Proton and Deuteron Spin Structure from SLAC Experiment E155

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Representing the E155 Collaboration

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- Inclusive DIS
- Description of Experiment
- Preliminary Results
- E155 extension
- Summary

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Smith College
SLAC
Stanford University
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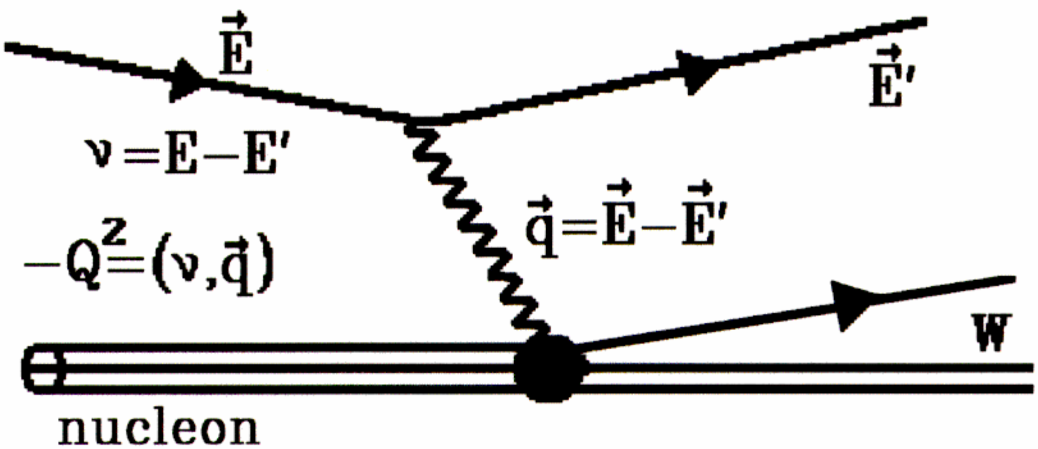
Inclusive Deep Inelastic Scattering



- θ : scattering angle
- Q^2: 4-momentum transfer squared
- ν : energy transfer
- $x = \frac{Q^2}{2M\nu}$: Bjorken scaling variable

Unpolarized Deep Inelastic Scattering

$$\frac{d\sigma}{d\Omega dE'} = \frac{4\alpha^2 E'^2 cos^2(\theta/2)}{Q^4}\left[\frac{F_2(x,Q^2)}{\nu} + \frac{2F_1(x,Q^2)}{M}\tan^2(\theta/2)\right]$$

F_1 and F_2 are the unpolarized structure functions.

In naive quark parton model F_1 is related to the spin averaged quark distribution functions:

$$F_1(x,Q^2) = \frac{1}{2}\sum_i e_i^2[q_i^{\uparrow}(x,Q^2) + q_i^{\downarrow}(x,Q^2)]$$

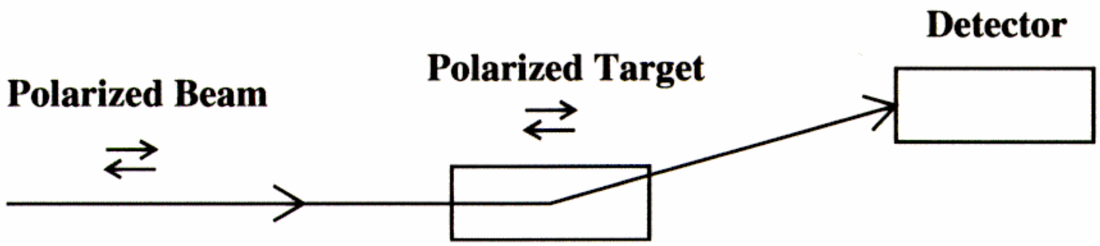
→ Up (down) arrow denotes spin aligned (anti-aligned) with nucleon spin

→ i is over the quark and antiquark

→ e_i is the corresponding charge

.

Polarized Deep Inelastic Scattering



$$A_{\parallel} = \frac{\sigma^{\uparrow\downarrow} - \sigma^{\uparrow\uparrow}}{\sigma^{\uparrow\downarrow} + \sigma^{\uparrow\uparrow}} = f_k\Big[g_1(x,Q^2)[E+E'\cos(\theta)] - \frac{Q^2}{\nu} g_2(x,Q^2)\Big]$$

$$A_{\perp} = \frac{\sigma^{\downarrow\leftarrow} - \sigma^{\uparrow\leftarrow}}{\sigma^{\downarrow\leftarrow} + \sigma^{\uparrow\leftarrow}} = f_k E' \sin(\theta)\Big[g_1(x,Q^2) + \frac{2E}{\nu} g_2(x,Q^2)\Big]$$

g_1 and g_2 are the polarized structure functions.

→ $A_{\parallel}$ is primarily sensitive to g_1

→ $A_{\perp}$ is more sensitive to g_2

→ f_k includes contribution from unpolarized structure functions

g_1 Structure Function

In QPM g_1 is related to the spin distribution functions:

$$g_1(x,Q^2) = \frac{1}{2}\sum_i e_i^2 \Delta q_i$$

$$\Delta q_i = q_i^{\uparrow}(x,Q^2) - q_i^{\downarrow}(x,Q^2)$$

The index i is over the quark and antiquark flavors and e_i is the corresponding charge

However, in pQCD g1 is also sensitve to the polarized gluon distribution ΔG:

$$g_1(x,Q^2) = \frac{1}{2}\sum_q e_q^2 \, [\, C_q \otimes \Delta q + C_G \otimes \Delta G \,]$$

where $C_{q,G}$ are the perturbative coefficients

Virtual Photon-Nucleon Asymmetries

$$A_1(x,Q^2) = \frac{\sigma_T^{1/2} - \sigma_T^{3/2}}{\sigma_T^{1/2} + \sigma_T^{3/2}} = \frac{g_1(x,Q^2) - \gamma^2 g_2(x,Q^2)}{F_1(x,Q^2)}$$

$\sigma_T^{1/2}$ and $\sigma_T^{3/2}$ are transverse virtual photoabsorbtion cross sections for final helicity states of 1/2 and 3/2

→ $\sigma_T^{1/2} \sim \frac{1}{2}\sum_i e_i^2 q_i^{\uparrow}$ and $\sigma_T^{3/2} \sim \frac{1}{2}\sum_i e_i^2 q_i^{\downarrow}$

→ $A_1 \approx g_1/F_1$ for $\gamma^2 = Q^2/\nu^2 = 0$ (high energy)

$$A_2(x,Q^2) = \frac{2\sigma_{TL}}{\sigma_T^{1/2} + \sigma_T^{3/2}} = \gamma\frac{g_1(x,Q^2) + g_2(x,Q^2)}{F_1(x,Q^2)}$$

→ σ_{TL} is the transverse-longitudinal interference term.

Spin Structure Measurements

Year	Exp.	Data	Target	Publications
1978	E80	$A_{\parallel}^{p}$	Butanol	PRL 37, 1258 (76)
				PRL 37, 1261 (76)
				PRL 41, 70 (78)
				PRL 45, 200 (80)
1983	E130	$A_{\parallel}^{p}$	Butanol	PRL 51, 1135 (83)
1988	EMC	$A_{\parallel}^{p}$	NH_3	PLB 206, 364 (88)
				NPB 328, 1 (89)
1991	SMC	$A_{\parallel}^{d}$	Butanol	PLB 302, 533 (93)
1992	E142	$A_{\parallel}^{n}, A_{\perp}^{n}$	^3He	PRL 71, 959 (93)
				PRD 54, 6620 (96)
1993	SMC	$A_{\parallel}^{p}, A_{\perp}^{p}$	Butanol	PLB 329, 399 (94)
				PLB 336, 125 (94)
1994	E143	$A_{\parallel}^{p}, A_{\perp}^{p}, A_{\parallel}^{d}, A_{\perp}^{d}$	$^{15}NH_3$, $^{15}ND_3$	PRL 74, 346 (95)
				PRL 75, 25 (95)
				PLB 364, 61 (95)
			HEP-PH 9802357	PRL 76, 587 (96)
				PRL 78, 815 (97)
1994	SMC	$A_{\parallel}^{d}$	Butanol	PRB 357, 248 (95)
1995	SMC	$A_{\parallel}^{d}$	Butanol	PRB 396, 338 (97)
1995	HERMES	$A_{\parallel}^{n}$	^3He	PLB 404, 383 (97)
1995	E154	$A_{\parallel}^{n}, A_{\perp}^{n}$	^3He	PRL 79, 26 (97)
				PLB 404, 377 (97)
				PLB 405, 180 (97)
1996	SMC	$A_{\parallel}^{p}$, $A_{\parallel}^{d}$	NH_3	CERN-EP 98-085
1996	HERMES	$A_{\parallel}^{p}$	H_2	HEP-EX 980715
1997	E155	$A_{\parallel}^{p}, A_{\perp}^{p}, A_{\parallel}^{d}, A_{\perp}^{d}$	$^{15}NH_3$, LiD	

Physics Asymmetries

$$A_{\parallel}(\mathrm{or} A_{\perp}) = C_1\Big(\Big(\frac{N_L - N_R}{N_L + N_R}\Big)\frac{1}{f P_b P_t} + C_2\Big) + A_{RC}$$

- N_L and N_R are rates for L and R beam helicity, corrected for pair-symmetric contributions and electronics dead time.
- C_1 and C_2 are for nuclear corrections and/or target contamination corrections.
- f is the dilution factor (≈ 0.15 for NH_3, $\approx 0.35-0.40$ for LiD)
- P_b, P_t are the beam and target polarizations
- A_{RC} radiative correction

Neutron Extraction

$$g^n(x, Q^2) = \frac{2g^d(x, Q^2)}{(1 - 1.5\omega_d)} - g^p(x, Q^2)$$

- $\omega_d = 0.05 \pm 0.01$ = probability deuteron is in D-state

E155 Keys

- Decrease statistical uncertainties

→ Collected ≈ 200 million deep inelastic events

- Reduce systematic uncertainties

- Cover wide x and Q^2 range in single experiment

→ Use 48.3 GeV electron beam

→ Add third spectrometer

- Improve precision on Q^2 dependence of g_1 to constrain ΔG

Polarized Electron Beam

- Intense 48.3 GeV Beam
- Highly polarized : $P_b = 0.813 \pm 0.020$
- Beam polarization measured with two independent Møller detector systems

$$A = \frac{N_{e^-}(\uparrow\uparrow) - N_{e^-}(\uparrow\downarrow)}{N_{e^-}(\uparrow\uparrow) + N_{e^-}(\uparrow\downarrow)}$$
$$= -P_{beam}P_{foil}\frac{(7+\cos^2\theta_{cm})\sin^2\theta_{cm}}{(3+\cos^2\theta_{cm})^2}$$

→ Single arm system and double arm coincidence system agree within 1%

→ 20-50 μm thick target foils

- Helicity varied randomly from pulse to pulse (120 Hz)

Polarized Targets

- Solid cryogenic targets
- Dynamic nuclear polarization using microwaves

- $^{15}NH_3$ used for proton target

→ Improved μwave power delivery $\rightarrow < P_t > \approx$ 80%

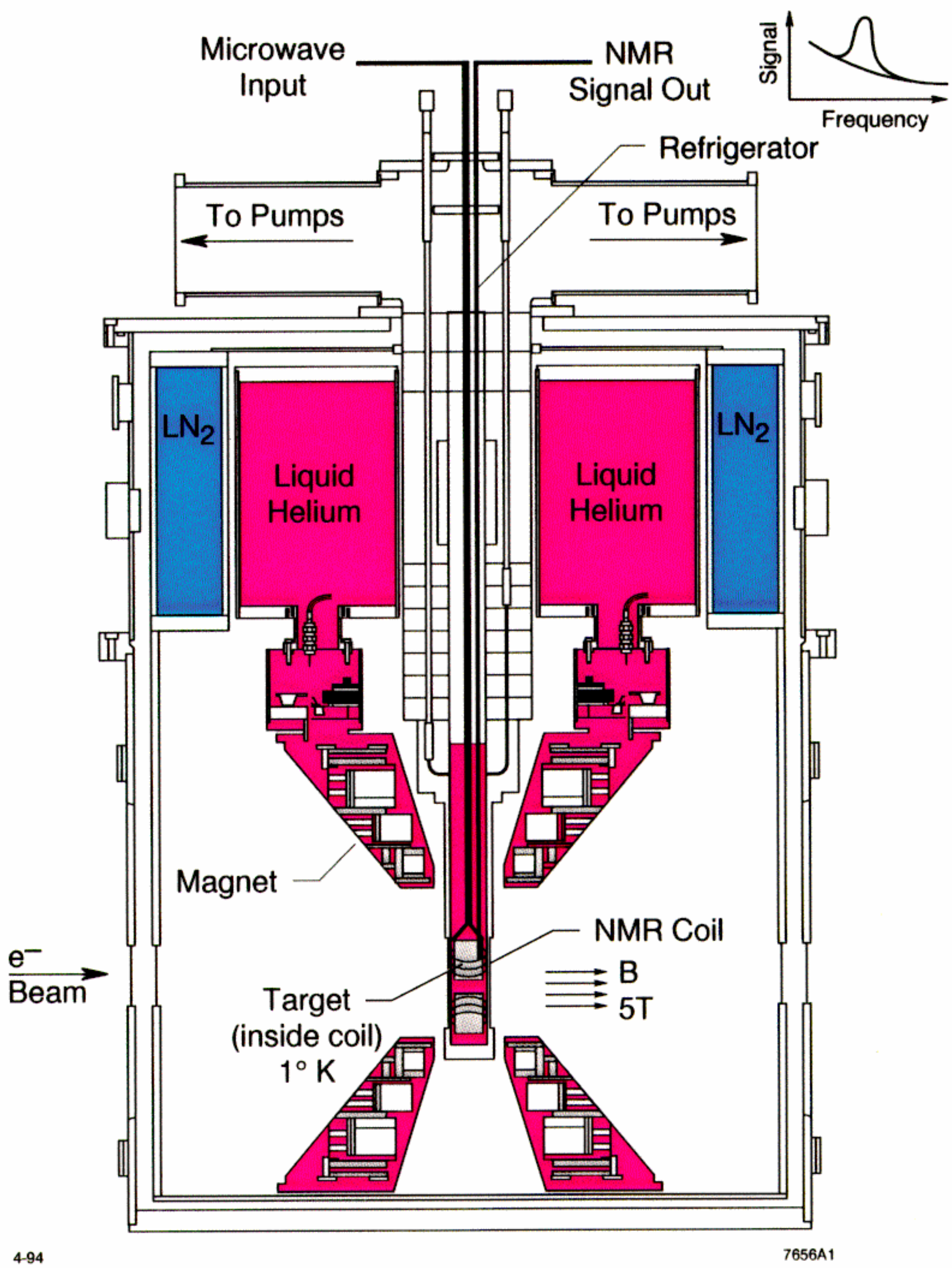
- ^{6}LiD used for deuteron target

→ LiD $\approx$ 50% improvement in dilution over $^{15}ND_3$

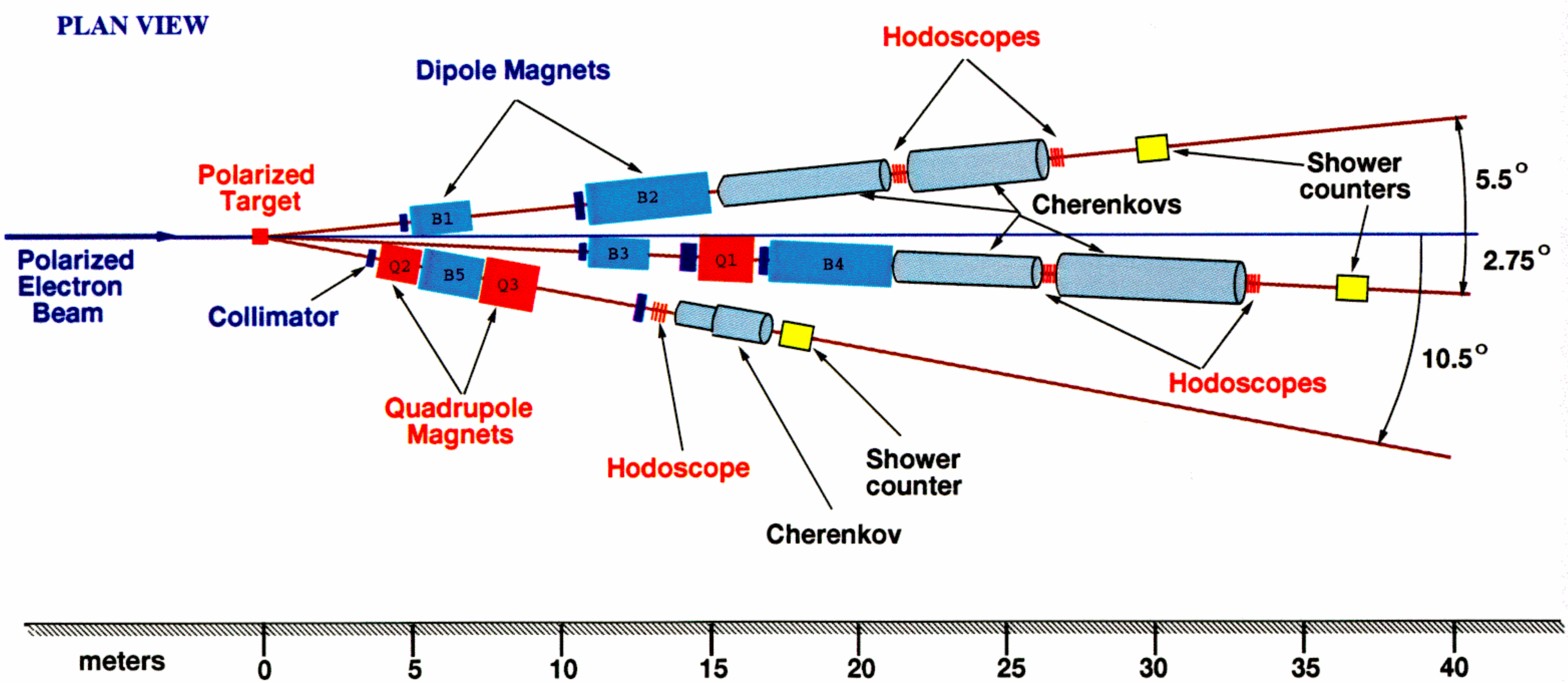
→ LiD 6 times as radiation resistant

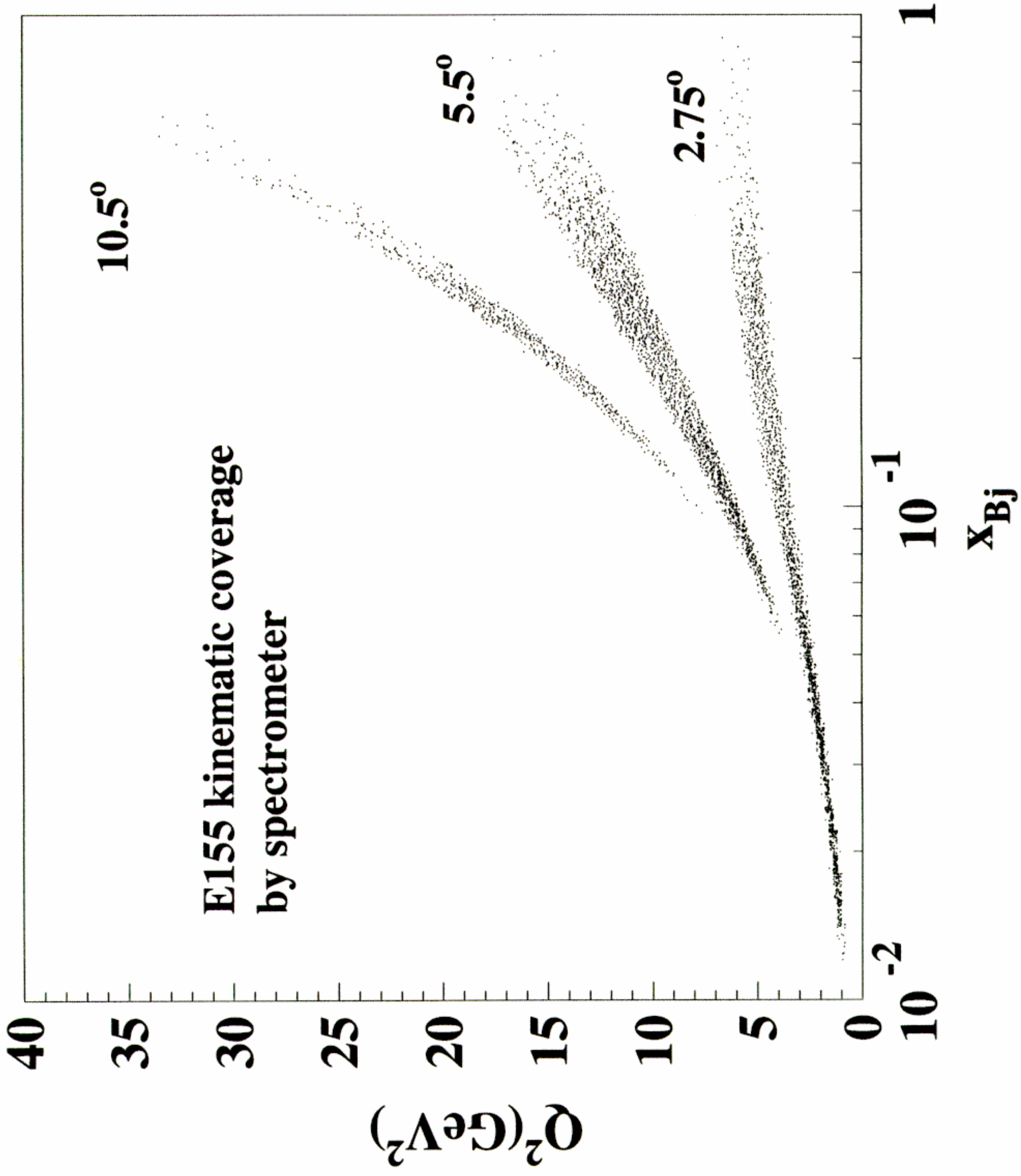
→ $< P_t > \approx 20\%$

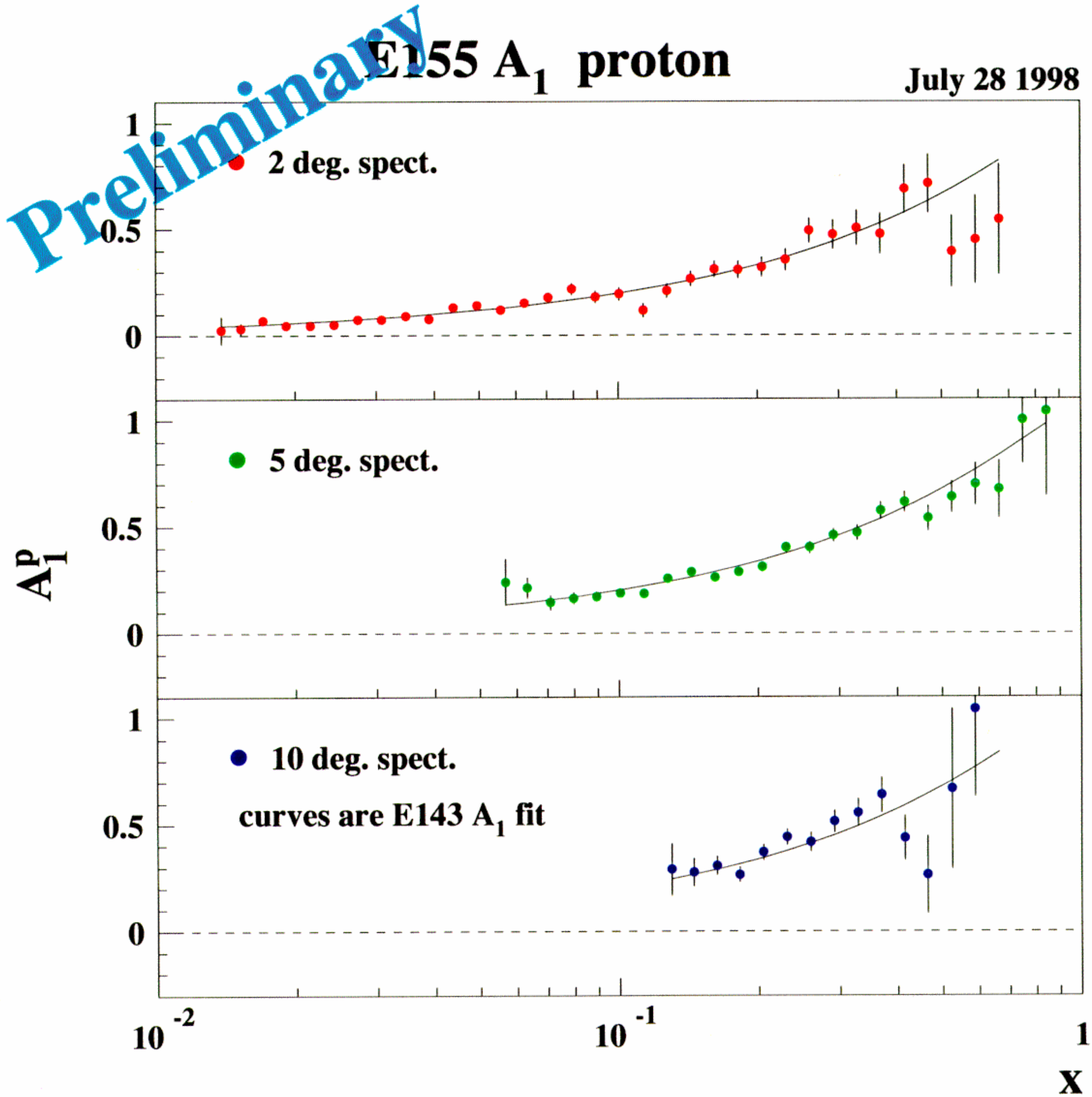
E143/E155 Target

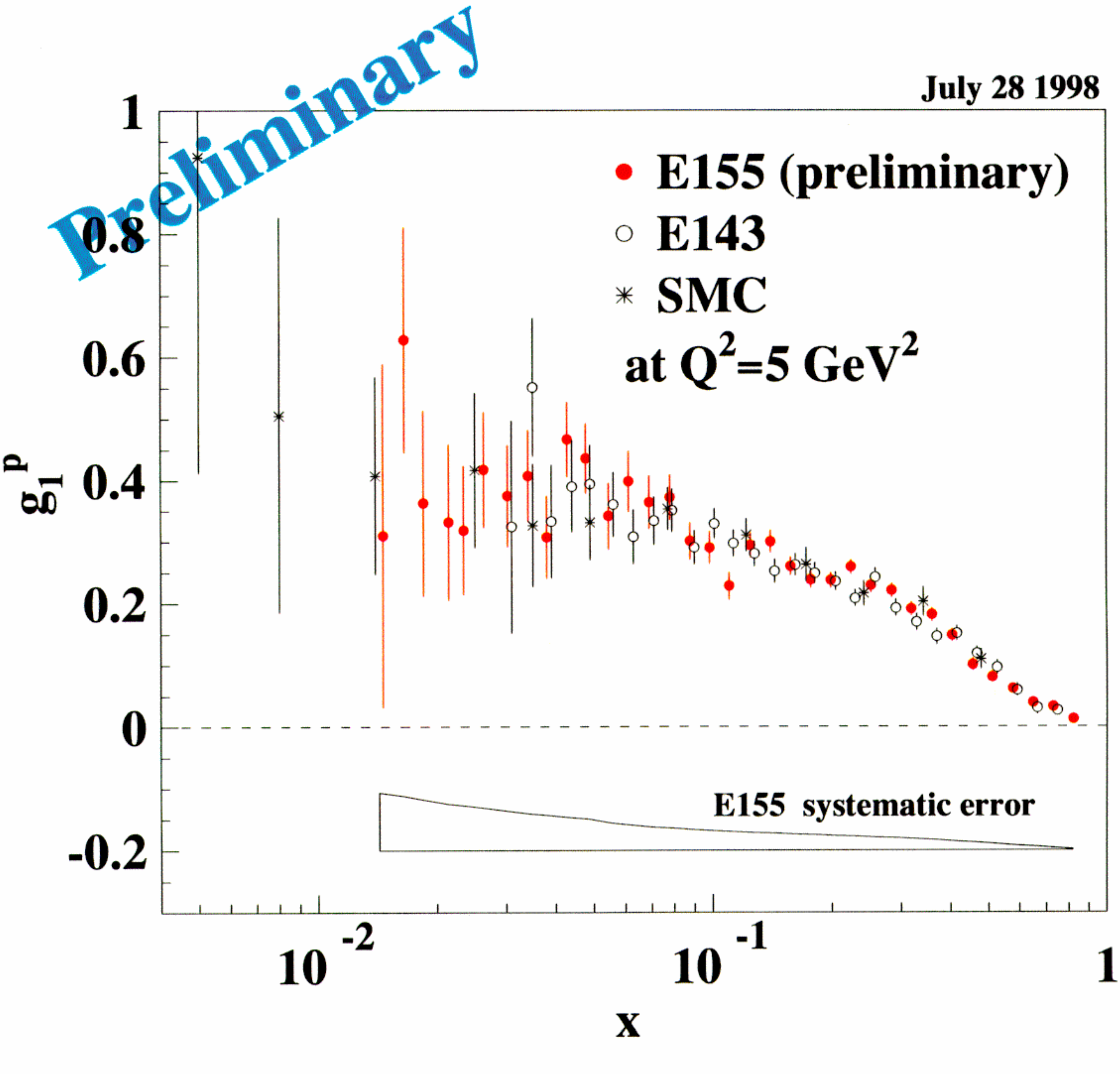


E155 Spectrometers



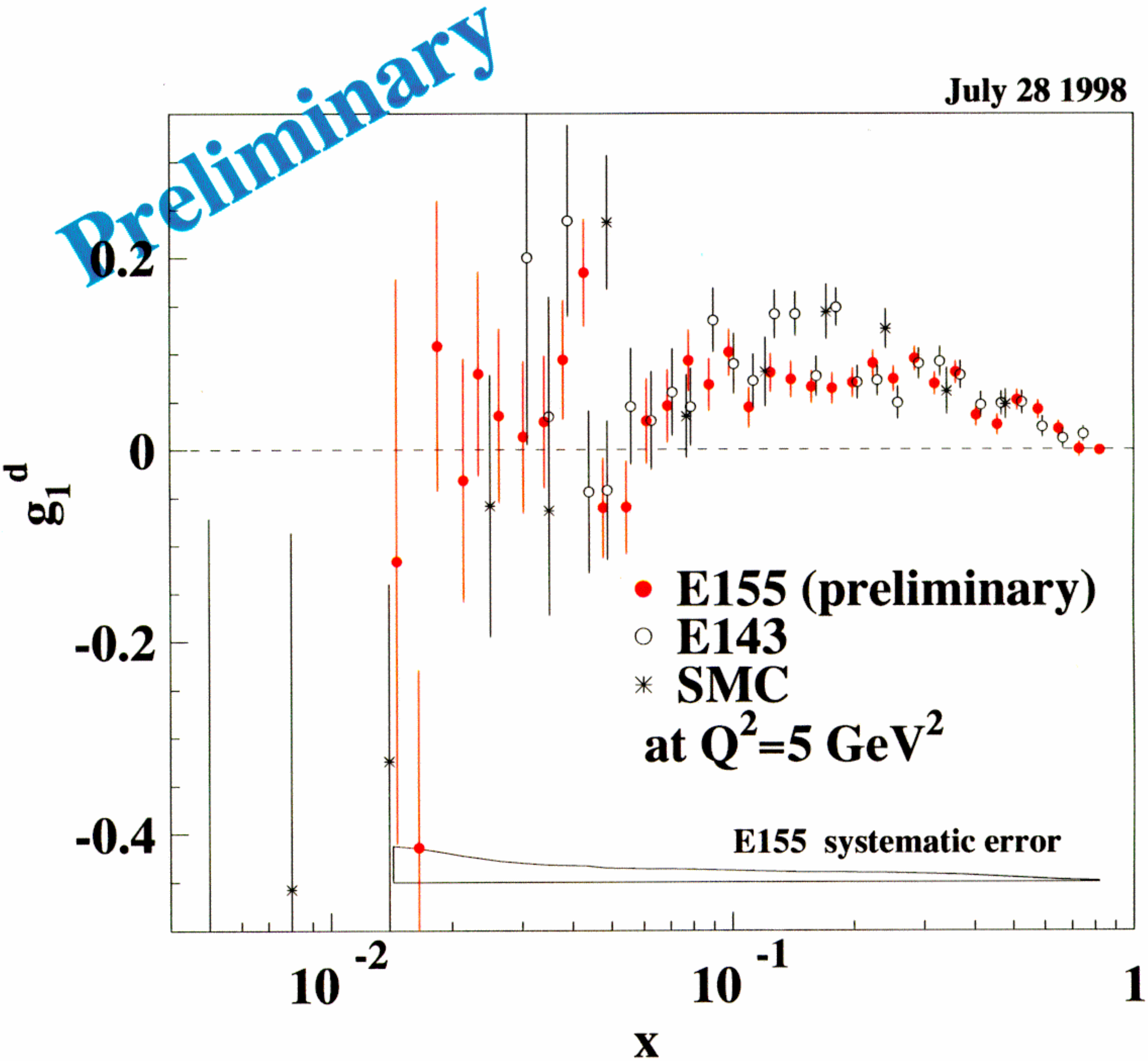

E155 kinematic coverage
by spectrometer
10.5°
5.5°
2.75°
Q^2(GeV^2)
x_{Bj}
10^{-2}
10^{-1}
1
0
5
10
15
20
25
30
35
40

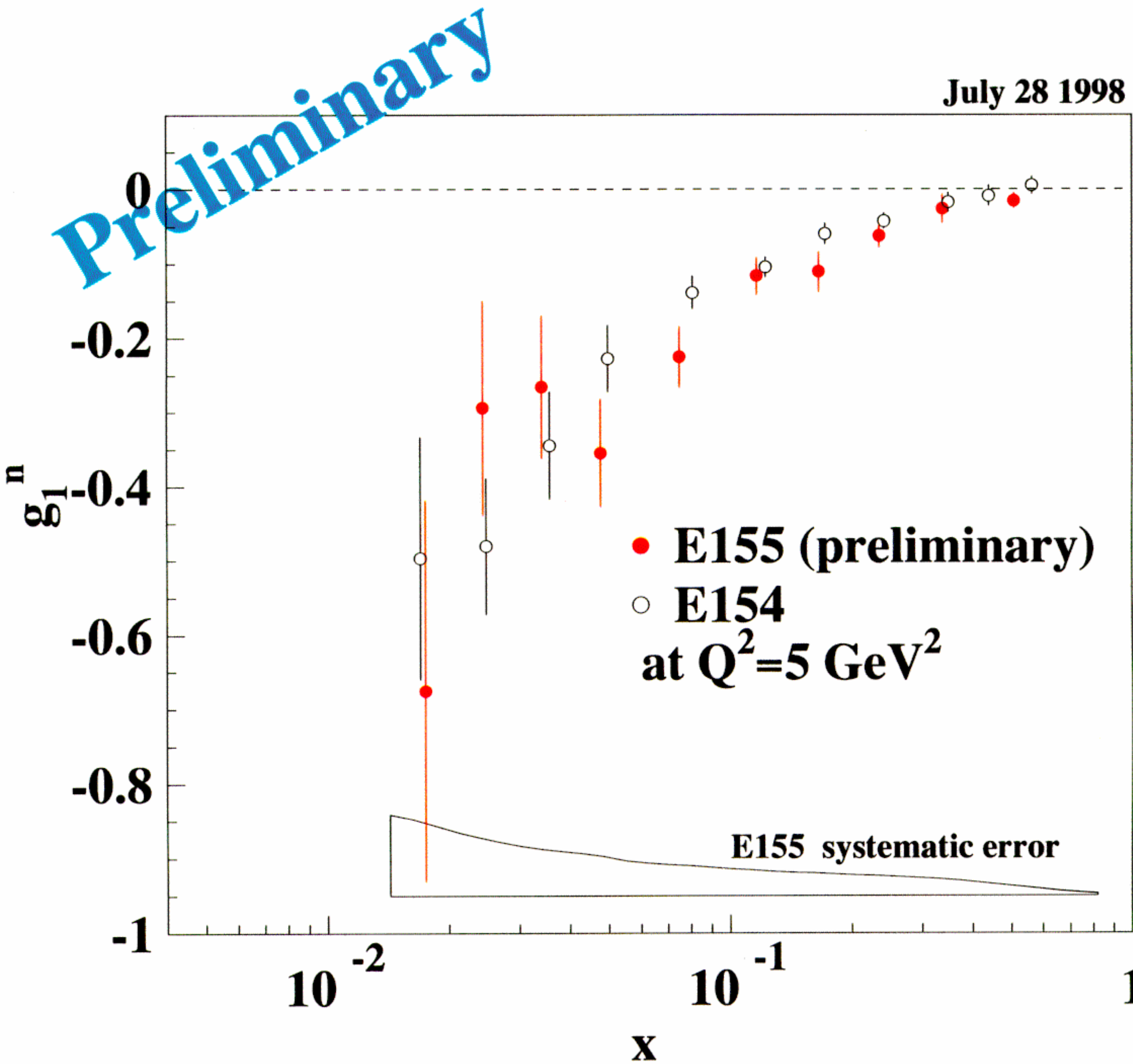

Preliminary
E155 A1 proton
July 28 1998
2 deg. spect.
5 deg. spect.
10 deg. spect.
curves are E143 A1 fit
A1p
x
10 -2
10 -1
1
0
0.5
1



Preliminary
July 28 1998
E155 (preliminary)
E143
SMC
at Q^2=5 GeV^2
E155 systematic error
g_1^p
1
0.8
0.6
0.4
0.2
0
-0.2
10^{-2}
10^{-1}
1
x

L. Sorrell, SSI 1998





Preliminary
July 28 1998
0
-0.2
-0.4
-0.6
-0.8
-1
g_1^n
E155 (preliminary)
E154
at Q^2=5 GeV^2
E155 systematic error
10^{-2}
10^{-1}
1
x

Global pQCD Fitting

- Use pQCD expansion for g_1:

$$g_1(x,Q^2) = \frac{1}{2}\sum_q e_q^2 \left[C_q \otimes \Delta q + C_G \otimes \Delta G \right]$$

→ C_q contribution starts at order 1, C_G at order α_S^1

- Evolve Δq and ΔG from initial Q_0^2 to Q^2 using NLO DGLAP equations.

- Parameterize non-perturbative inputs.

$$EG: \quad \Delta f(x,Q_0^2) = A_f x^{\alpha_f} f(x,Q_0^2)$$

where f = valence Δu_v and Δd_v, sea, gluons

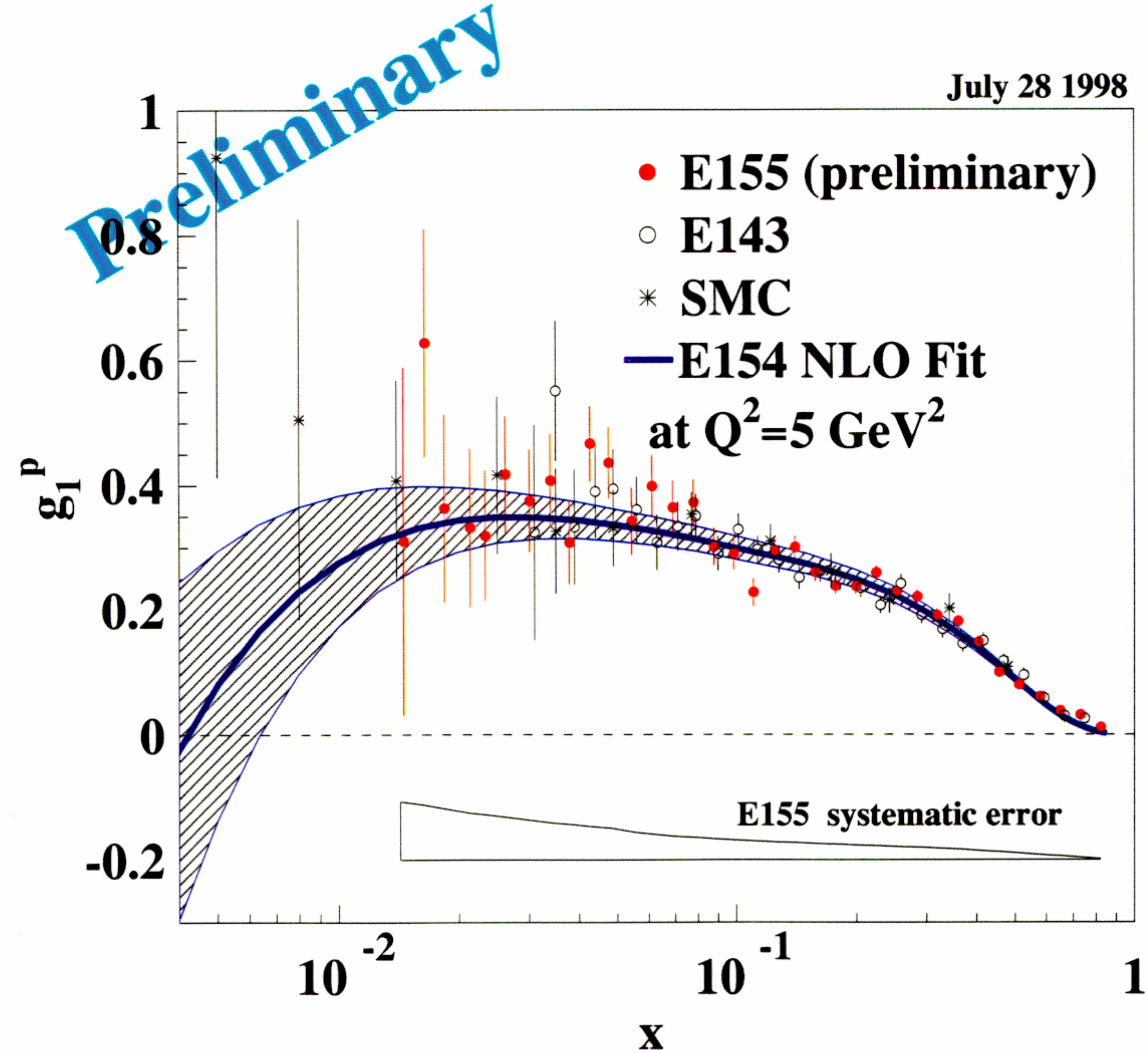
- Factorization Scheme Dependence

→ Common schemes are $\overline{MS}$ and Adler-Bardeen

→ Ambiguity in definition of contributions

$$\Delta\Sigma(AB) = \Delta\Sigma(\overline{MS}) + \frac{N_f}{2\pi}\alpha_S \Delta G$$

$\alpha_S(Q^2)\Delta G(Q^2)$ is independent of Q^2 to $O(\alpha_S^2)$



Preliminary
July 28 1998
E155 (preliminary)
E143
SMC
E154 NLO Fit
at Q^2=5 GeV^2
E155 systematic error
g_1^p
x
1
0.8
0.6
0.4
0.2
0
-0.2
10^{-2}
10^{-1}
1

$g_2(x, Q^2)$ Structure Function

- Wandzura-Wilczek g_2 expression (twist-2 only)

  $g_2^{WW}(x,Q^2) = -g_1(x,Q^2) + \int_x^1 \frac{dy}{y} g_1(y,Q^2)$

- In general there are additional contributions.

$$g_2(x,Q^2) = \underbrace{g_2^{WW}(x,Q^2)}_{\text{twist-2}} - \int_x^1 \frac{\partial}{\partial y}\Big(\underbrace{\frac{m}{M}h_T(y,Q^2)}_{\text{twist-2}} + \underbrace{\xi(y,Q^2)}_{\text{twist-3}}\Big)\frac{dy}{y}$$

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

- $\overline{g_2}$ includes quark-gluon correlations (ξ) inside the nucleon
- Twist-2 term (quark transverse spin distribution h_T) in $\overline{g_2}$ suppressed by $\frac{m}{M} << 1$
- Burkhardt-Cottingham (BC) sum rule from virtual Compton scattering dispersion relations in $Q^2 \to \infty$ limit: $\int_0^1 g_2(x,Q^2)dx = 0$

Operator Product Expansion (OPE) For g_1 and g_2

OPE used in QCD to separate the physics into a perturbative piece (easily treated) and a non-perturbative piece (unknown matrix elements).

$$\Gamma_1^{(n)} = \int_0^1 x^n g_1(x, Q^2)dx = \frac{a_n}{2}, \quad n = 0, 2, 4, \ldots$$

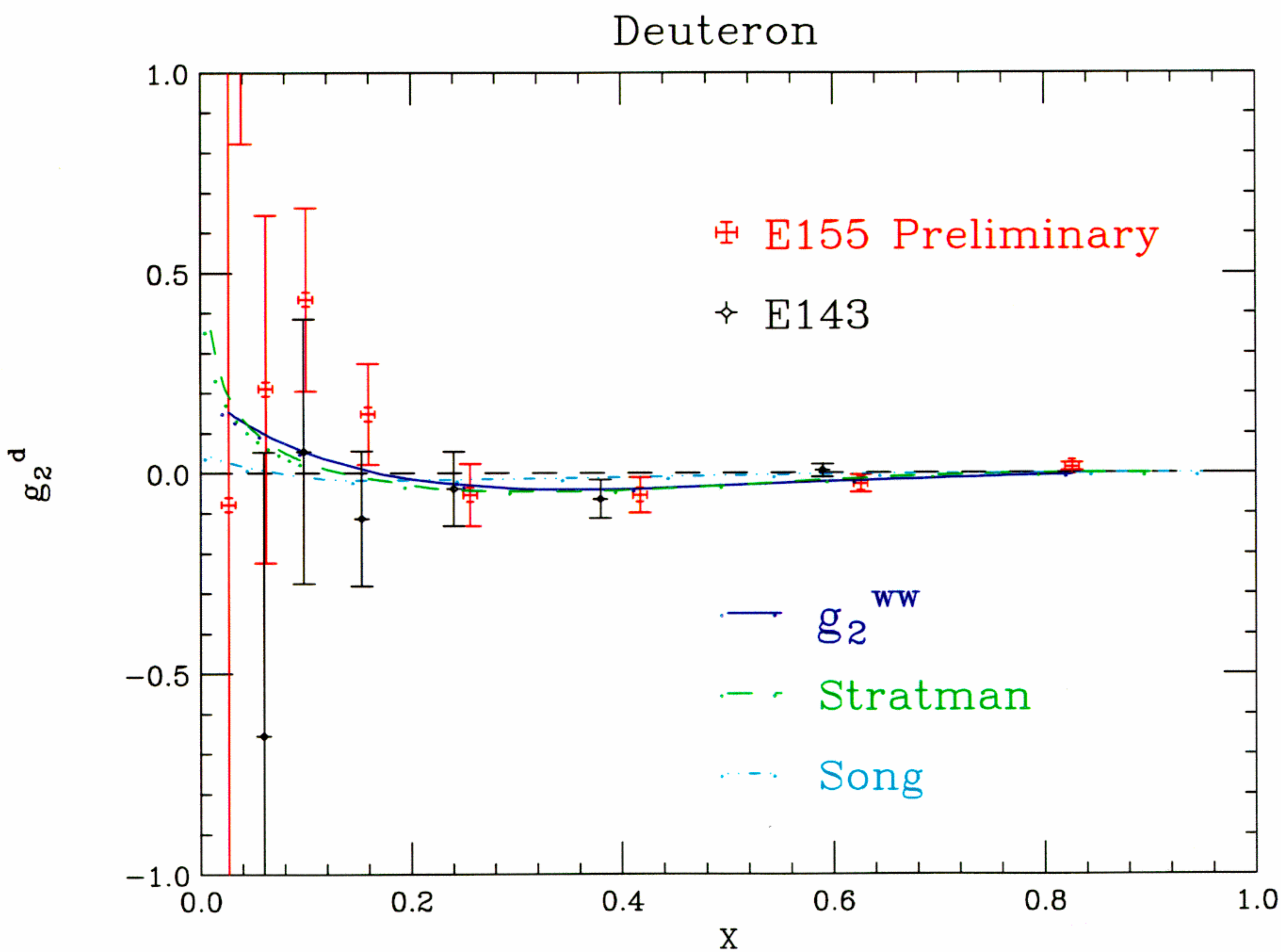
$$\Gamma_2^{(n)} = \int_0^1 x^n g_2(x, Q^2)dx = \frac{1}{2}\frac{n}{n+1}(d_n - a_n)$$

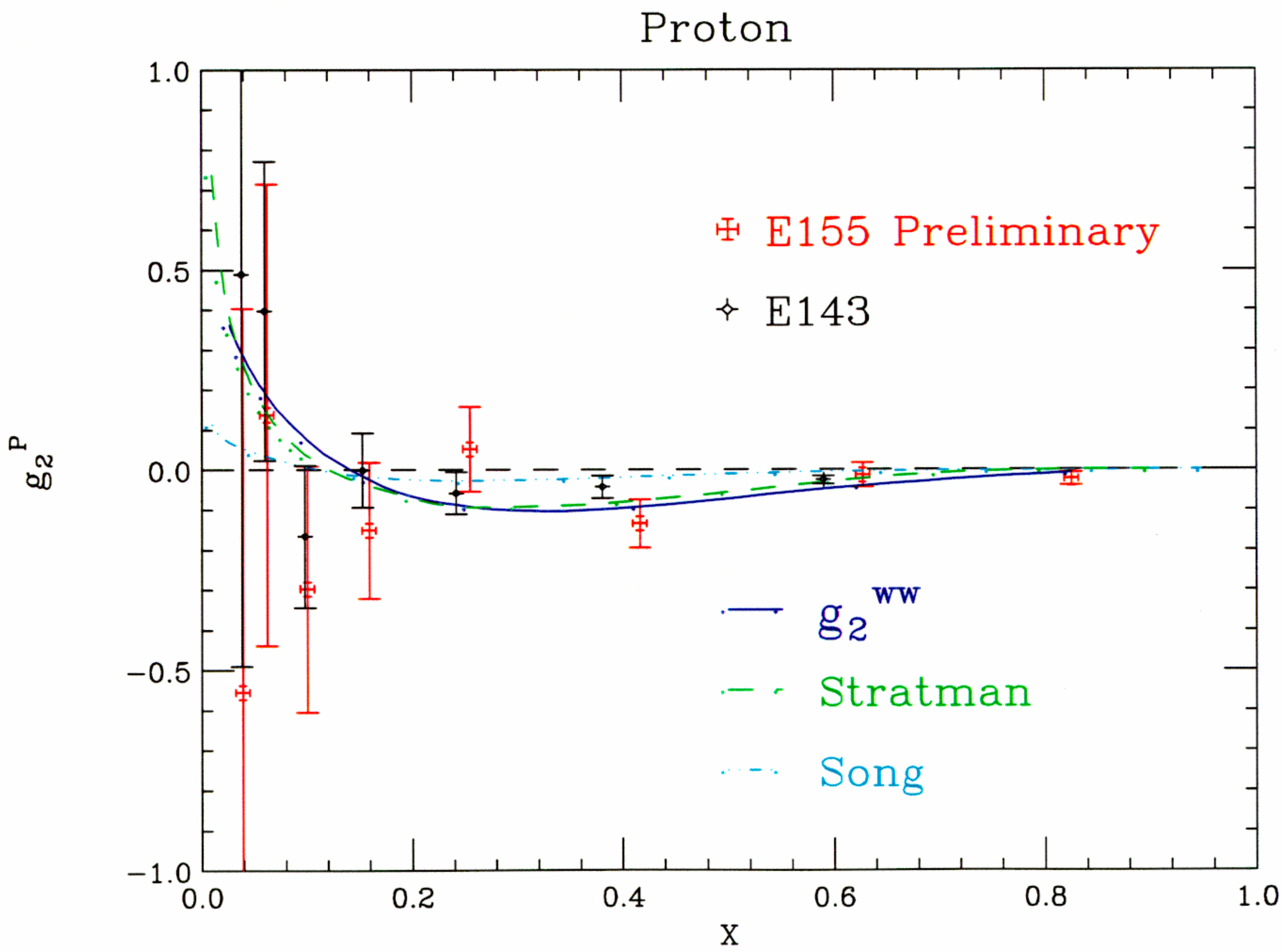
n=2,4,...

a_n are the twist-2 and d_n are the twist-3 matrix elements.

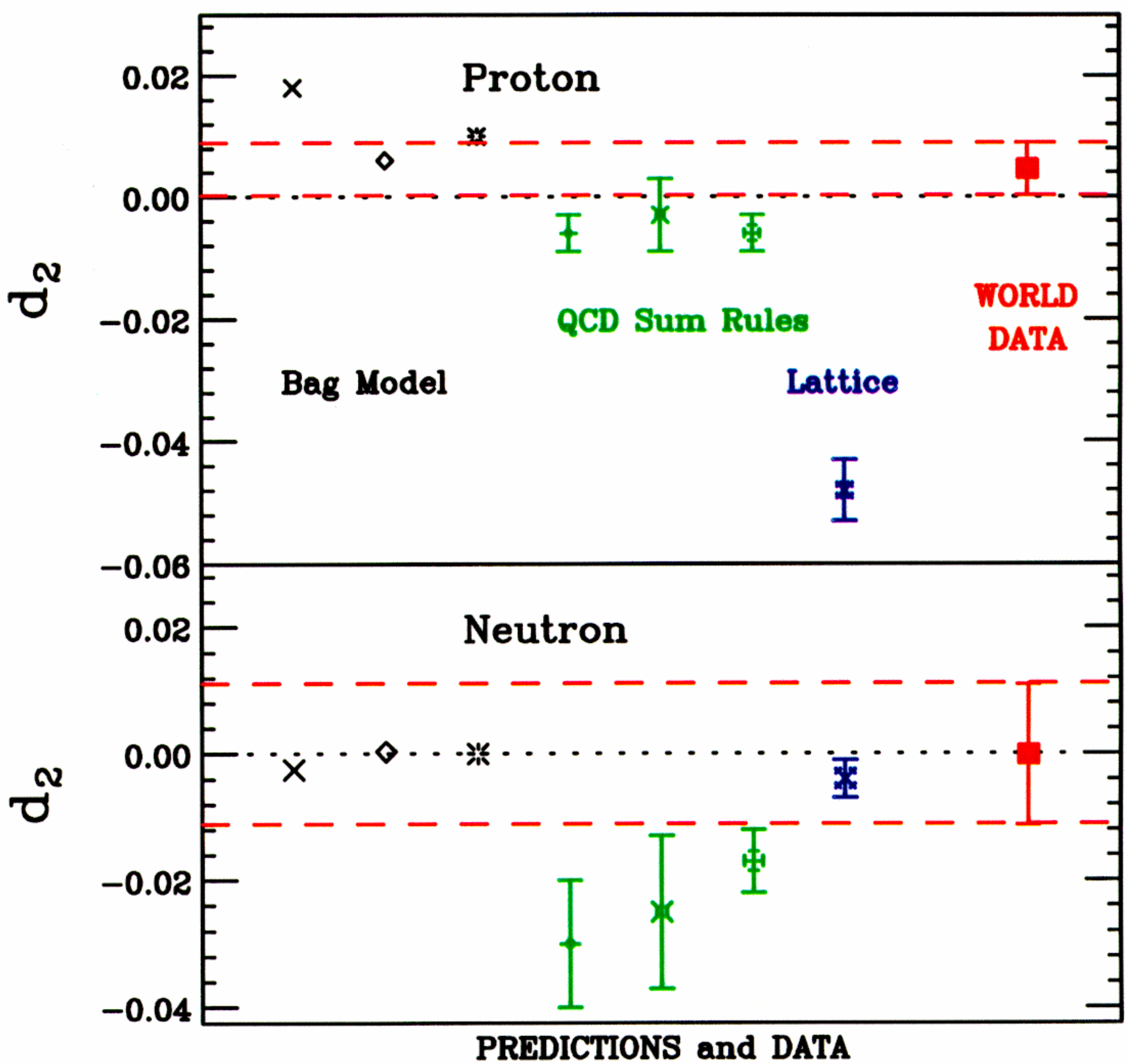
$$d_2 = \int_0^1 x^2[2g_1(x, Q^2) + 3g_2(x, Q^2)]dx$$

$$= 3\int_0^1 x^2\overline{g_2}(x, Q^2)dx$$


Deuteron
E155 Preliminary
E143
g2 ww
Stratman
Song
g2 d
X
1.0
0.5
0.0
−0.5
−1.0
0.0
0.2
0.4
0.6
0.8
1.0

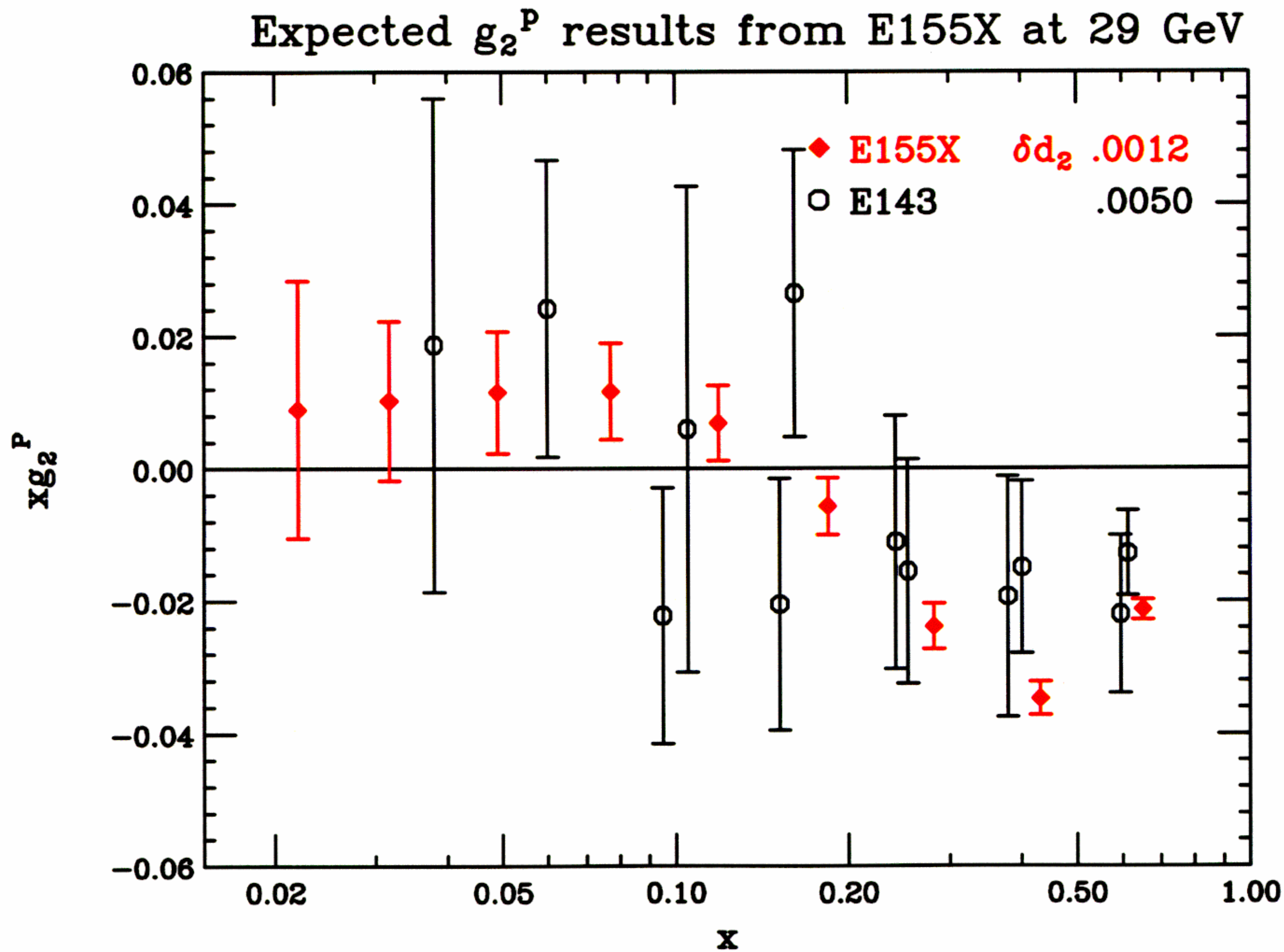

Proton
E155 Preliminary
E143
g_2^{ww}
Stratman
Song
g_2^p
X
1.0
0.5
0.0
−0.5
−1.0
0.0
0.2
0.4
0.6
0.8
1.0

Twist 3 Matrix Element d_2

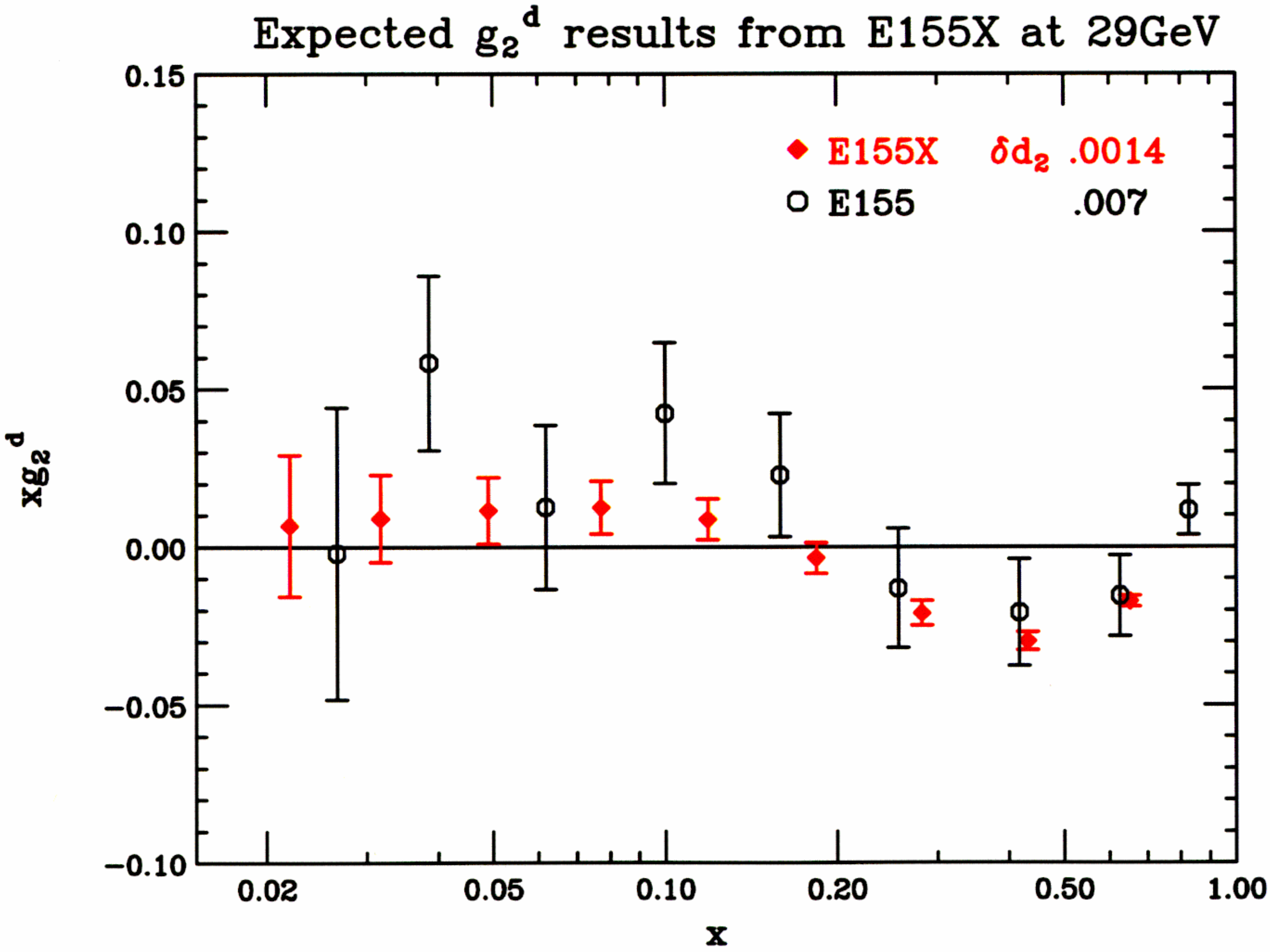


E155x

- An extension to E155 has been approved to precisely measure g_2.
- The experiment is planned for February and March 1999.
- The goal is to measure g_2 (and A_2) for the proton and deuteron over a wide range in x and Q^2.
- Significant improvement in sensitivity to contributions beyond g_2^{WW}

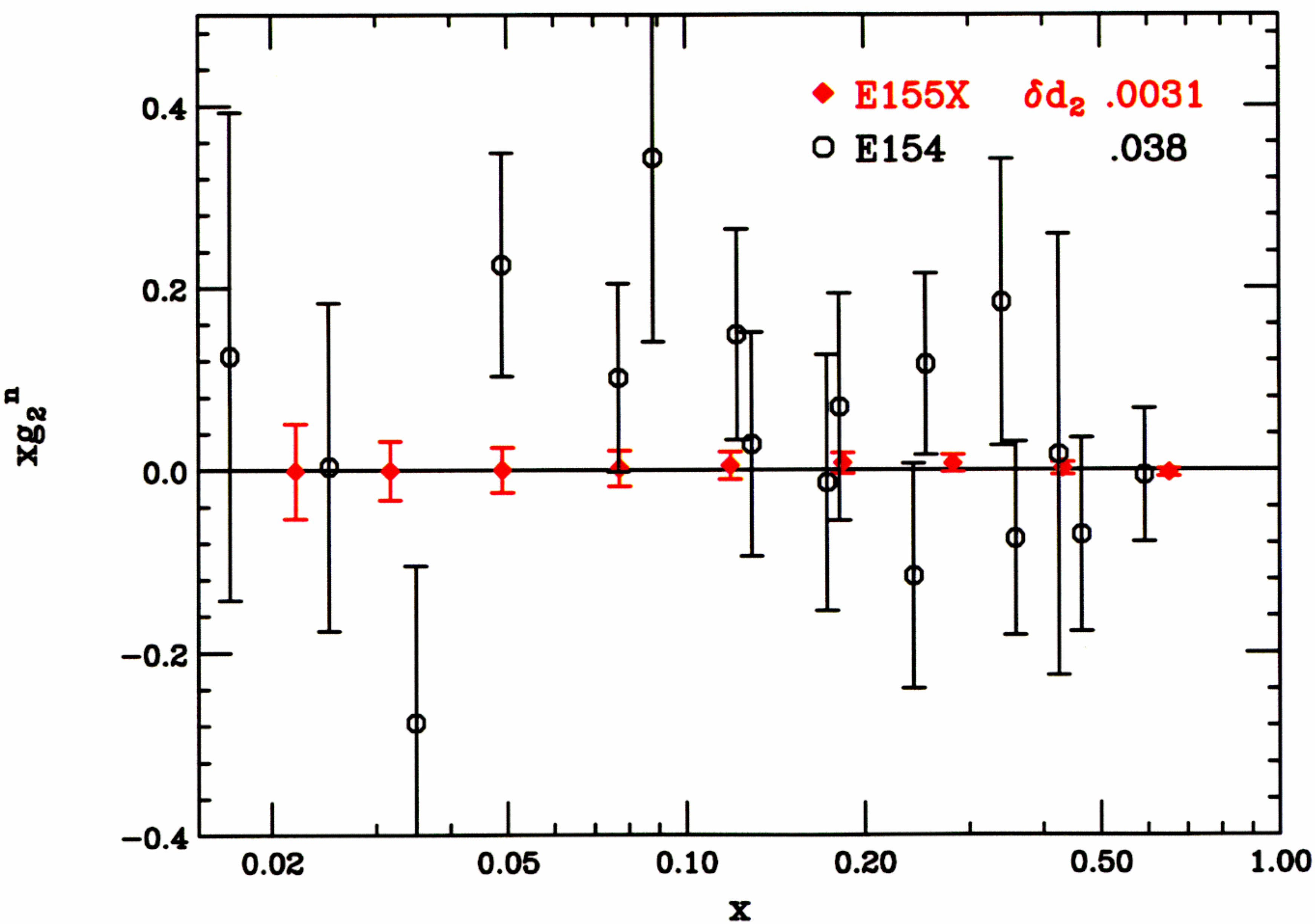


Expected g2P results from E155X at 29 GeV
E155X δd2 .0012
E143 .0050
xg2P
x
0.06
0.04
0.02
0.00
−0.02
−0.04
−0.06
0.02
0.05
0.10
0.20
0.50
1.00

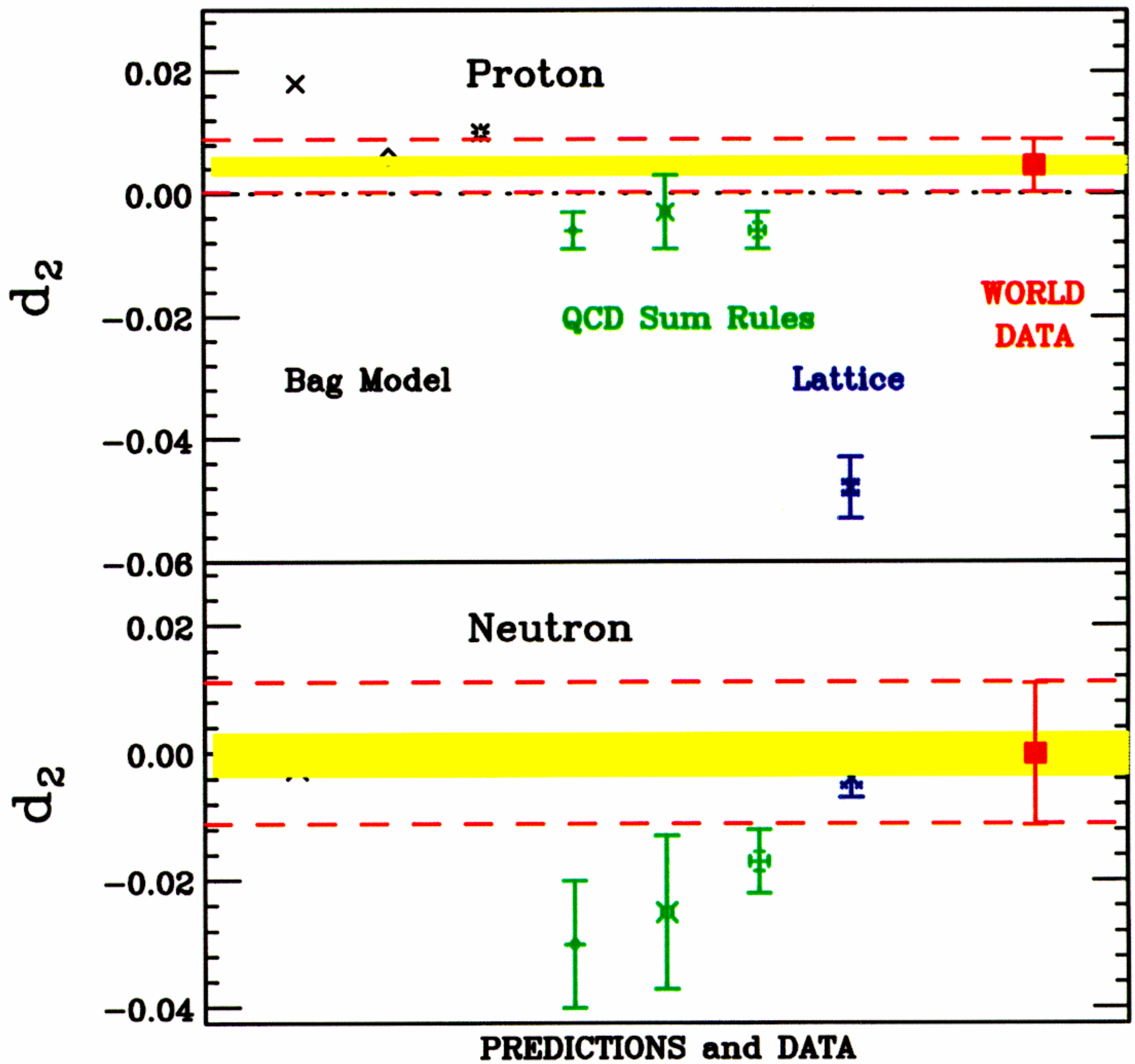


Expected g_2^d results from E155X at 29GeV
E155X δd_2 .0014
E155 .007
0.15
0.10
0.05
0.00
−0.05
−0.10
xg_2^d
0.02
0.05
0.10
0.20
0.50
1.00
x

Expected g_2^n results from E155X at 29 GeV



E155X sensitivity for d_2



Summary

- E155 has precision data on g_1 over a wide x and Q^2 range for the proton and deuteron
- NLO analysis should yield improved constraints on gluon polarization
- Extension run will provide precision g_2 data on proton and deuteron
- More direct information on gluon polarization will have to come from RHIC, COMPASS, SLAC E156?, polarized HERA?