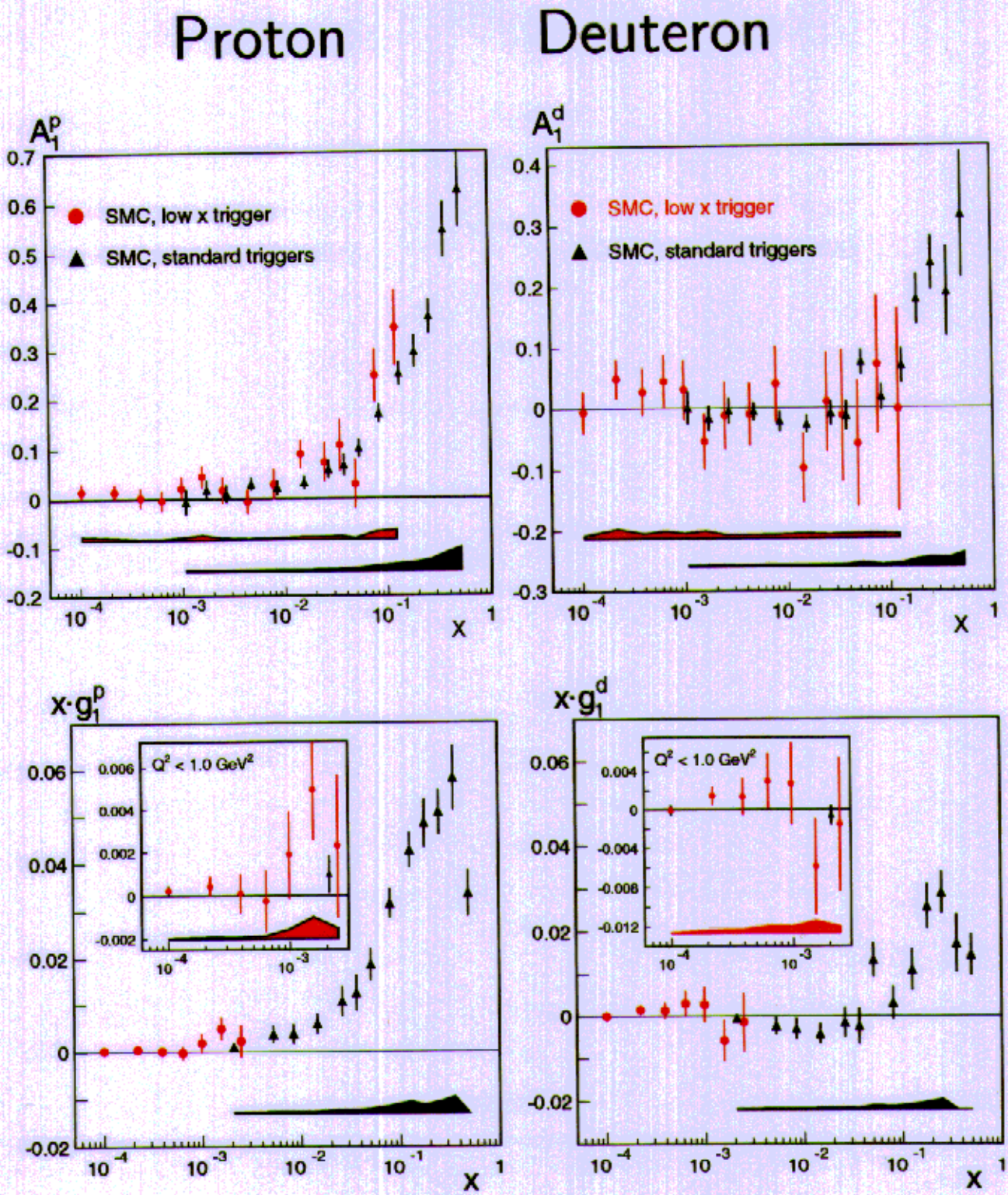


SMC LOW Q^2 DATA

- extend to $x = 6 \cdot 10^{-5}$ at $Q^2 = 0.01$ GeV^2
- effective dilution factor f', NH_3 target
  use hadron-tagging for $x < 0.02$
- μe scattering dominates at $x \simeq m_e/m_\mu$, remove by
  - hadron selection ----
  - kinematic cuts .....

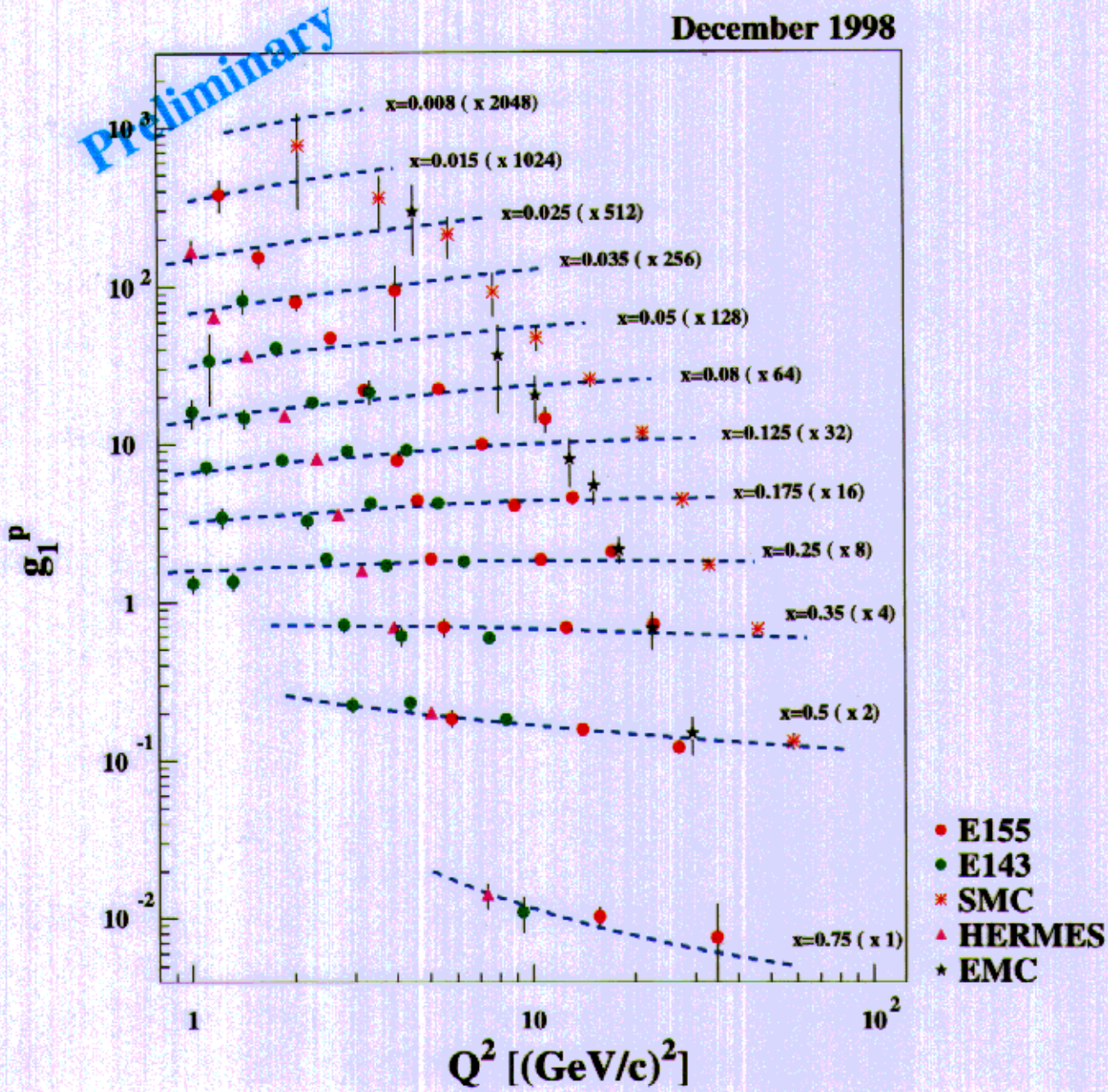


SMC LOW Q^2 DATA: A_1, xg_1



PROTON $g_1(x, Q^2)$

E155, G. S. Mitchell, DPF'99



---- phenomenological fit

QCD ANALYSIS

- **DGLAP** $\qquad t = \dfrac{\ln Q^2}{\Lambda^2}$

$$\frac{d}{dt}\Delta q^{ns} = \frac{\alpha_s(t)}{2\pi} P_{qq}^{ns} \otimes \Delta q^{ns}$$

$$\frac{d}{dt}\begin{pmatrix} \Delta\Sigma \\ \Delta g \end{pmatrix} = \frac{\alpha_s(t)}{2\pi}\begin{pmatrix} P_{qq}^{s} & 2n_f P_{qg}^{s} \\ P_{gq}^{s} & P_{gg} \end{pmatrix} \otimes \begin{pmatrix} \Delta\Sigma \\ \Delta g \end{pmatrix}$$

- singlet quark mixes with gluon

- g_1

$$g_1^{p,n}(x,Q^2) = \frac{1}{12}\left(\pm\Delta q_3 + \frac{1}{3}\Delta q_8\right) \otimes C^{ns} +$$

$$\frac{1}{9}\left(\Delta\Sigma \otimes C^{s} + \Delta g \otimes 2n_f C^{g}\right)$$

- $\Delta q_3(x,Q^2) = \Delta u(x,Q^2) - \Delta d(x,Q^2)$

$\Delta q_8(x,Q^2) = \Delta u(x,Q^2) + \Delta d(x,Q^2) - 2\Delta s(x,Q^2)$

QCD Analyses

- choose scheme
- choose Q_0^2
- choose parametrisations of $\Delta\Sigma$, Δq^{ns}, Δg at Q_0^2
- fit g_1 data
- recent fits:

Altarelli, Ball, Forte, Ridolfi	AB
Leader, Sidorov, Stamenov (DIS'99)	AB, $\overline{\mathrm{MS}}$, JET
E154	AB, $\overline{\mathrm{MS}}$
E155 preliminary	
SMC	AB, $\overline{\mathrm{MS}}$

$\Delta\Sigma$, $\Delta\Sigma^{AB}$ & a_0

- FIRST MOMENT $\Gamma_1(Q^2) = \int_0^1 g_1(x,Q^2)\,dx$

$$\Gamma_1(Q^2) = \frac{1}{12}\left(\pm\Delta q_3 + \frac{1}{3}\Delta q_8\right) C^{ns}(Q^2) +$$

$$+\frac{1}{9}\underbrace{\left(\Delta\Sigma(Q^2)\, C^s(Q^2) + 2n_f\,\Delta g(Q^2)\, C^g(Q^2)\right)}_{=:\ a_0(Q^2)\, C^s(Q^2)}$$

Axial Charge

- $\boxed{\text{"}\overline{MS}\text{" SCHEME}}$ $\quad C^g(Q^2) \equiv 0$

  NO GLUON CONTRIBUTION TO Γ_1

  $\Delta\Sigma$ scale dependent

- $\boxed{\text{"AB" SCHEME}}$

$$a_0(Q^2) = \Delta\Sigma^{AB} - n_f \frac{\alpha_s}{2\pi}\Delta g(Q^2)$$

EXPLICIT ANOMALY CONTRIBUTION TO Γ_1

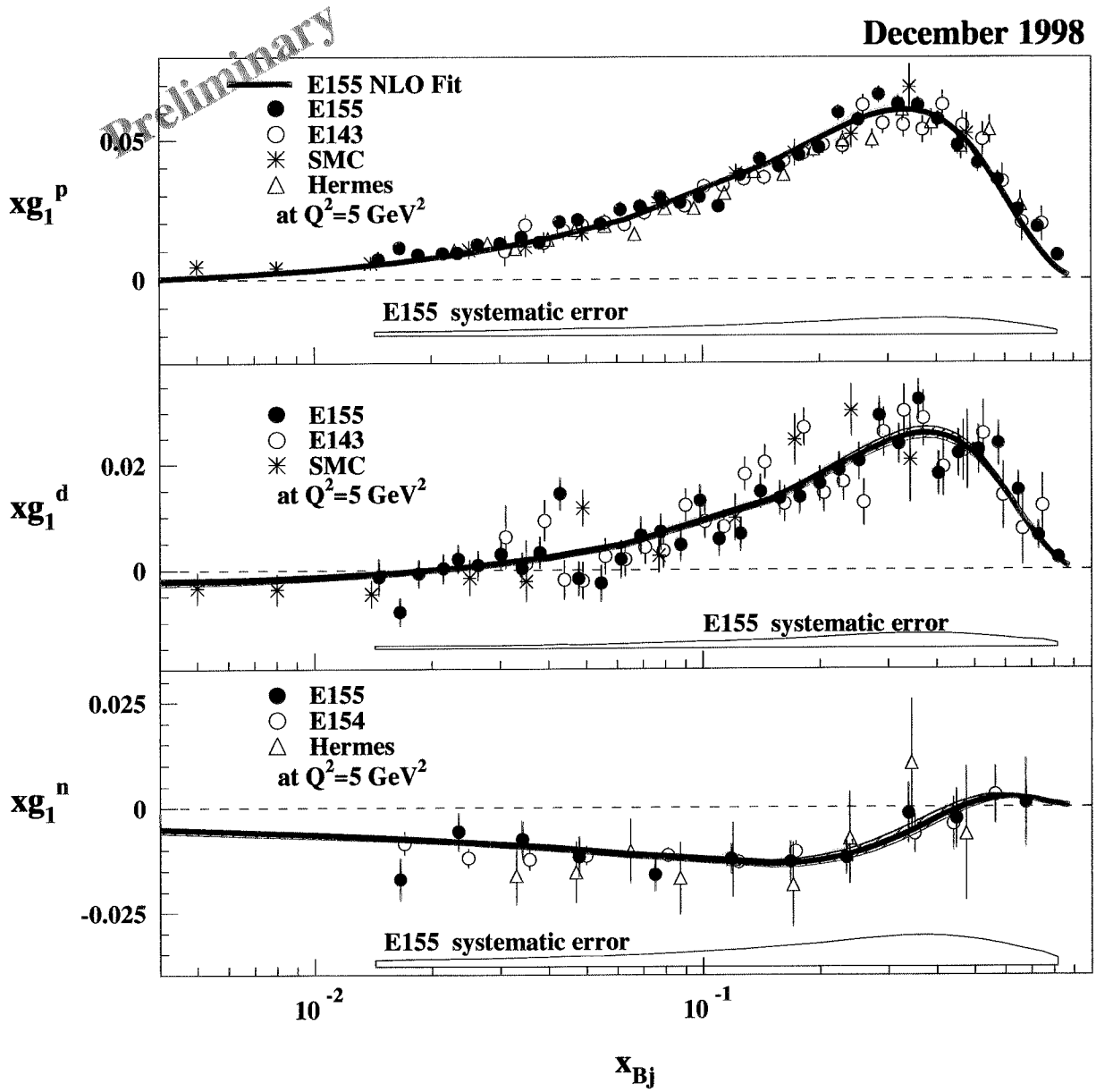
$\Delta\Sigma^{AB}$ scale independent

"quark - spin CONTENT"

- Δg is the same in $\overline{MS}$ and AB

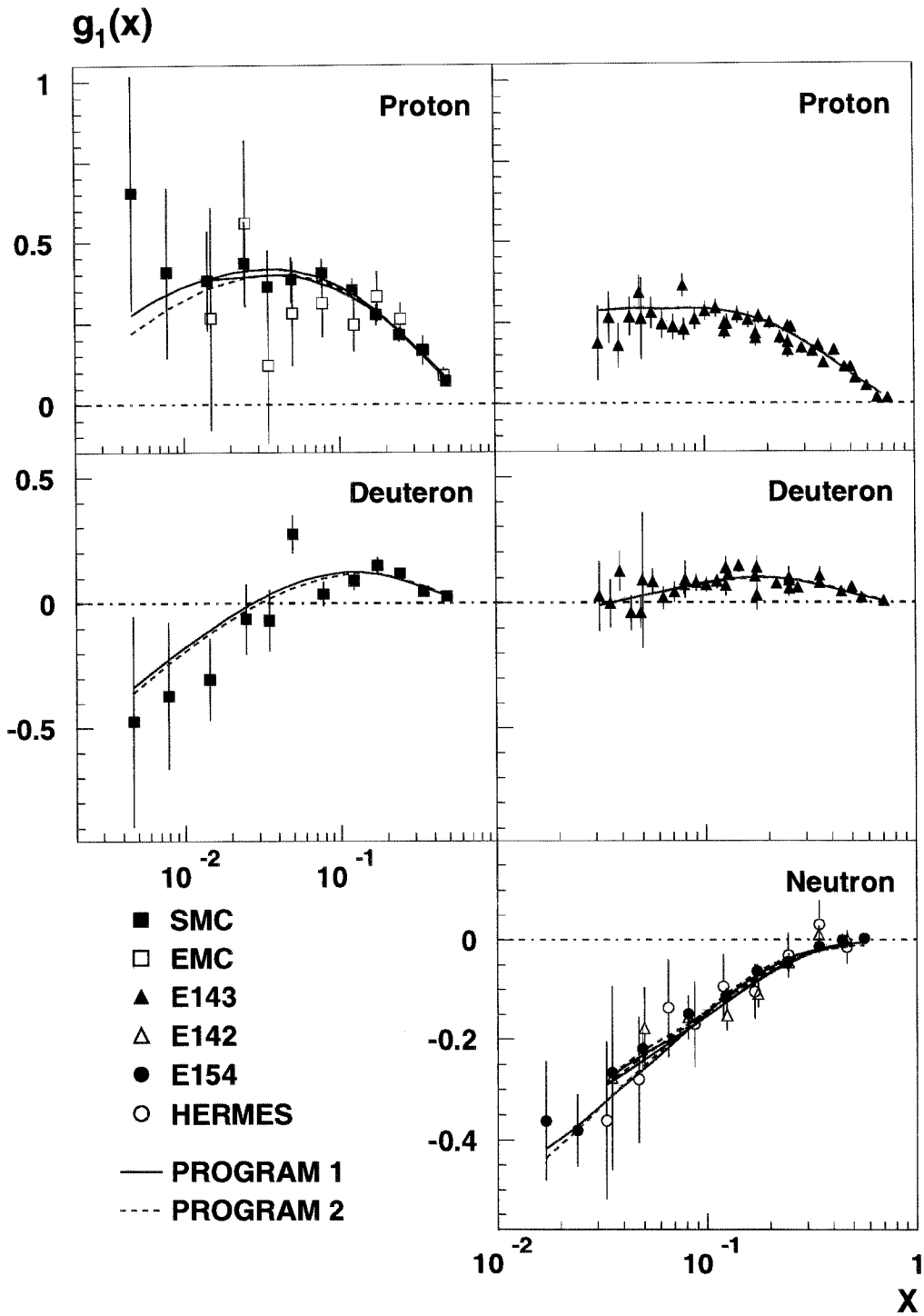
$xg_1(x,\ 5\ \mathrm{GeV}^2)$

- Preliminary E155 NLO Fit



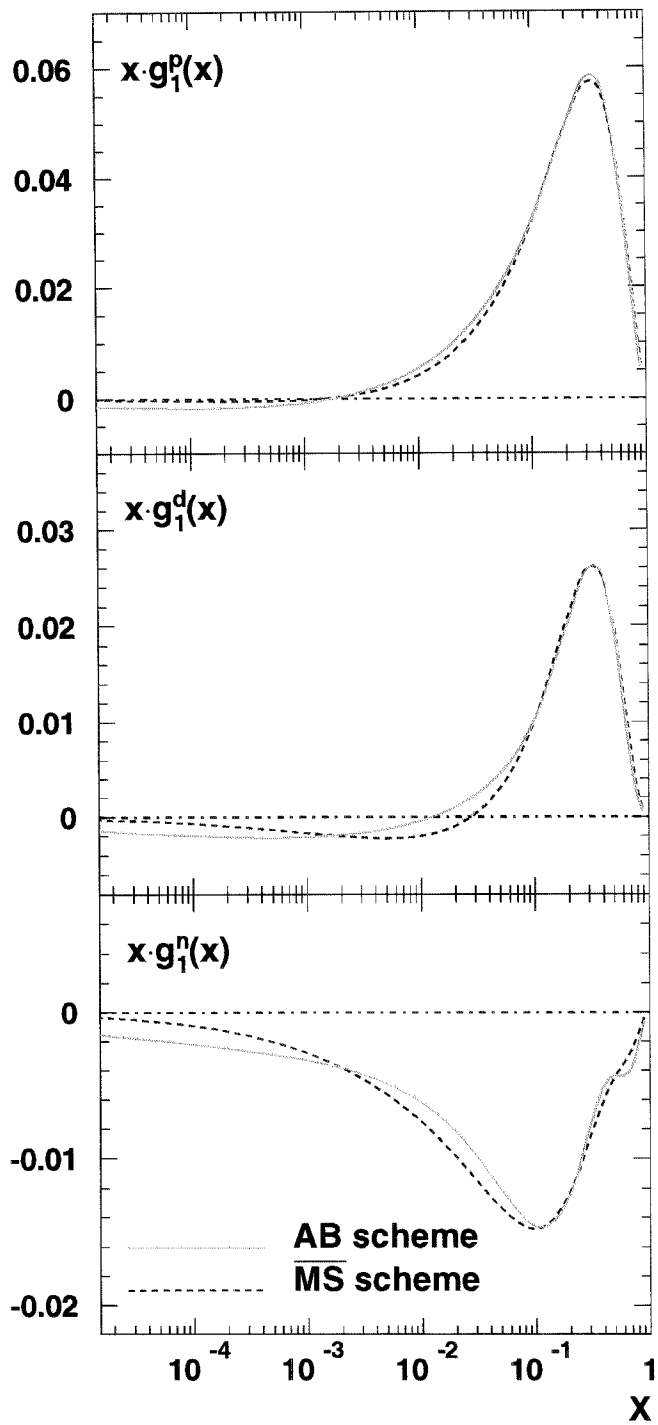
SMC NLO FIT

- comparison of two programs



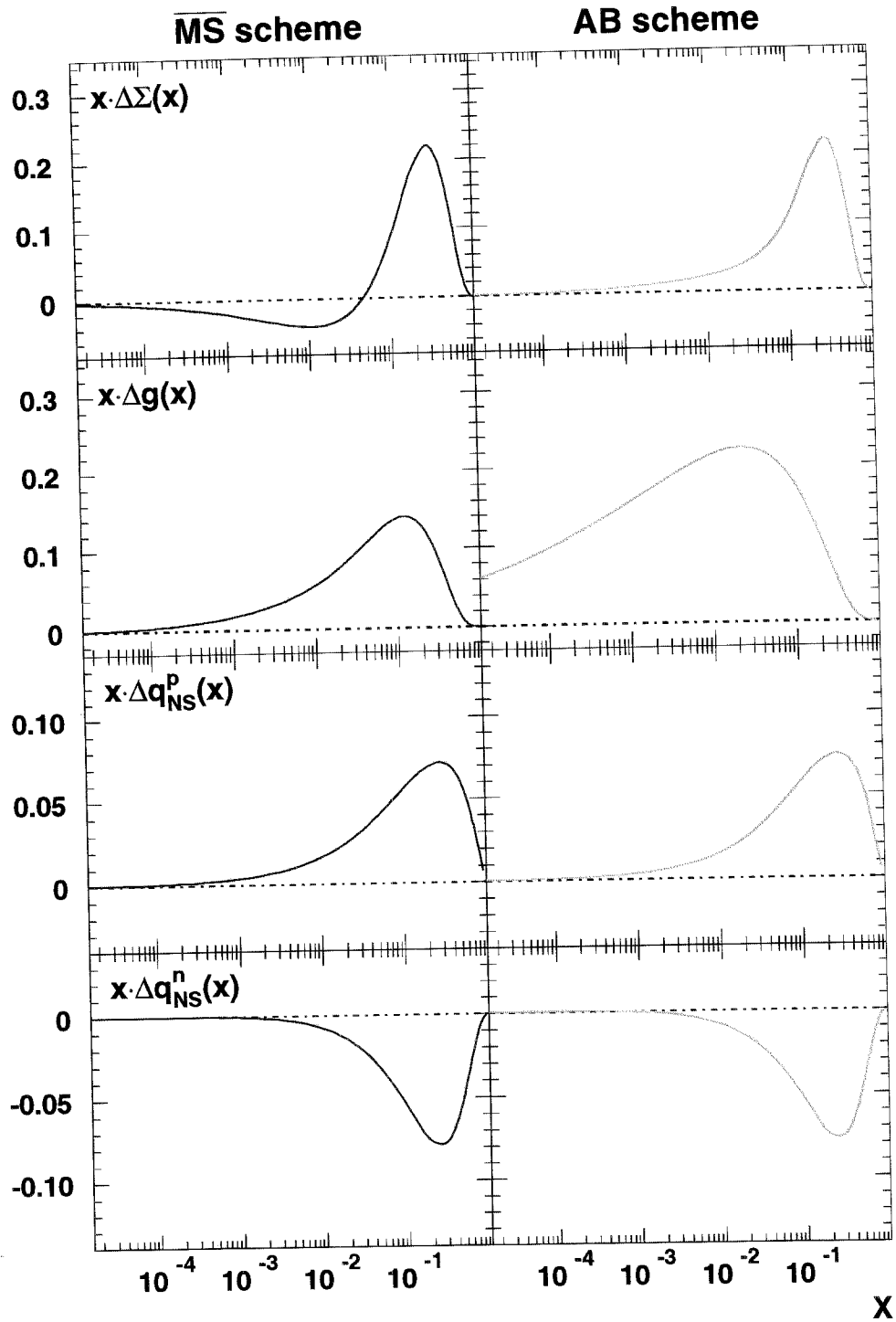
SMC NLO FIT

- Comparison of AB and $\overline{\mathrm{M}S}$ fits



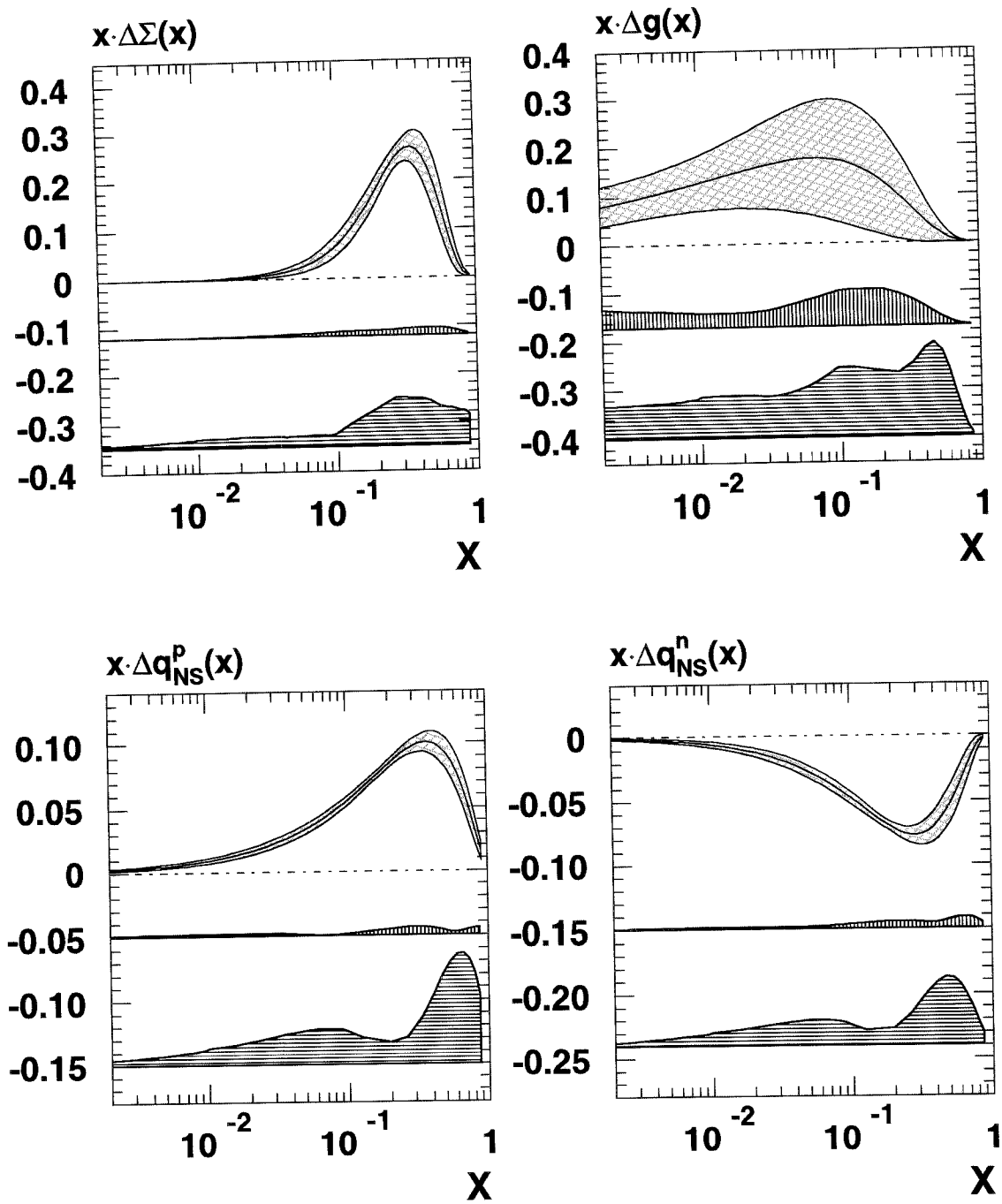
SMC NLO FIT

- Comparison of AB and $\overline{MS}$ schemes



SMC NLO FIT

- distribution functions



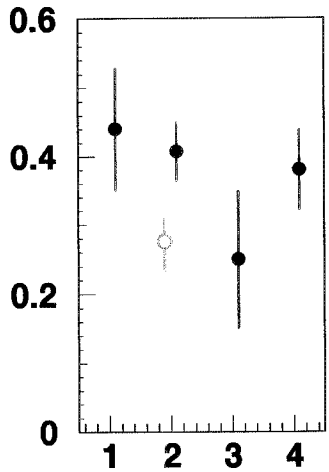
Moments of NLO fits

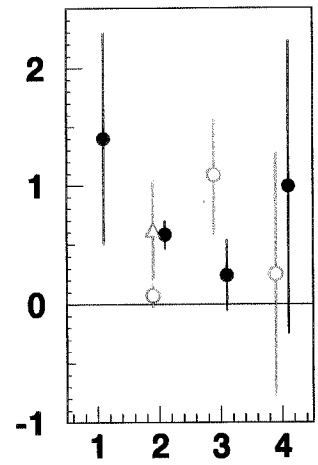
à la Windmolders, DIS99

1: Altarelli, Ball, Forte, Ridolfi
2: Leader, Sidorov, Stamenov; DIS'99
3: E154
4: SMC

$\overline{MS}$ AB

$\Delta\Sigma$(AB)



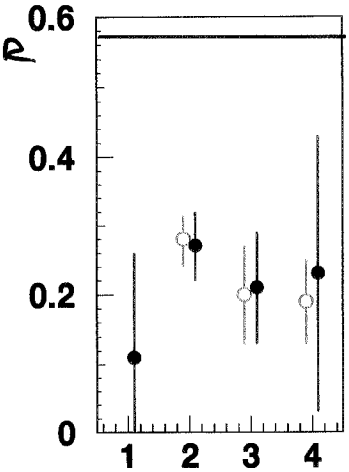


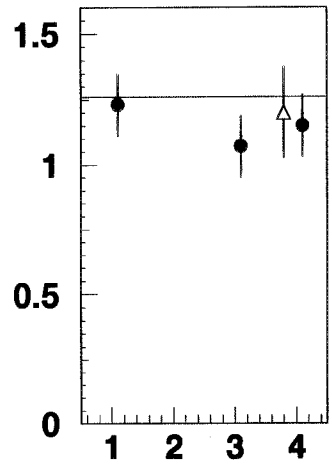
Δg (1 GeV^2)

different shape for Δg

ELLIS-JAFFE SR

a_0





$|g_a/g_v|$

ns-fit

Björken SR

FIRST MOM. T_1

- FROM MEASURED INTEGRAL @ Q^2_m

$$T_1 = \int_0^{x_{min}} + \int_{x_{min}}^{x_{max}} + \int_{x_{max}}^{\infty}$$

EXTRAPOLATIONS

small

(REGGE)

QCD-Fit

→

- SU3 SYM assumed

$$C^S \cdot a_0(Q^2) = T_1(Q^2) - \frac{1}{12}\left(\left|\frac{g_a}{g_v}\right| - \frac{1}{3}(3F-D)\right) C^{ns}(Q^2)$$

- QCD Extrapolation:

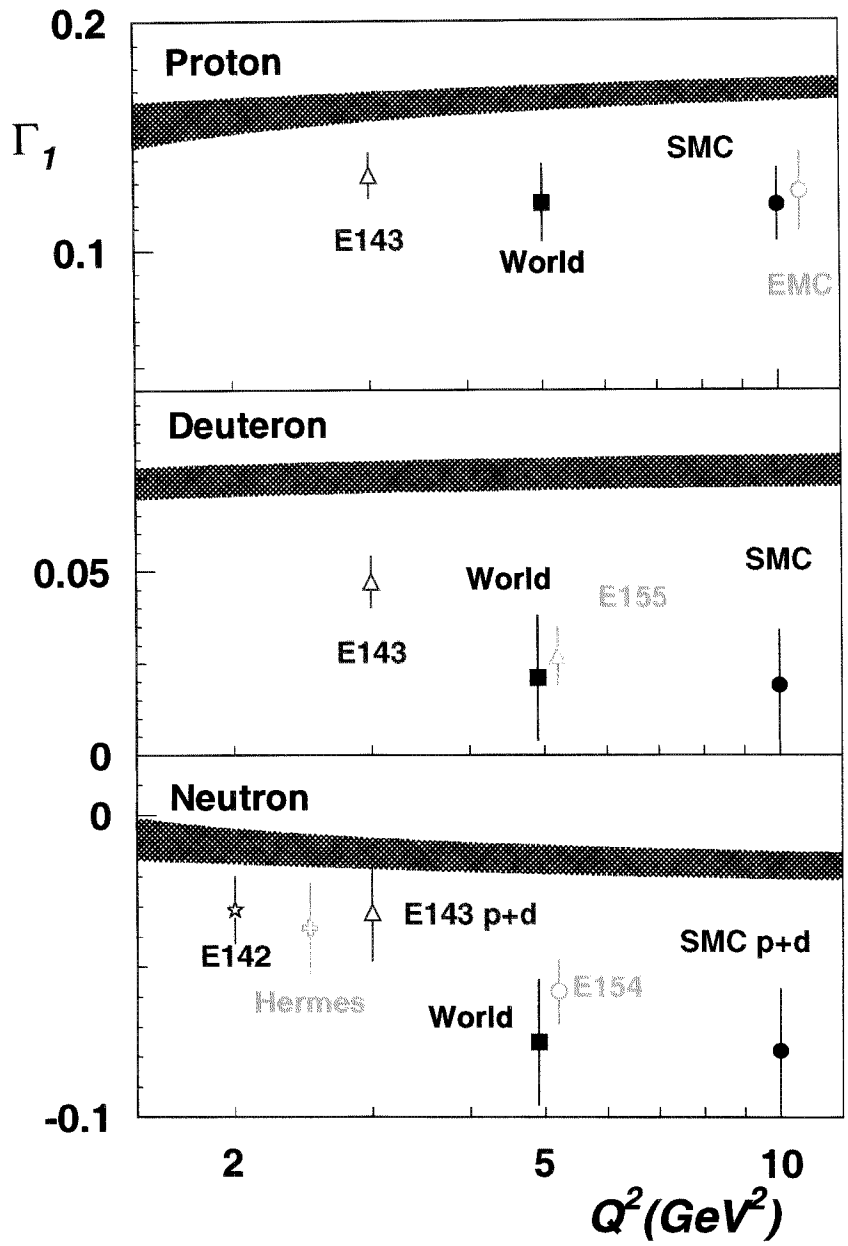
	p	d	n
SMC	0.12 15	0.06 13	
E154			0.18 10
E155		0.14 7	

$$0.14 \pm 0.07$$

SOMEWHAT LOWER THAN FROM QCD Fits ~ 0.20

First moment Γ_1 of g_1

- SMC World data (EMC, SMC, E142, E143, E154, Hermes)
- QCD extrapolations: SMC, E154, World
  Regge extrapolations: E142, E143, Hermes



Status of A_2 and g_2

- $|A_2| \leq \sqrt{R}$

$$
\begin{aligned}
g_2(x,Q^2) &= g_2^{\mathrm{WW}} + \bar{g}_2(x,Q^2) \\
g_2^{\mathrm{WW}}(x,Q^2) &= -g_1(x,Q^2) + \int_x^1 \frac{g_1(y,Q^2)}{y}\,\mathrm{d}y
\end{aligned}
$$

- twist-3 term $\bar{g}_2$, matrix element d_2

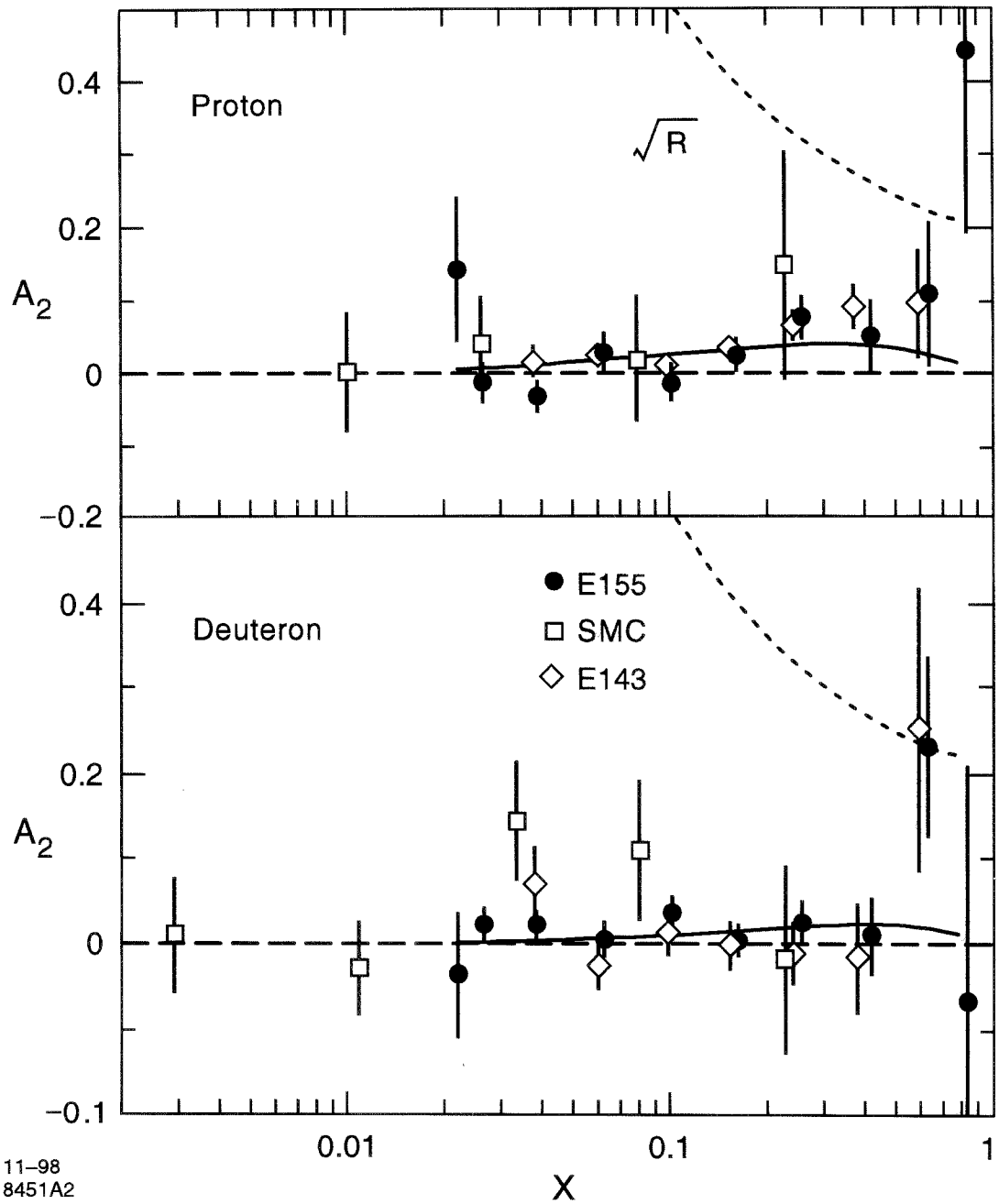
$$
d_2 = 3\int_0^1 x^2\,\bar{g}_2(x,Q^2)\,\mathrm{d}x
$$

- data:

SMC	exploratory $|A_2| << \sqrt{R}$
E142–E155	$A_2^p > 0$, A_2^n compatible with 0
E155x prelim.	precise data!

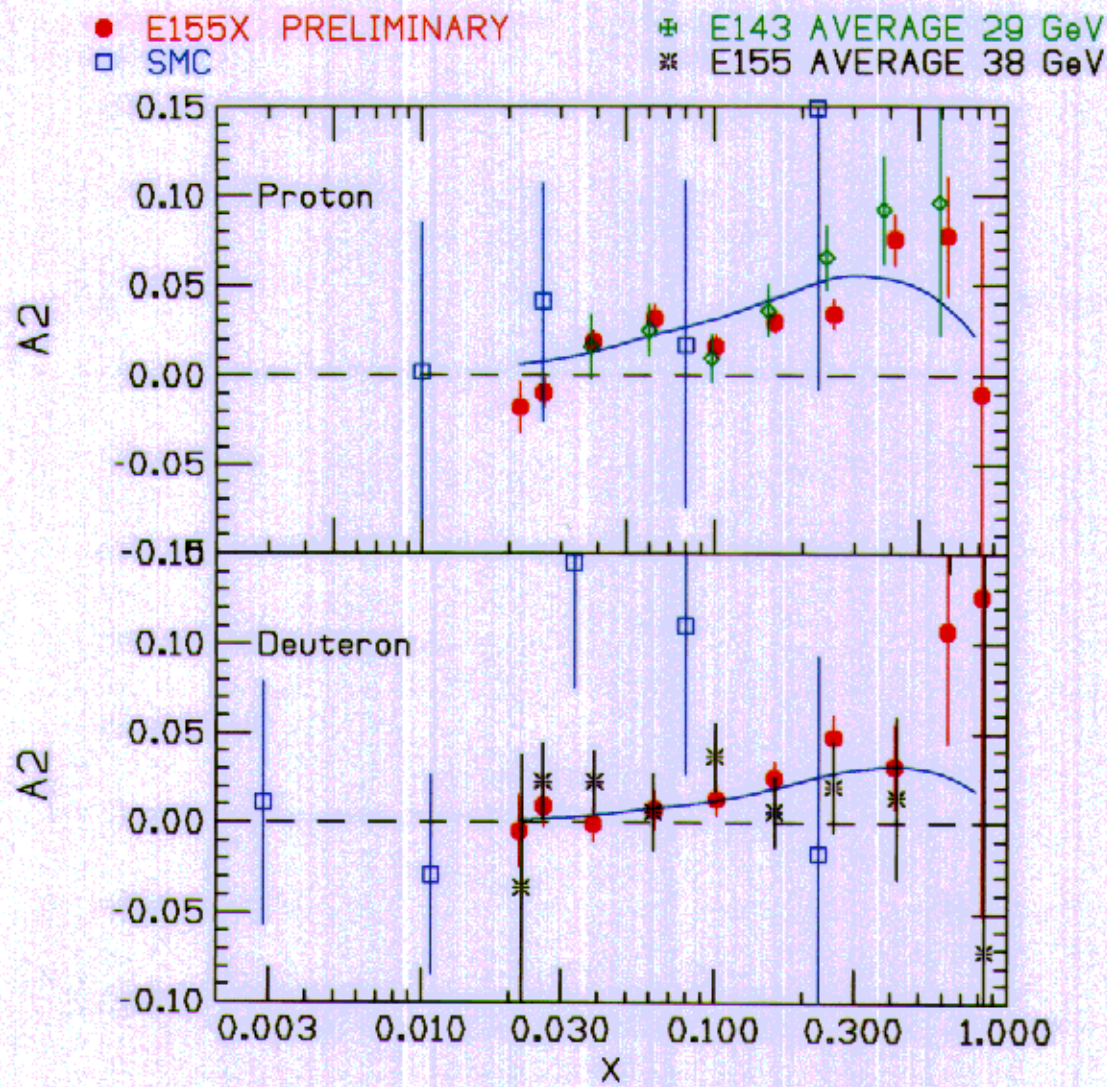
Asymmetry A_2

- ---- positivity limit: $|A_2| \leq \sqrt{R}$
- —— Wandzura-Wilczek term A_2^{WW}



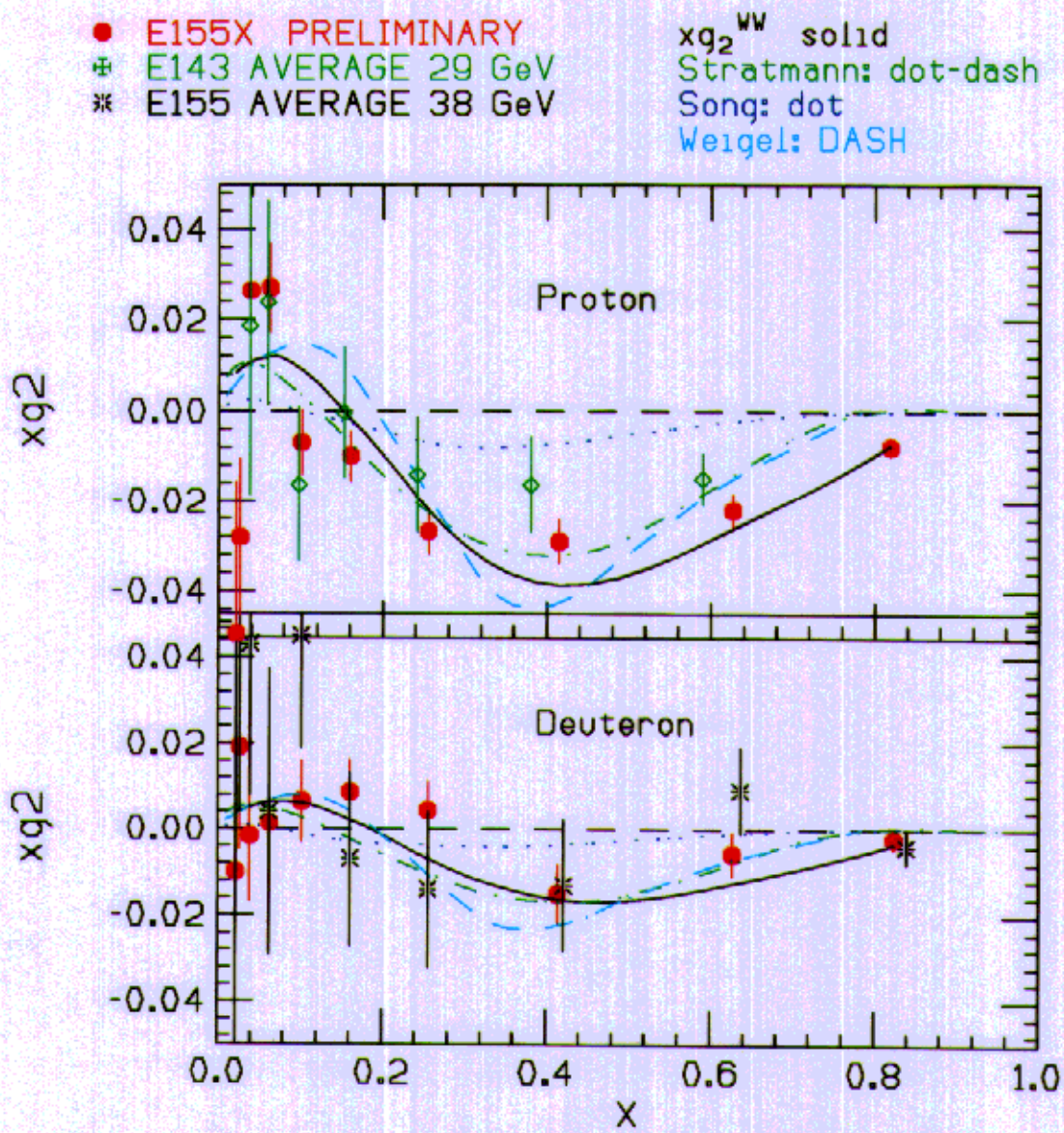
Preliminary E155x A_2

- precise E155x data! (preliminary)
- — Wandzura-Wilczek term A_2^{WW}



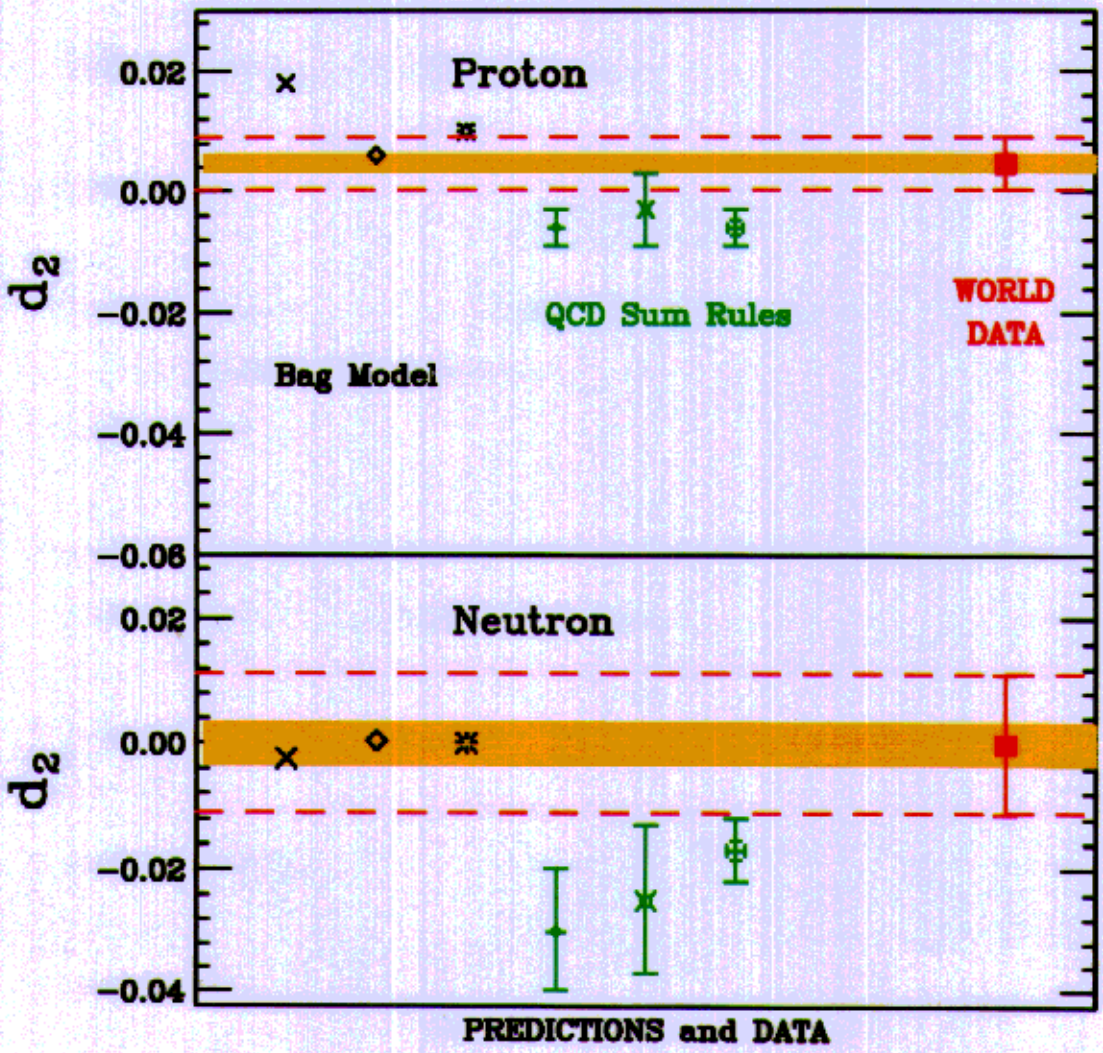
Structure function xg_2

- —— twist-2 term: g_2^{WW}
- -- -- bag model calculations



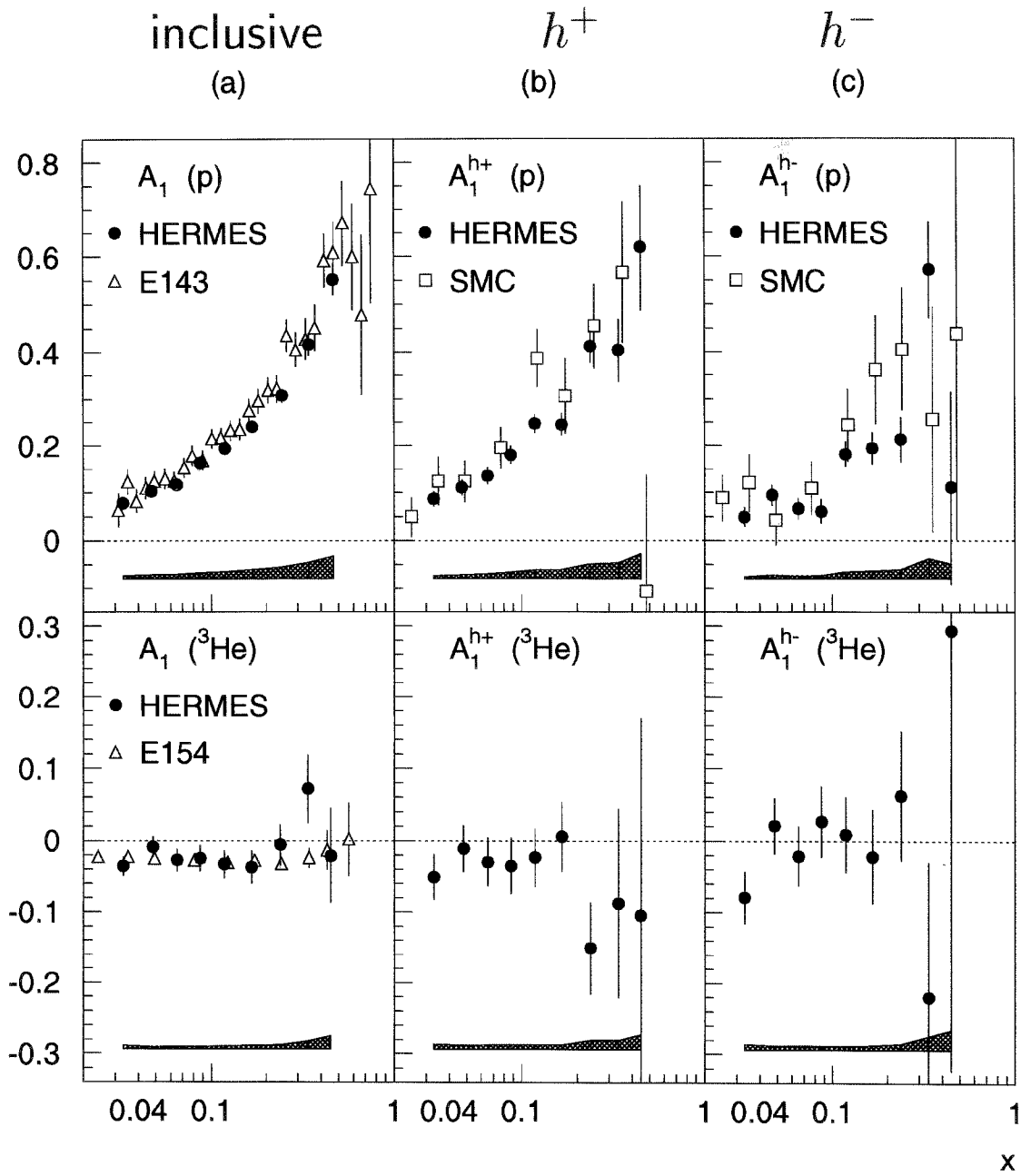
TWIST-3 ME d_2

- World data , $d_2^{\mathrm{P}} = 0.007 \pm 0.004$, $d_2^{\mathrm{d}} = 0.004 \pm 0.010$
  E142, E143, E154, E155
- theory: bag model, QCD sum rules
- projected E155x precision



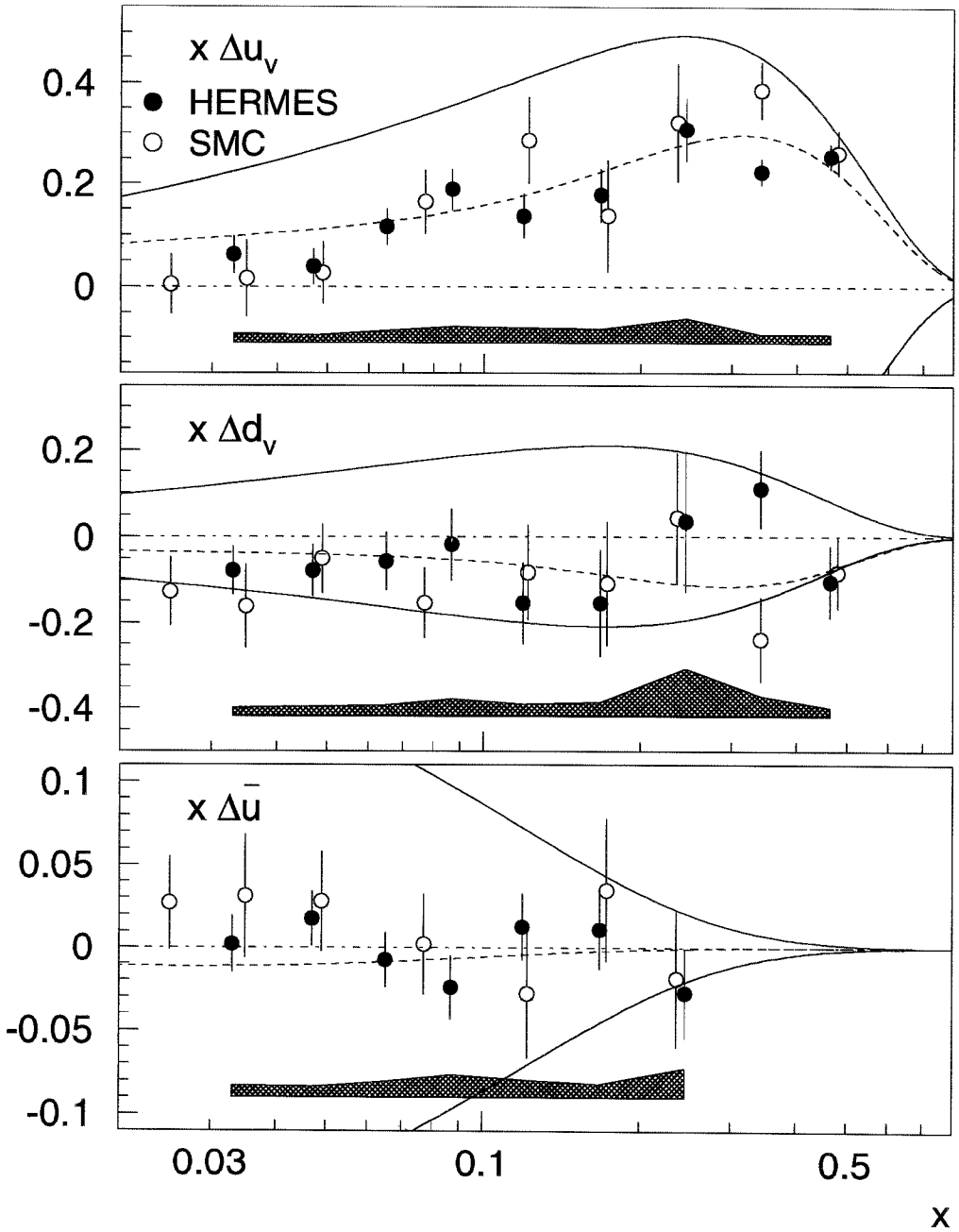
SEMI-INCLUSIVE ASYMMETRIES

- Hermes and SMC ($x > 0.04$)



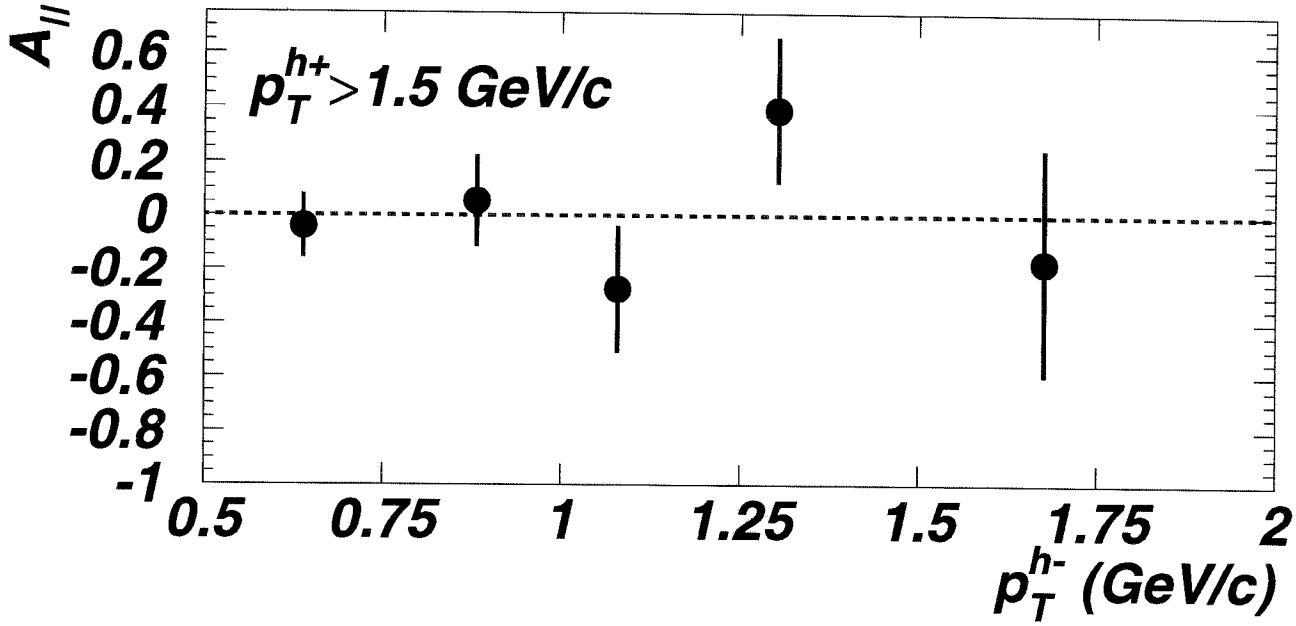
Valence and sea polarisation

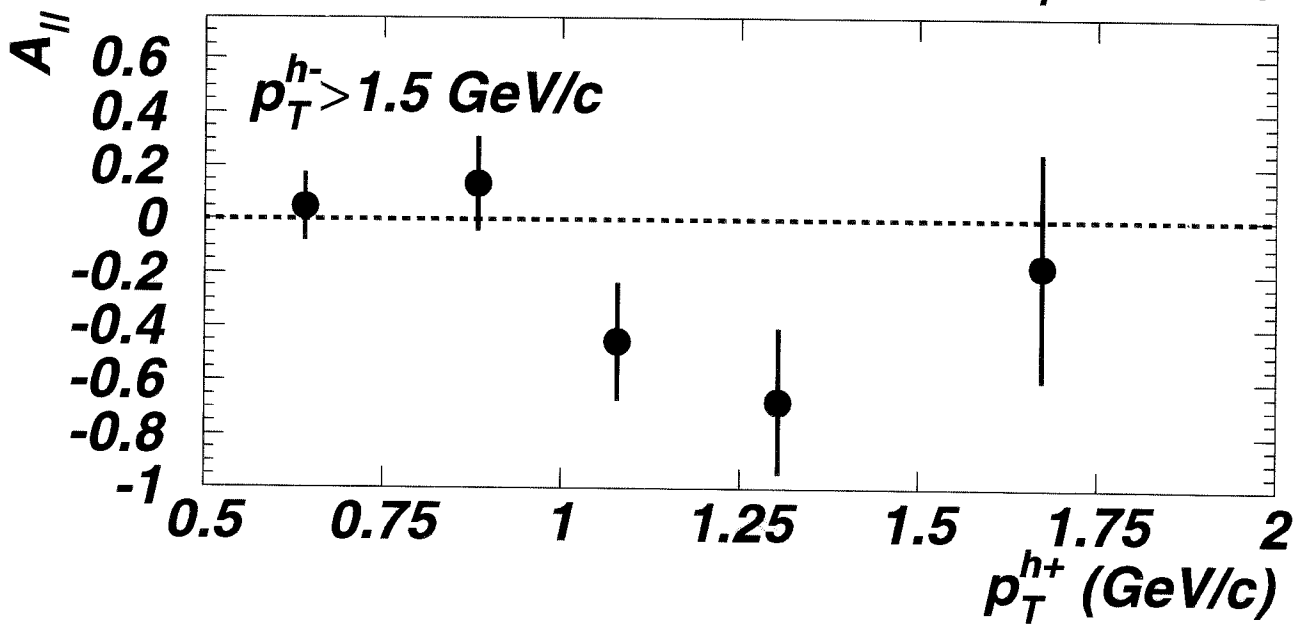
- Hermes and SMC ($x > 0.04$)



HERMES HIGH p_T HADRON PAIRS

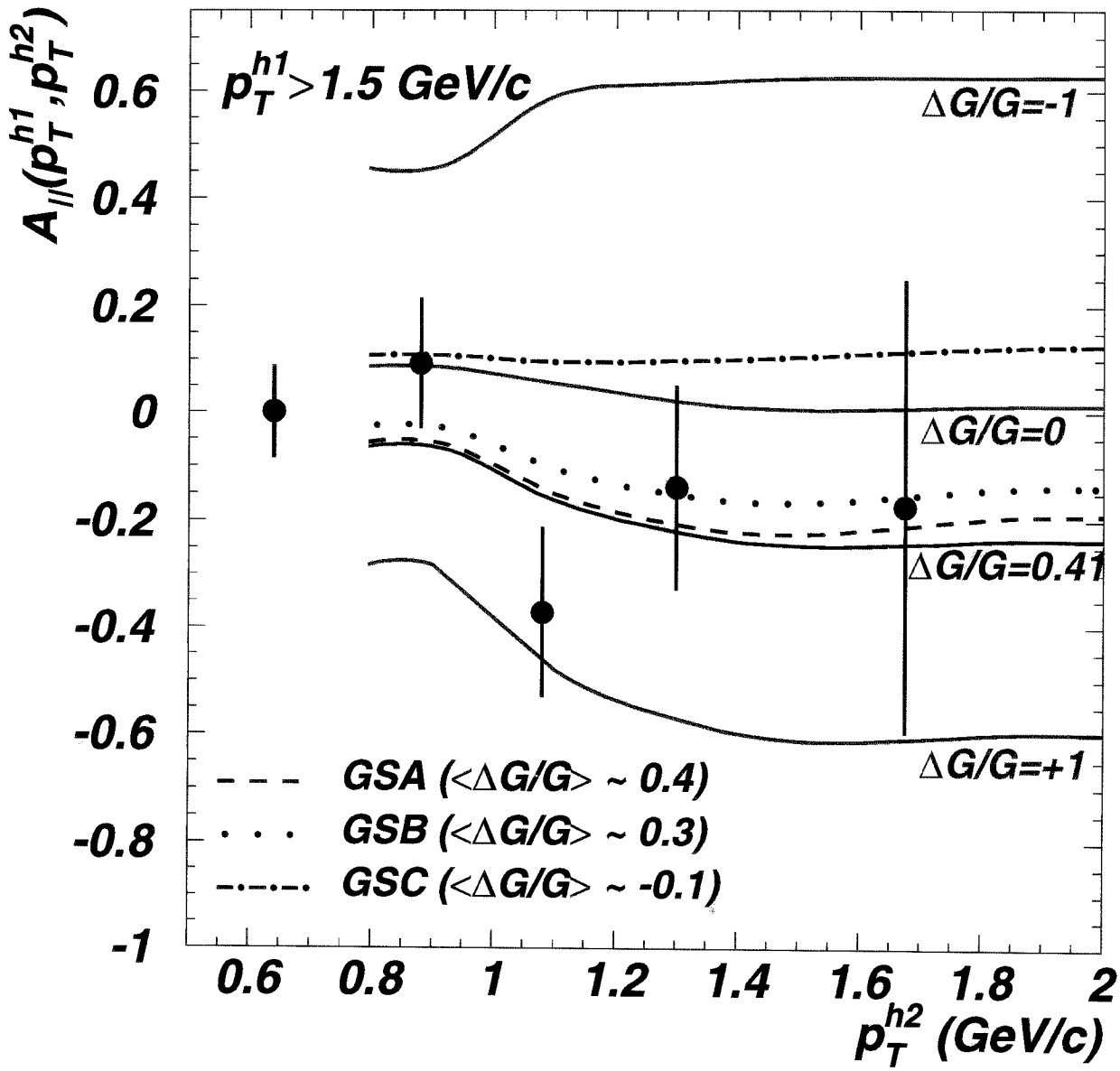
- no effect for positive hadrons
- two points below zero at moderate p_T^2





HIGH p_T HADRON PAIRS

- Comparison for several gluon polarisations
- $\Delta g \neq 0$?????? ; Hermes $\frac{\Delta G}{G} = 0.41 \pm 0.18 \pm 0.03$ @ $\langle x \rangle = 0.17$



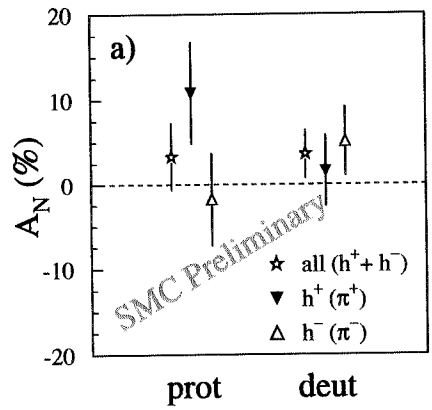
SMC Collins asymmetry

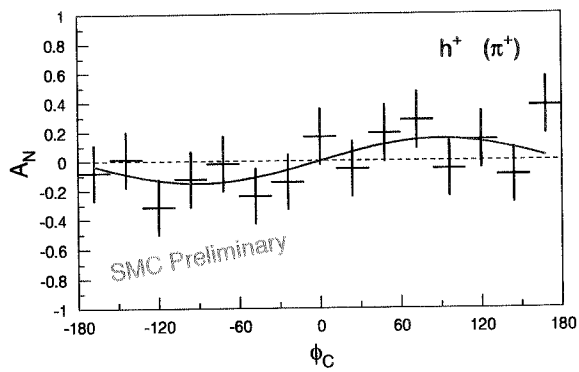
A. Bravar, DIS'99

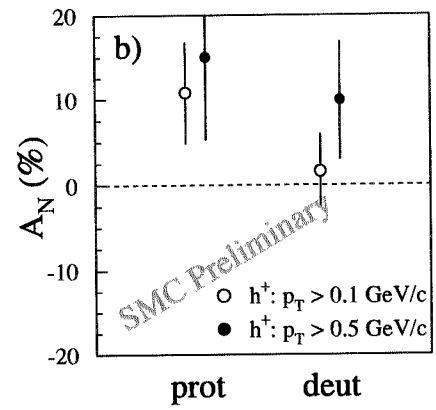
Transversely polarised target

$A_N = 0.11 \pm 0.06$ for π^+, $A_N = -0.02 \pm 0.06$ for π^-

azimuthal asymetry



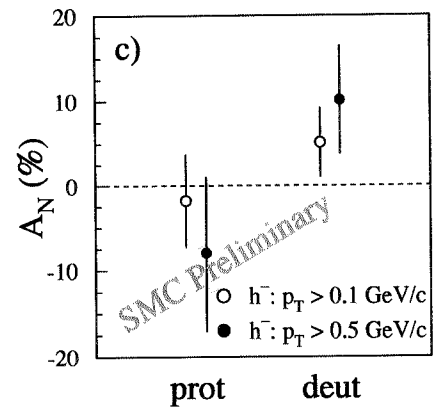




$$d\sigma(\phi_c) \sim (1 + A_N \sin\phi_c)\, d\phi_c$$

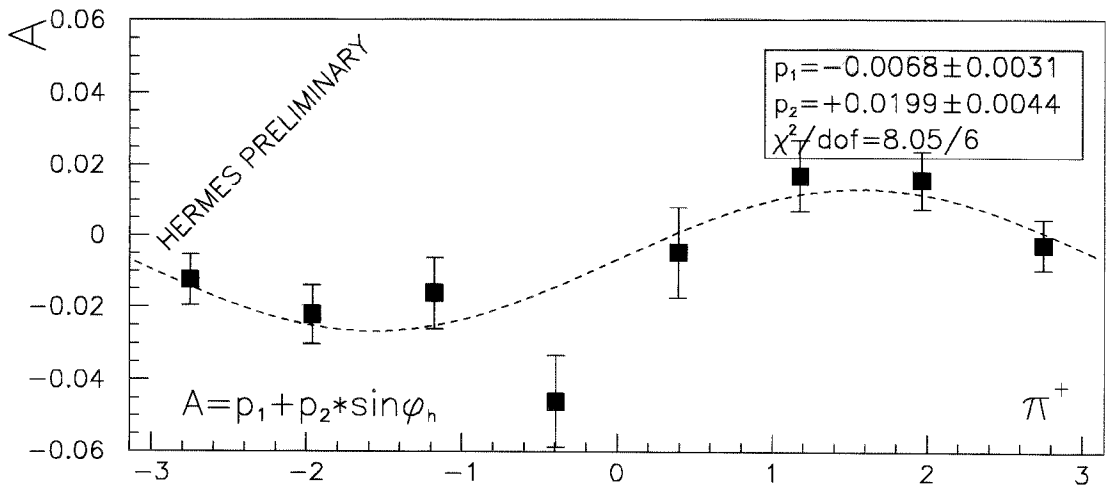
ϕ_c Collins angle

$$A_N = H(x) \cdot a_c(z, P_T)$$

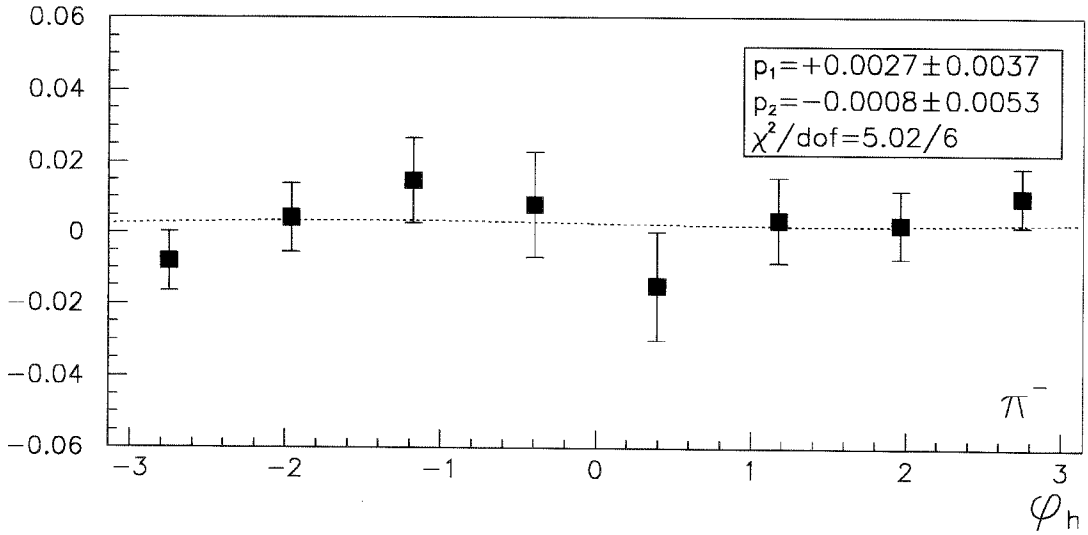


HERMES $\pi^{\pm}$ AZIMUTHAL ASYMMETRIES

- Longitudinally polarised target!



π^+



π^-

$$A_N^+ = 0.02 \pm 0.004$$

$$A_N^- = -0.001 \pm 0.005$$

Summary and Conclusions

- new g_2 data from E155x
- new g_1 data from E155, Hermes (g_1^p) and SMC (low x, Q^2)
- g_1 analysis finalised by SMC, E142, E143, E154
- NLO QCD analyses describe data well
  Ellis-Jaffe SR violated, Bjorken SR verified
- However, Δg hardly constraint
- Need direct measurements of Δg

Compass	at CERN: open charm from PGF
	setting up, start physics data taking 2001
RHIC	complementary, polarised data from 2001
Hermes	difficult