Nucleon Spin Structure Functions:

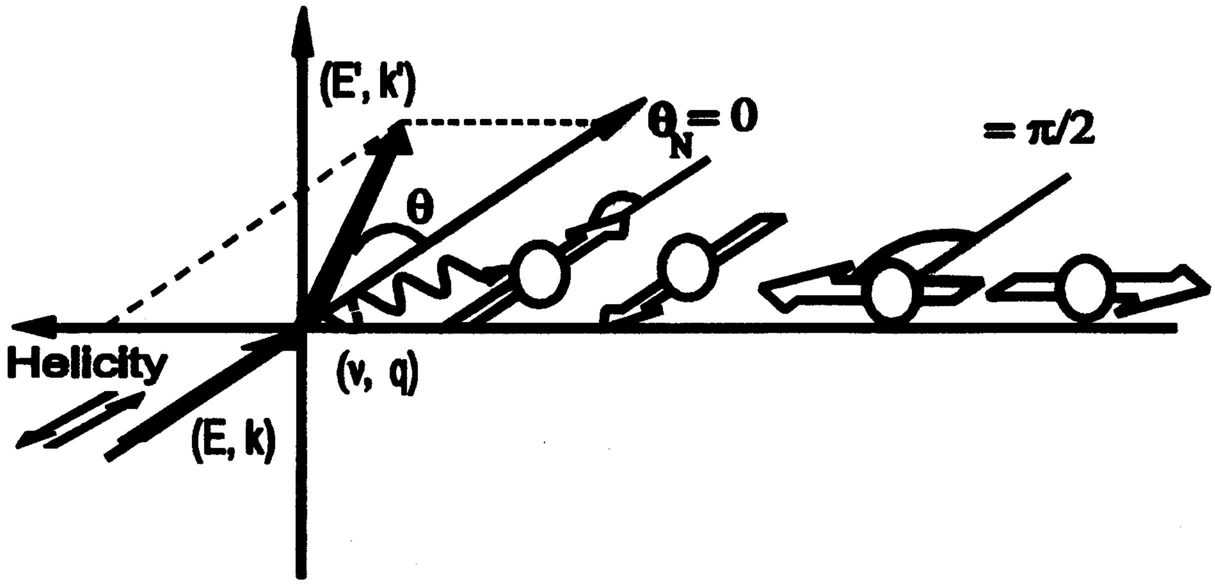
Status and Future

OSCAR A. RONDON
INPP-University of Virginia

- What are the nucleon spin structure functions (s.s.f.) g_1 and g_2?
- What data are available on g_1 and g_2?
- Where could additional measurements be interesting?
- What is possible?
- Questions
- New results on polarized duality (preliminary).

Workshop on the Quark-Hadron Transition
Hampton U. at JLab - April 17-18, 2000

Lepton Nucleon Polarized Inelastic Scattering



Longitudinal nucleus and lepton helicities:

$$\frac{d^2\sigma(\theta_N{=}0)}{d\Omega dE'} - \frac{d^2\sigma(\theta_N{=}\pi)}{d\Omega dE'} = \frac{4\alpha^2 E'}{Q^2 E}[(E + E'\cos\theta)MG_1 - Q^2 G_2]$$

Transverse nucleus and longitudinal lepton helicities:

$$\frac{d^2\sigma(\theta_N{=}\pi/2)}{d\Omega dE'} - \frac{d^2\sigma(\theta_N{=}3\pi/2)}{d\Omega dE'} = \frac{4\alpha^2 E'}{Q^2 E} E'\sin\theta(MG_1 + 2EG_2)$$

Spin structure functions G_1 and G_2 in polarized D.I.S.:

$$Lim_{Q^2,\nu\to\infty}\left[\begin{array}{rcl}(M^2\nu)G_1(Q^2,\nu) & = & g_1(x) \\ (M\nu^2)G_2(Q^2,\nu) & = & g_2(x)\end{array}\right]; \quad x = \frac{Q^2}{2M\nu}$$

g_1 in the parton model and OPE

g_1 is the sum of charge weighted quark helicity densities $q_i^{\uparrow\downarrow}(x)$:

$$g_1(x) = \frac{1}{2}\sum_i e_i^2 [q_i^{\uparrow}(x) - q_i^{\downarrow}(x)], \quad i = u, \bar{u}, d, \bar{d} \ldots$$

First moments $\int_0^1 g_1 dx$ related by OPE to quark matrix elements:

$$\Gamma_1^{p,n}(x) = \frac{1}{2}\sum_i e_i^2 \Delta q_i = \frac{1}{36}[\pm 3E_3 a_3 + E_8 a_8 + 4E_0 a_0]$$

$$\Gamma_1^p - \Gamma_1^n(x) = \frac{1}{6}E_3 a_3 = \frac{g_A}{6}E_3$$

Coefficient functions $E_{0,3,8}$ are QCD corrections **for finite Q^2**.
A-V matrix elements a_0, singlet, a_3, a_8 non-**singlet are**:

$$a_0 = \Delta u + \Delta d + \Delta s = \Delta\Sigma$$
$$a_3 = \Delta u - \Delta d$$
$$a_8 = \Delta u + \Delta d - 2\Delta s$$

Scheme	Quark contribution to nucleon spin
$\overline{\mathrm{MS}}$	$\Delta\Sigma(Q^2) = a_0(Q^2)$
AB	$\Delta\Sigma = a_0(Q^2) + f\alpha_s(Q^2)\Delta G(Q^2)/2\pi$

Transverse spin structure functions

E155 measured $g_2(x,Q^2)$ and $A_2(x,Q^2)$ for **proton and deuteron**

g_2 decomposition

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

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

Wandzura-Wilczek sum rule (twist-2)

$$\overline{g_2}(x,Q^2) = \int_x^1 \frac{\partial}{\partial y}\left(\frac{m}{M} h_T(y,Q^2) + \xi(y,Q^2)\right) \frac{dy}{y}$$

"Transversity" *(twist-2)*   *quark-gluon int.* *(twist-3)*

We can get the mixed twist $\overline{g_2}$ from g_2 and g_1.

We have also obtained

$$|A_2(x,Q^2)| = \left| \frac{Q/\nu}{F_1(x,Q^2)} (g_1(x,Q^2) + g_2(x,Q^2)) \right| \le \sqrt{R(x,Q^2)}$$

and computed sum rules from $0.02 < x < 1$ (measured $x \le 0.8$):

$$\int_0^1 g_2(x)\, dx = 0$$ Burkhardt-Cottingham Sum rule

$$\int_0^1 x^N g_2(x)\, dx$$ moments for Operator Product Expansion (OPE) Sum rules

Nucleon Spin Asymmetries

Spin structure functions and spin asymmetries

- DIS: Parton model interpretation of spin structure

$$A_1(x) \cong \frac{g_1(x)}{F_1(x)} = \frac{\Sigma e_i^2 \Delta q_i(x)}{\Sigma e_i^2 q_i(x)}$$

$$A_2(x) = \frac{Q}{\nu}\left(\frac{g_1(x) + g_2(x)}{F_1(x)}\right)$$

- Resonances: forward virtual Compton scattering

$$A_1(Q^2,\nu) = \frac{\sigma^T_{1/2} - \sigma^T_{3/2}}{\sigma^T_{1/2} + \sigma^T_{3/2}} = \frac{M\nu G_1 - Q^2 G_2}{W_1}$$

$$A_2(Q^2,\nu) = \frac{\sigma^{TL}}{2\sigma^T} = \frac{\sqrt{Q^2}(MG_1 + \nu G_2)}{W_1}$$

Connection: scaling limit

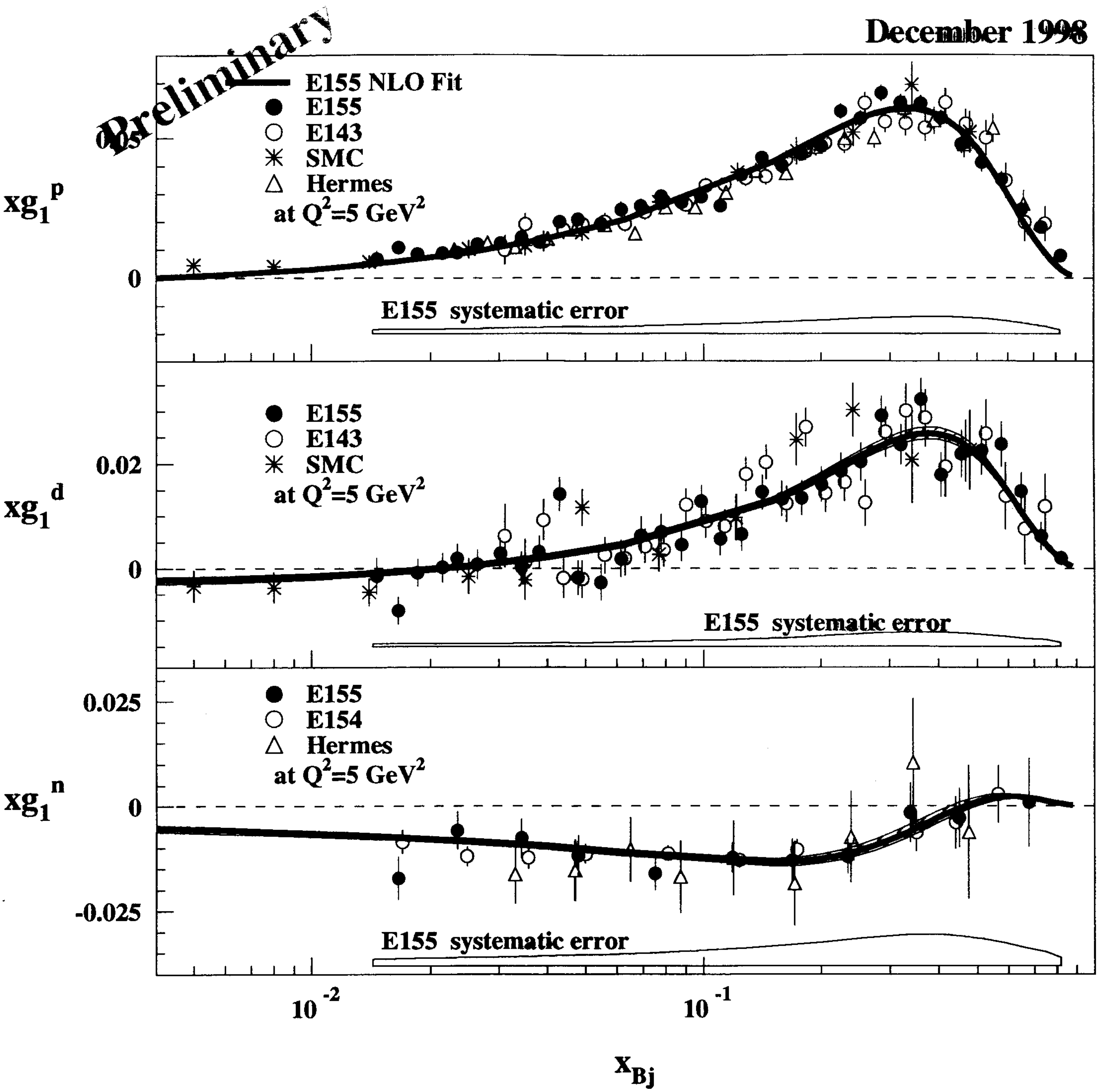
$$\lim_{Q^2,\nu\to\infty} G_1(Q^2,\nu) = g_1(x)/(M^2\nu)$$

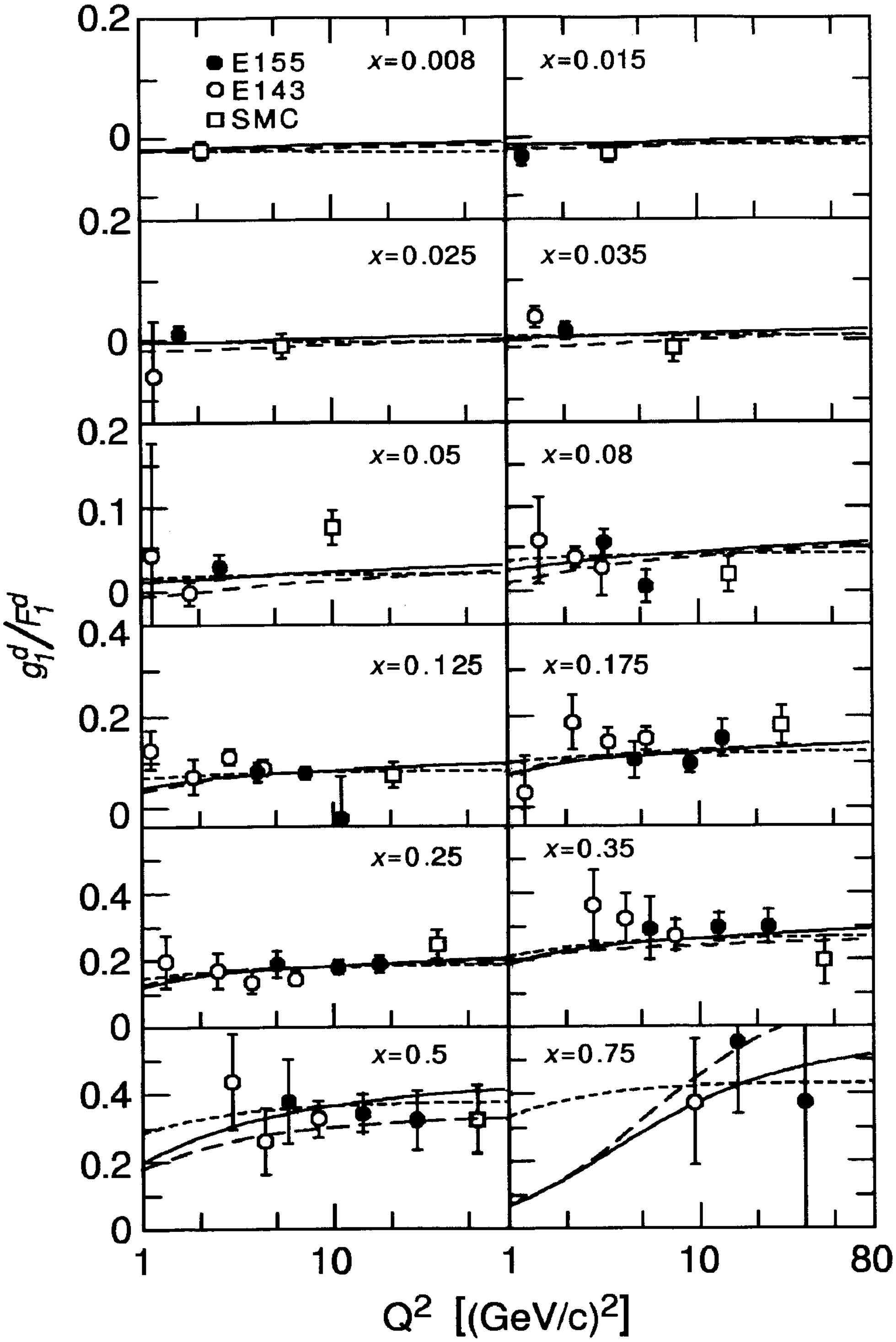
$$\lim_{Q^2,\nu\to\infty} G_2(Q^2,\nu) = g_2(x)/(M\nu^2)$$

$$\lim_{Q^2,\nu\to\infty} W_1(Q^2,\nu) = F_1(x)/M$$

$$2\sigma^T = \sigma^T_{1/2} + \sigma^T_{3/2}$$

O RONDON 6/34


Preliminary
December 1998
E155 NLO Fit
E155
E143
SMC
Hermes
at Q²=5 GeV²
xg₁ᵖ
0.05
0
E155 systematic error
E155
E143
SMC
at Q²=5 GeV²
xg₁ᵈ
0.02
0
E155 systematic error
E155
E154
Hermes
at Q²=5 GeV²
xg₁ⁿ
0.025
0
-0.025
E155 systematic error
10⁻²
10⁻¹
x_Bj



NLO fits: —— E154; – – – SMC;
----- E155 parameterization:

$$(g_1/F_1) = x^{\alpha}(a+bx+cx^2)(1+\beta/Q^2)$$

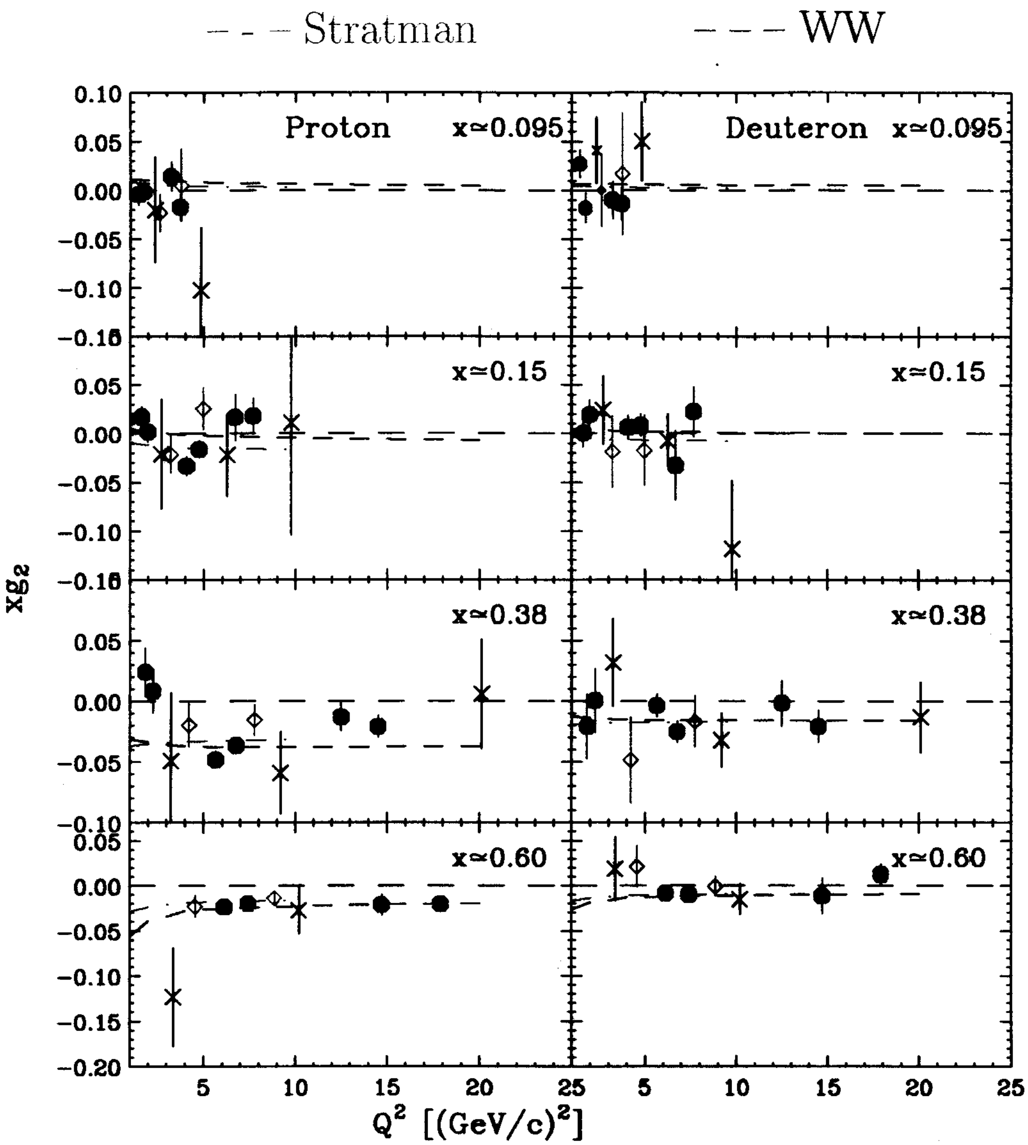
Statistical errors (+systematic in quadrature=outer bars)

D. Rondon 8/99

PP. 1

Q^2-DEPENDENCE OF xg_2

PRELIMINARY

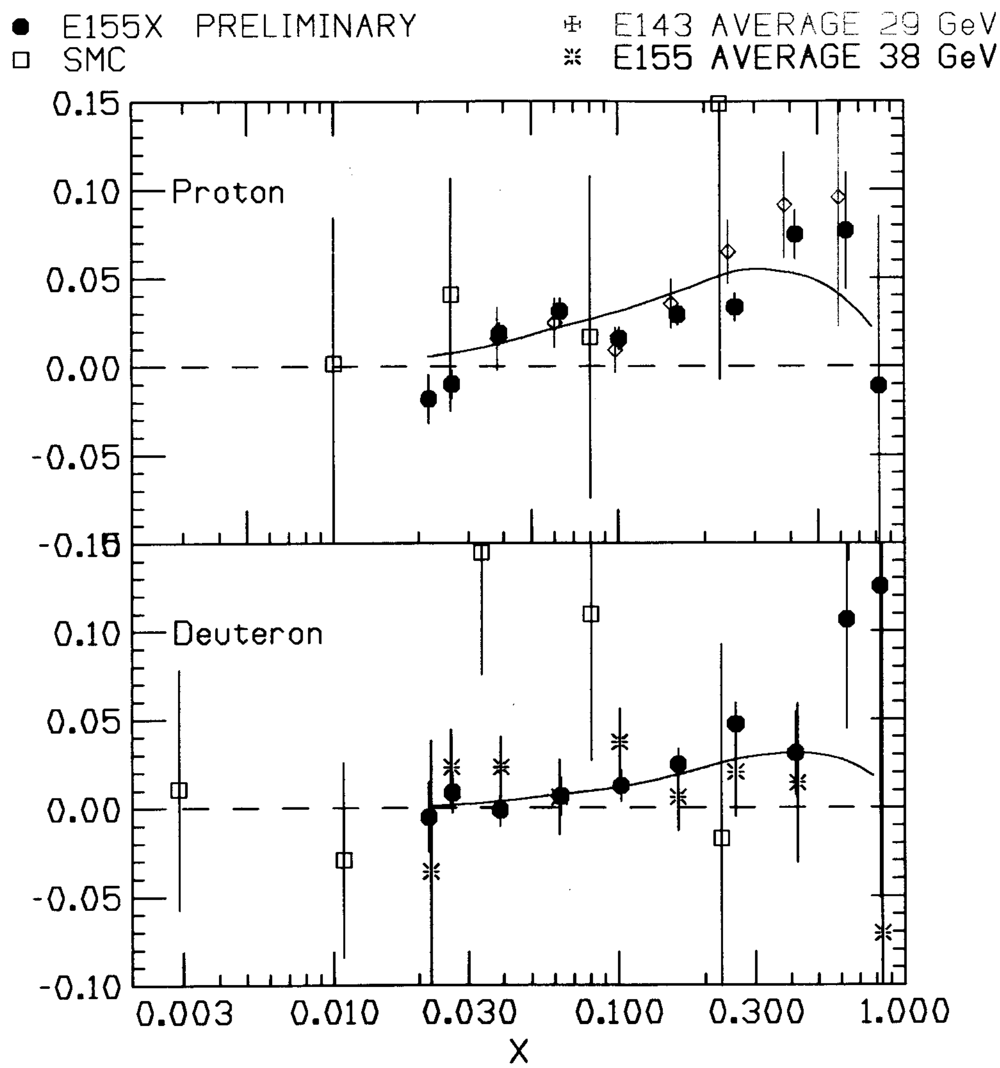


◇ E143

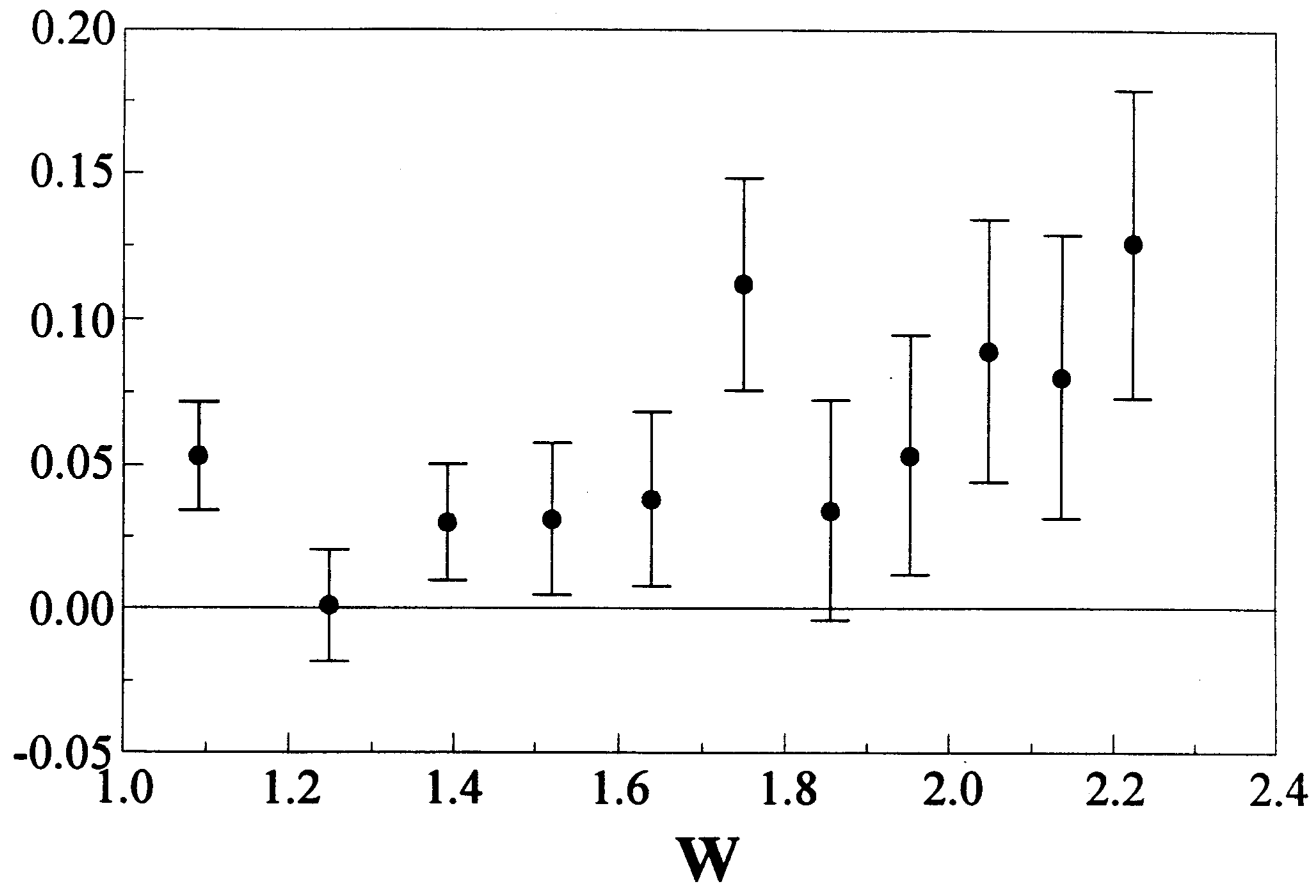
● E155x

× E155

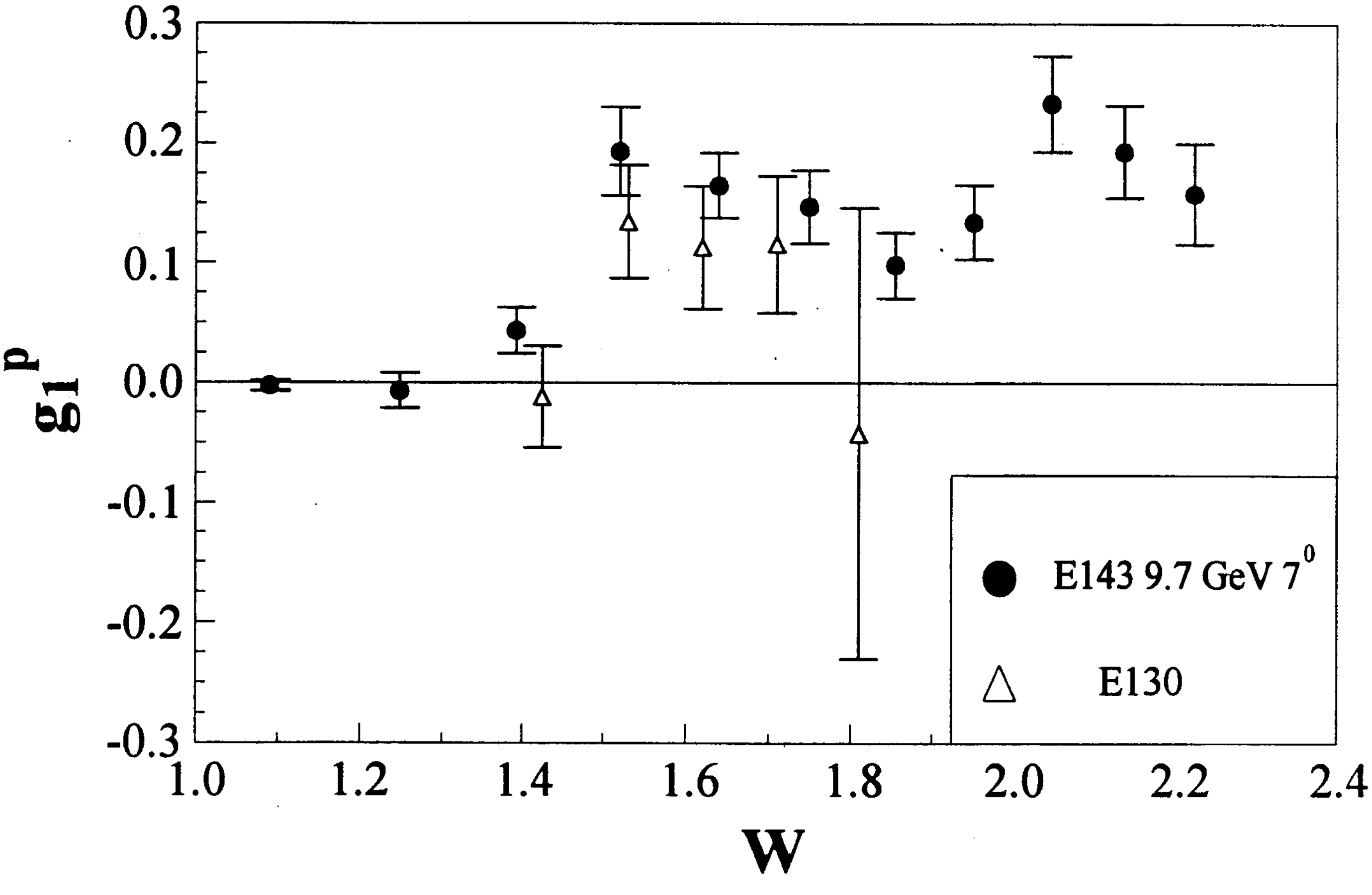
O. RONDON
9/34



E155X PRELIMINARY
SMC
E143 AVERAGE 29 GeV
E155 AVERAGE 38 GeV
Proton
Deuteron
A2
A2
X
0.15
0.10
0.05
0.00
-0.05
-0.10
0.003
0.010
0.030
0.100
0.300
1.000

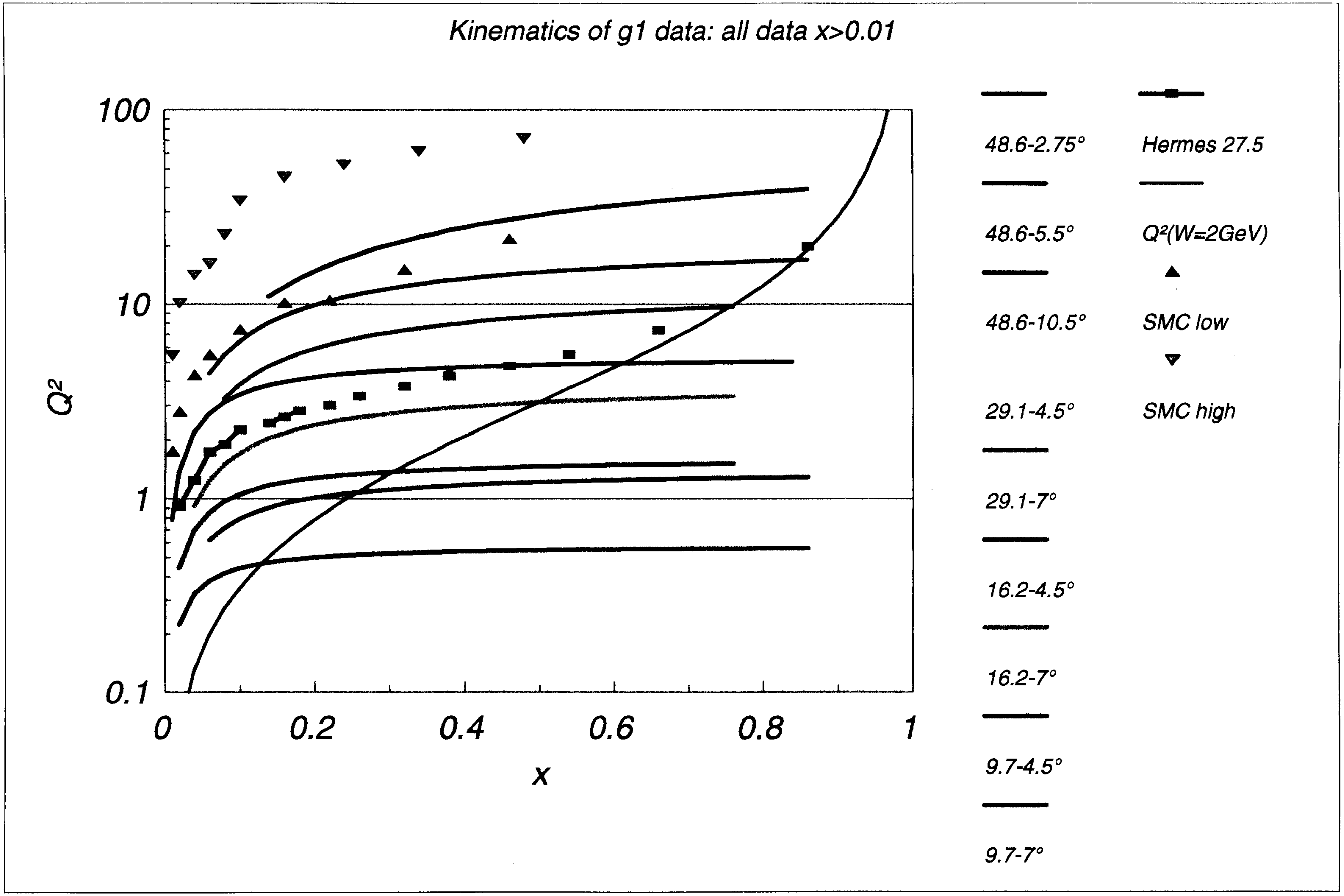


0.20
0.15
0.10
0.05
0.00
-0.05
g_1^d
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
W

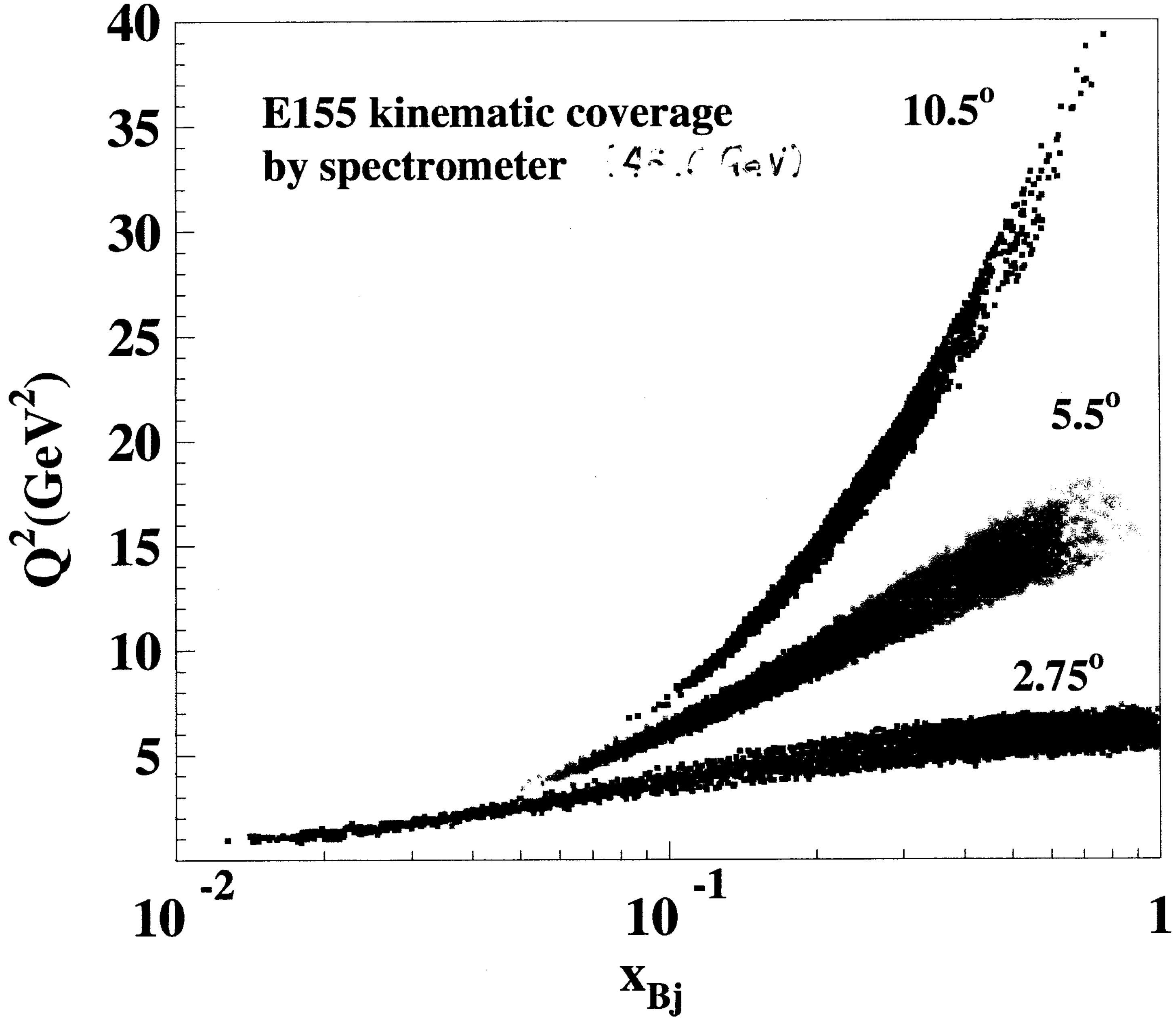


0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
g_1^p
E143 9.7 GeV 7^0
E130
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
W

P8.1

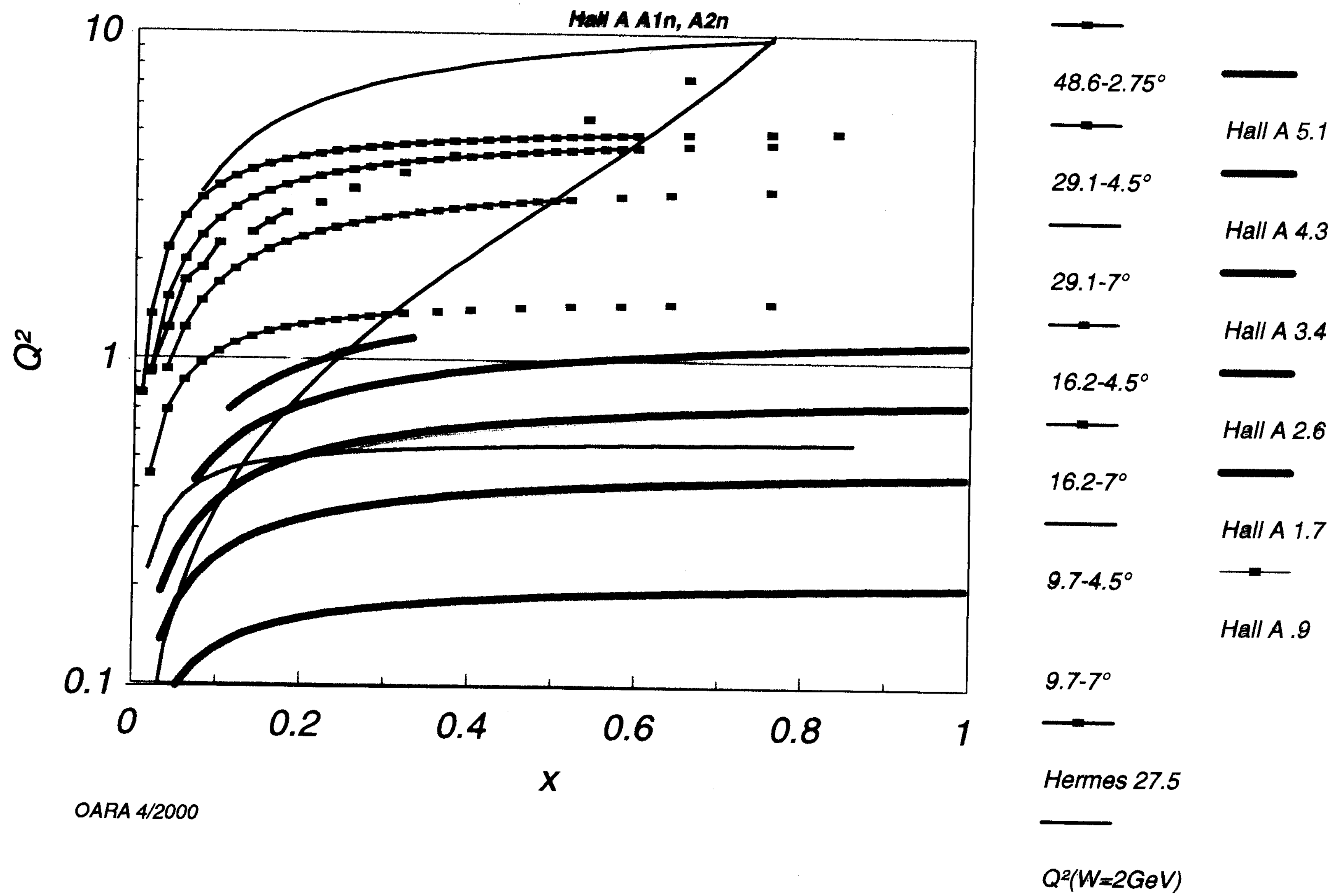

Kinematics of g1 data: all data x>0.01
100
10
1
0.1
Q²
0
0.2
0.4
0.6
0.8
1
x
48.6-2.75°
48.6-5.5°
48.6-10.5°
29.1-4.5°
29.1-7°
16.2-4.5°
16.2-7°
9.7-4.5°
9.7-7°
Hermes 27.5
Q²(W=2GeV)
SMC low
SMC high

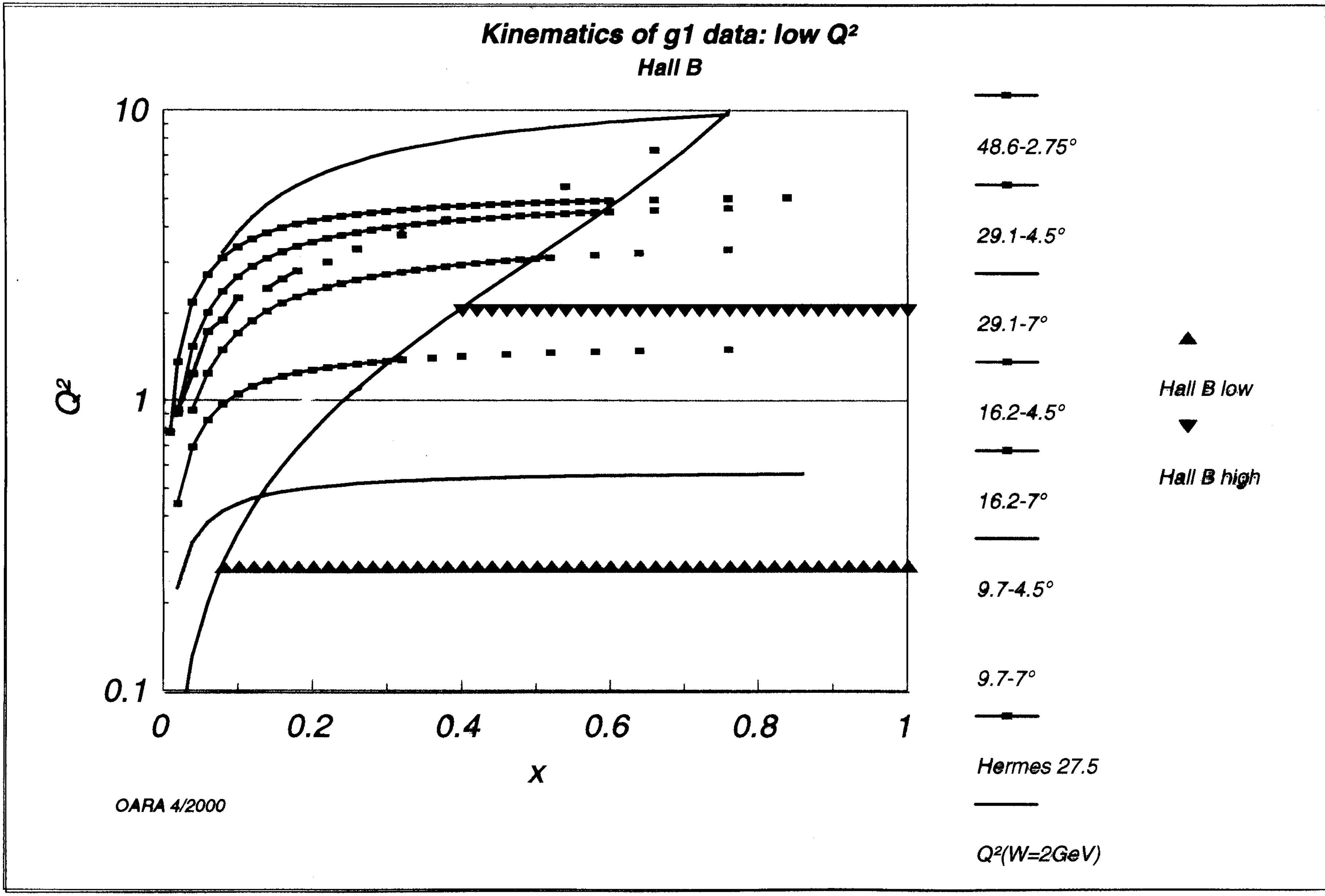
[K

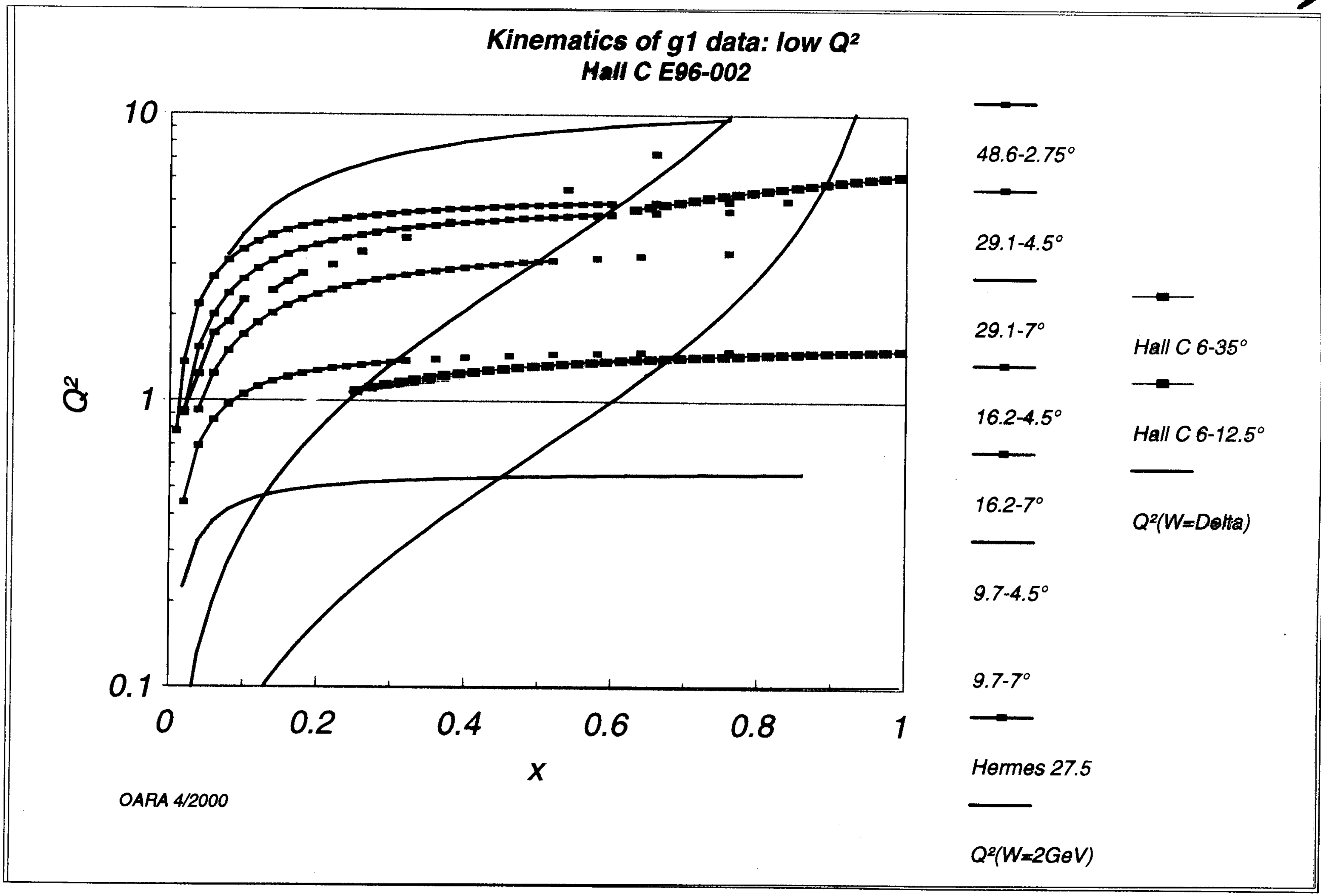

E155 kinematic coverage
by spectrometer
10.5°
5.5°
2.75°
Q²(GeV²)
40
35
30
25
20
15
10
5
10⁻²
10⁻¹
1
x_Bj

PRN.1

Kinematics of g1 data: low Q^2



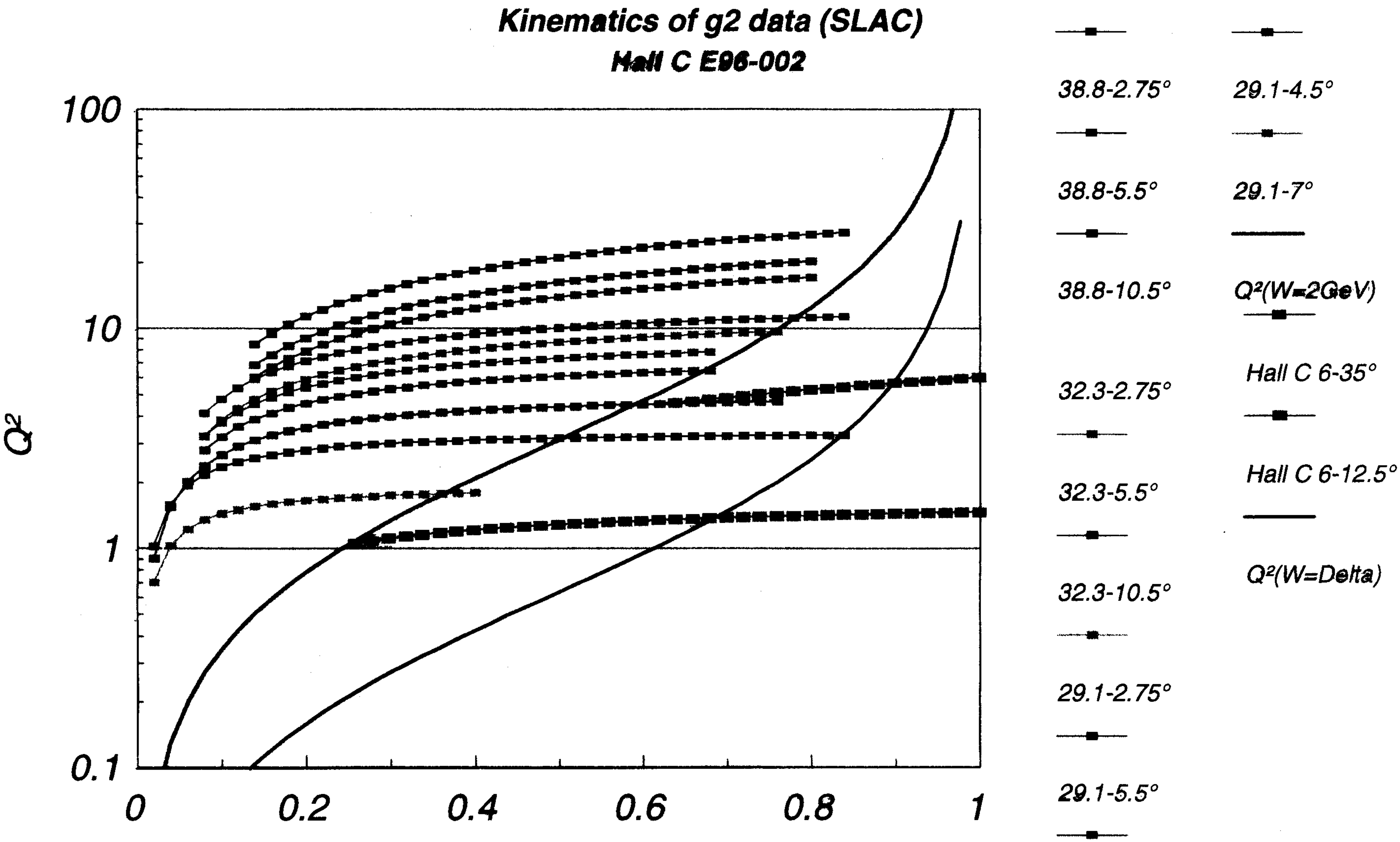

Kinematics of g1 data: low Q²
Hall B
10
1
0.1
Q²
0
0.2
0.4
0.6
0.8
1
X
OARA 4/2000
48.6-2.75°
29.1-4.5°
29.1-7°
16.2-4.5°
16.2-7°
9.7-4.5°
9.7-7°
Hermes 27.5
Q²(W=2GeV)
Hall B low
Hall B high


Kinematics of g1 data: low Q²
Hall C E96-002
10
1
0.1
Q²
0
0.2
0.4
0.6
0.8
1
X
OARA 4/2000
48.6-2.75°
29.1-4.5°
29.1-7°
16.2-4.5°
16.2-7°
9.7-4.5°
9.7-7°
Hermes 27.5
Q²(W=2GeV)
Hall C 6-35°
Hall C 6-12.5°
Q²(W=Delta)

O. RONDON

Kinematics of g2 data (SLAC)

Hall C E96-002



OARA 4/2000

TJNAF PROPOSAL

Precision measurement of the nucleon spin structure functions in the region of the nucleon resonances

TJNAF E[illegible] (PAC 11)

S. Bültmann, D.G. Crabb, C. Cothran, D. Day, E. Frlez,

J. S. McCarthy, P. McKee, D. Počanić, C. Smith,

O. Rondon-Aramayo (spokesman), A. Tobias and B. Zihlman

Institute of Nuclear and Particle Physics

Department of Physics, University of Virginia

Charlottesville, VA 22901, USA

J. Jourdan, T. Petitjean, I. Sick, G. Warren and J. Zhao

Department of Physics and Astronomy, Universität Basel, CH-4056, Basel, Schweiz

R. Carlini, J-P. Chen, J. Gomez, D. Mack,

J. Mitchell

Thomas Jefferson National Accelerator Facility

Newport News, VA, 23606

Abstract

We propose to make high precision and high resolution measurements of the spin structure of the proton and deuteron in the region of the nucleon resonances, at two values of Q^2: ~ 1 GeV^2 and ~ 5.5 GeV^2. Fundamental properties of the nucleon and QCD will be explored with adequate precision to obtain conclusive information. We plan to use TJNAF's polarized electron beam at 6 GeV, the Virginia-Basel solid polarized target with NH_3 and ND_3 materials and the Hall C High Momentum Spectrometer.

Spin Structure Functions at Jefferson Lab

Nucleon spin structure: a fundamental nucleon property

- Reasonably well measured in **Deep Inelastic Scattering**.
- Poorly known in the nucleon resonances region.

Study the Nucleon Resonances in two Q^2 regions:

- Medium Q^2 (1.3 GeV^2): high *precision* and high *resolution* measurement of the spin asymmetries to study W dependence and **polarized local duality**: connection with DIS.
- High Q^2 (~ 5.5 GeV^2): study **polarized local duality** and test **pQCD predictions** for the resonances' helicity amplitudes.

Why Jefferson Lab?

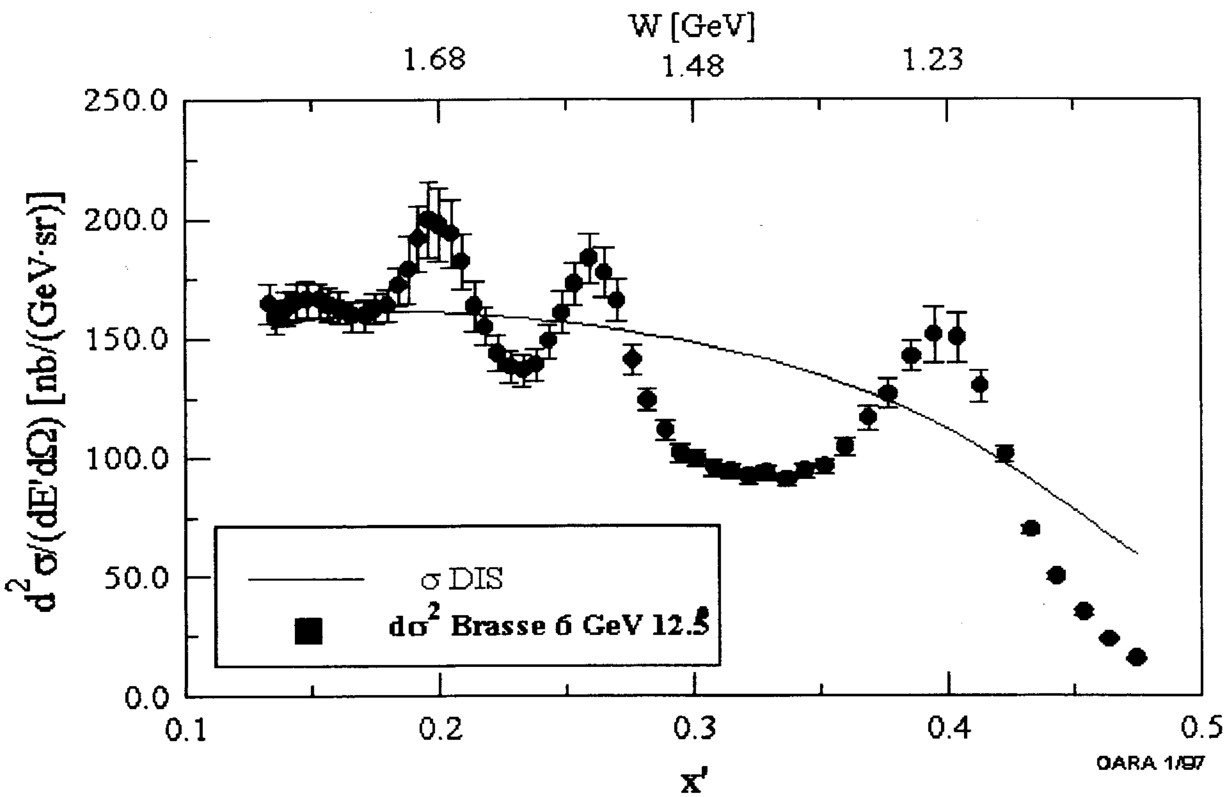
- **Polarized 6 GeV** beam allows favorable kinematic conditions.
- Proton and deuteron **polarized targets** in Hall C.
- DC beam removes count rate limitations due to low duty factor
- Hall C HMS has:
  - > large solid angle (> 6 msr);
  - > adequate momentum bite (± 10 %)
  - > good momentum resolution (0.3% *dp*/*p*).

Spin structure physics at TJNAF

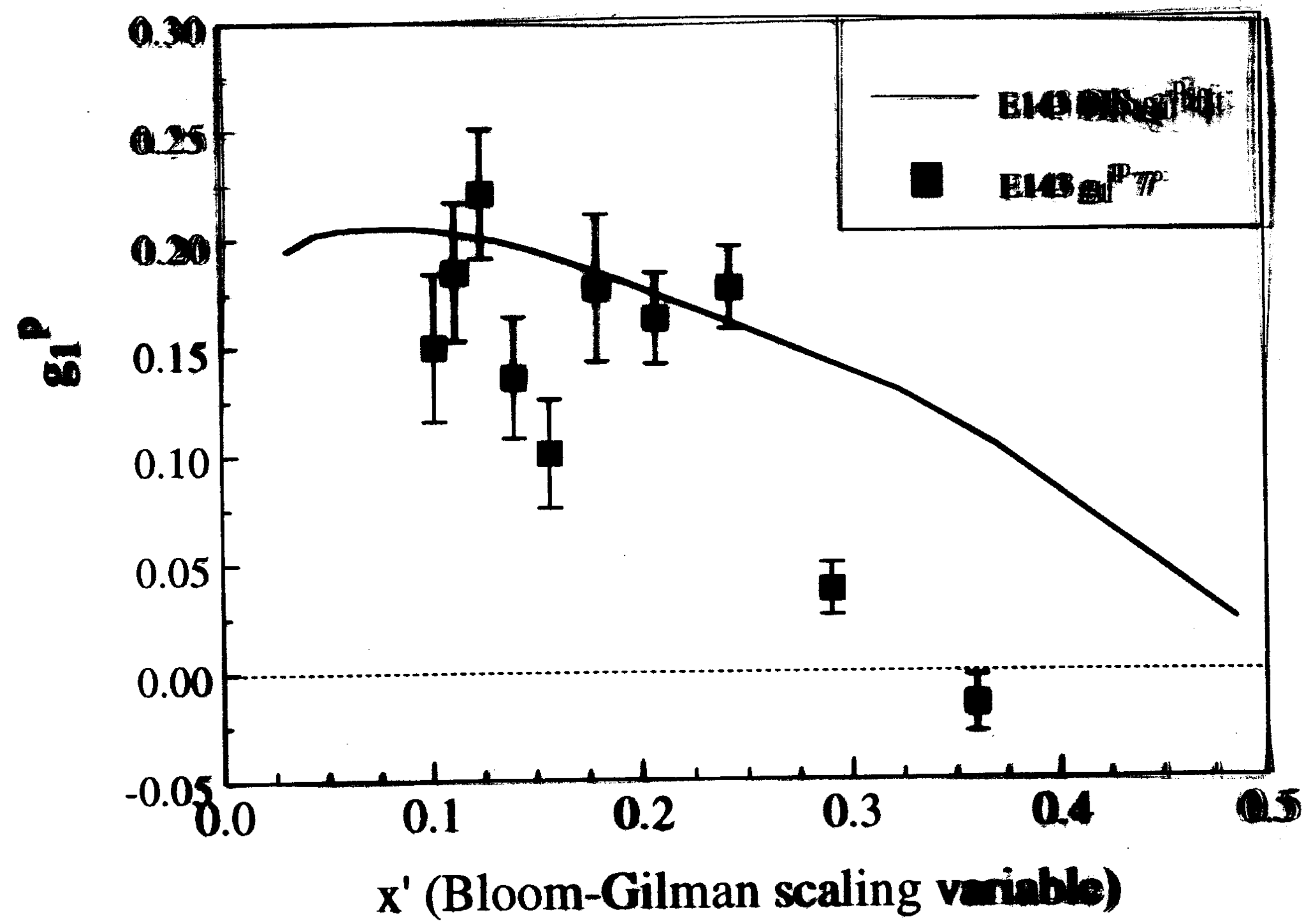
From partons to constituent quarks:

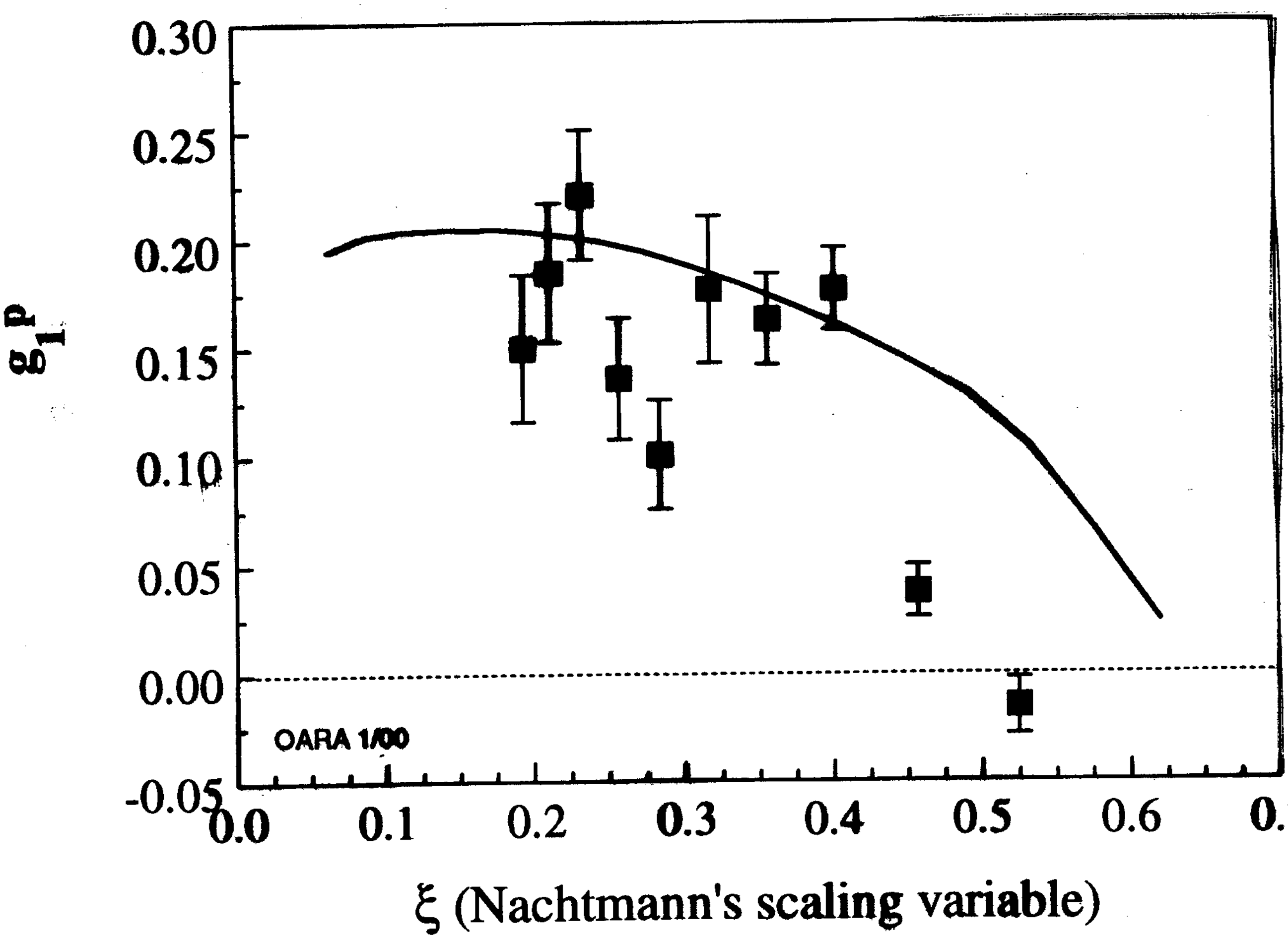
Local duality (Bloom-Gilman):

The unpolarized structure functions in the region of the resonances average out to the extrapolation of their DIS counterparts.



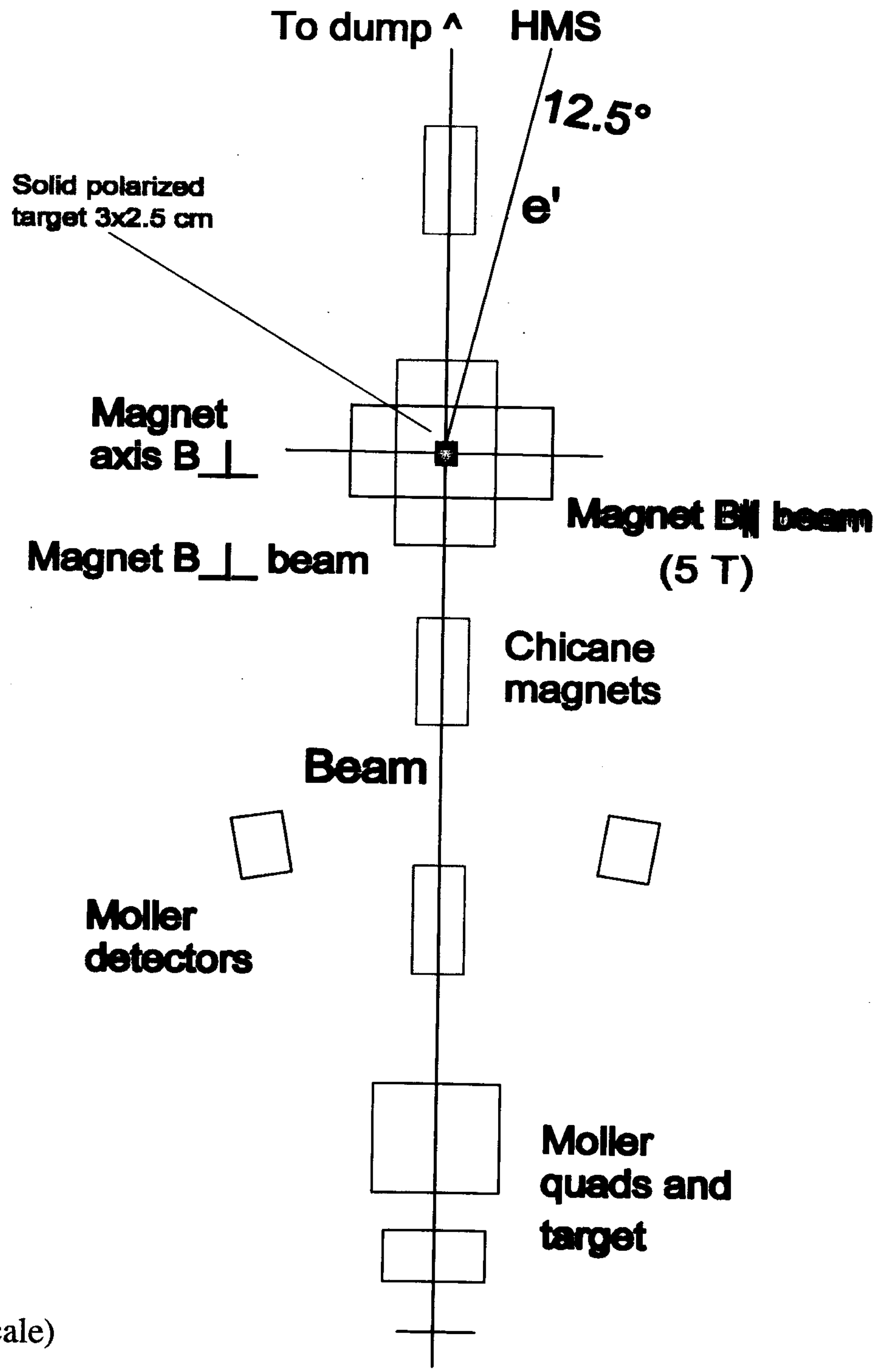
Does unpolarized local duality ⇒ polarized structure functions?


0.30
0.25
0.20
0.15
0.10
0.05
0.00
-0.05
g_1^P
0.0
0.1
0.2
0.3
0.4
0.5
x' (Bloom-Gilman scaling variable)


0.30
0.25
0.20
0.15
0.10
0.05
0.00
-0.05
g_1^P
OARA 1/00
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
ξ (Nachtmann's scaling variable)

Schematic layout and kinematic parameters

Beam = 6 GeV, 70% polarized electrons
Scattering angle $\theta_e = 12.5°$ $\langle Q^2 \rangle = 1.25\ [\text{GeV/c}]^2$



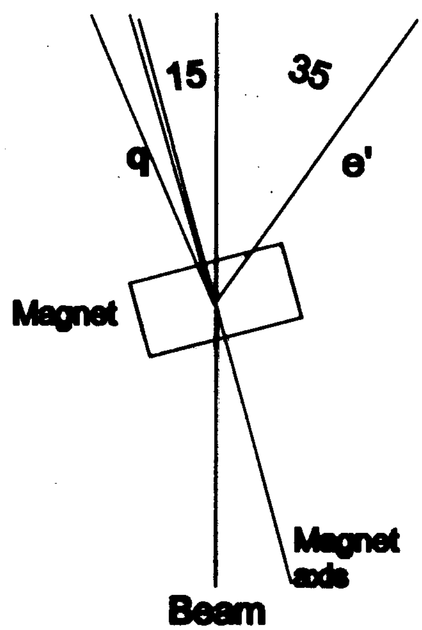
(Not to scale)

D. RONDON
22/34

Schematic layout and kinematic parameters (high Q^2)

Beam E = 6 GeV, 70% polarized electrons.
Scattering angle $\theta_e = 35°$ $Q^2 = 4.7 - 5.8$ GeV^2
$\theta_q = 22°$ to $15°$ $\theta_e + \theta_q = 57°$ to $50°$ (magnet opening 50°)
Use $\theta_N < -7°$ (target angle w. r. t. **q**; $\theta_{N\text{-beam}} = 15°$)
Maximum $G_0\ G_+$ contribution:

$$(k_L / k_T) \sin 7° (G_0 / G_+)[5.7 \text{ GeV}^2] < 0.5\%$$



D. RONDON 23/34

Rates and times (Q^2 = 1.3 GeV^2).

Solid angle	$\Delta\Omega$ = 6.4 msr (Hall C HMS)
Invariant mass range	$0.94 \leq W \leq 2$ GeV
2 momentum settings	
Mass interval	ΔW = 30 MeV ($\Delta E'$ = 32-54 MeV)
Luminosity (H or D)	100×10^{33} cm^{-2}Hz (100 nA I_{beam})
P_b	7~~8~~0%
P_t	80% ($^{15}NH_3$), 25 ~~30~~%($^{15}ND_3$)
Dilution factors	f(H) ~ 0.13, f(D) ~ 0.23,
	≥ 0.15

$N_{counts} = (f\, P_t P_b\, \delta A)^{-2}$ = Rate × time

Statistical error for fixed beam time $\delta A = (f\, P_t P_b \sqrt{N})^{-1}$

Times [h]:		$^{15}NH_3$	$^{15}ND_3$
	$A_{\parallel}$	60	90
	$A_{\perp}$	30	45

Sources of systematic error.

	$^{15}NH_3$	$^{15}ND_3$
Nitrogen polarization	<1%	1%
Radiative corrections	2%	6%
Beam polarization	2%	2%
Target polarization	2.5%	4%
Dilution factor	2%	2%
Pions, deadtime	1%	1%
Errors from *R* and F_2	3%	3%
Totals	5.5%	8.5%

O, RONDON
24/34

Rates and times (high Q^2).

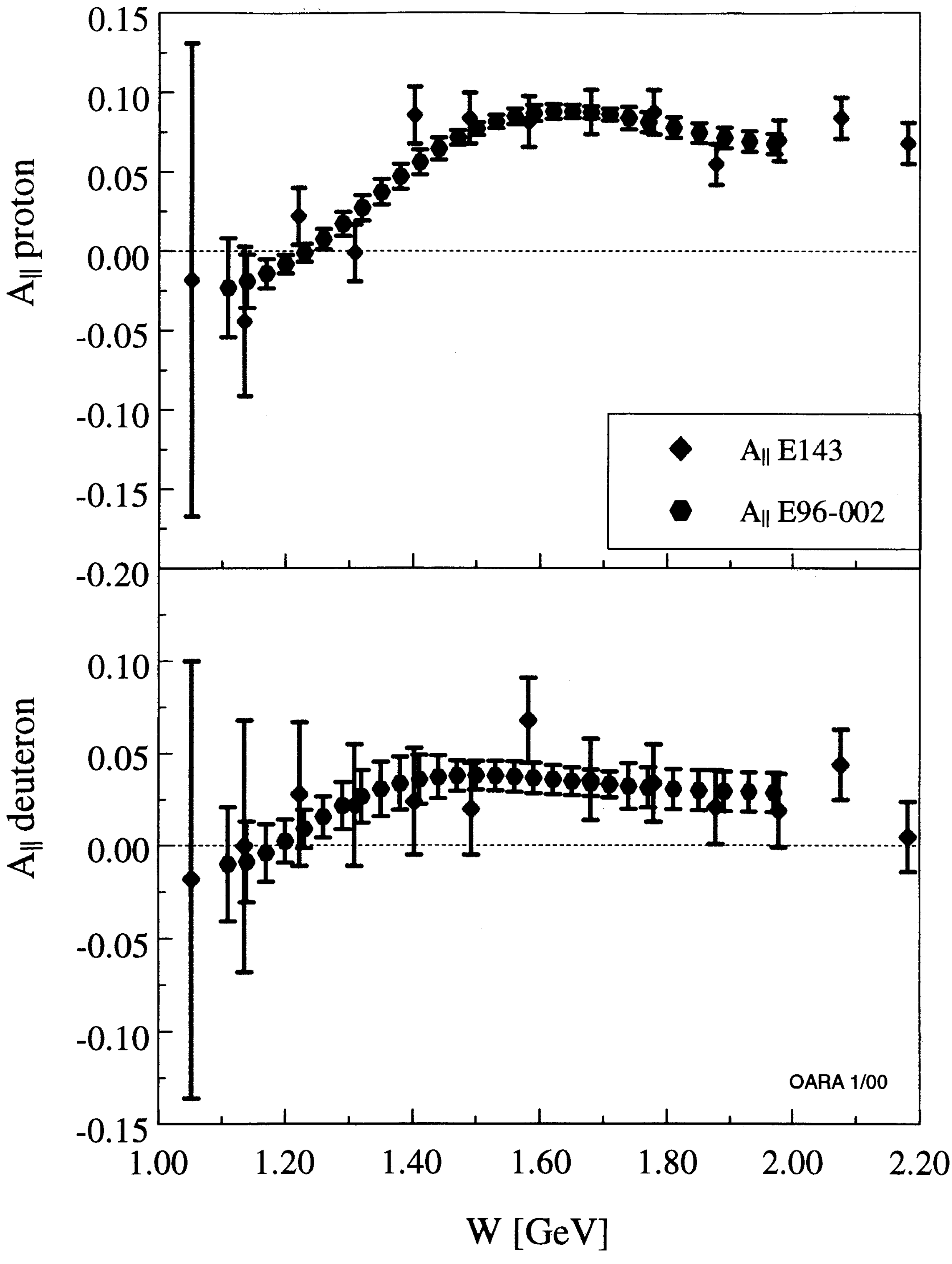
Solid angle	$\Delta\Omega = 6.4$ msr
Invariant mass range (1 momentum setting)	$1.1 \leq W \leq 1.83$ GeV
Mass interval	$\Delta W = 30$ MeV
Luminosity	100×10^{33} cm^{-2}Hz
P_b	7 ~~8~~0%
P_t $^{14}NH_3$	8 ~~7~~ 0%

$N_{counts} = (f\, P_t P_b\, A_{TT}\, \delta A/A)^{-2} =$ 5000 for $\mathbf{A_{TT} = 1}$,
$\delta A/A = 15\%$

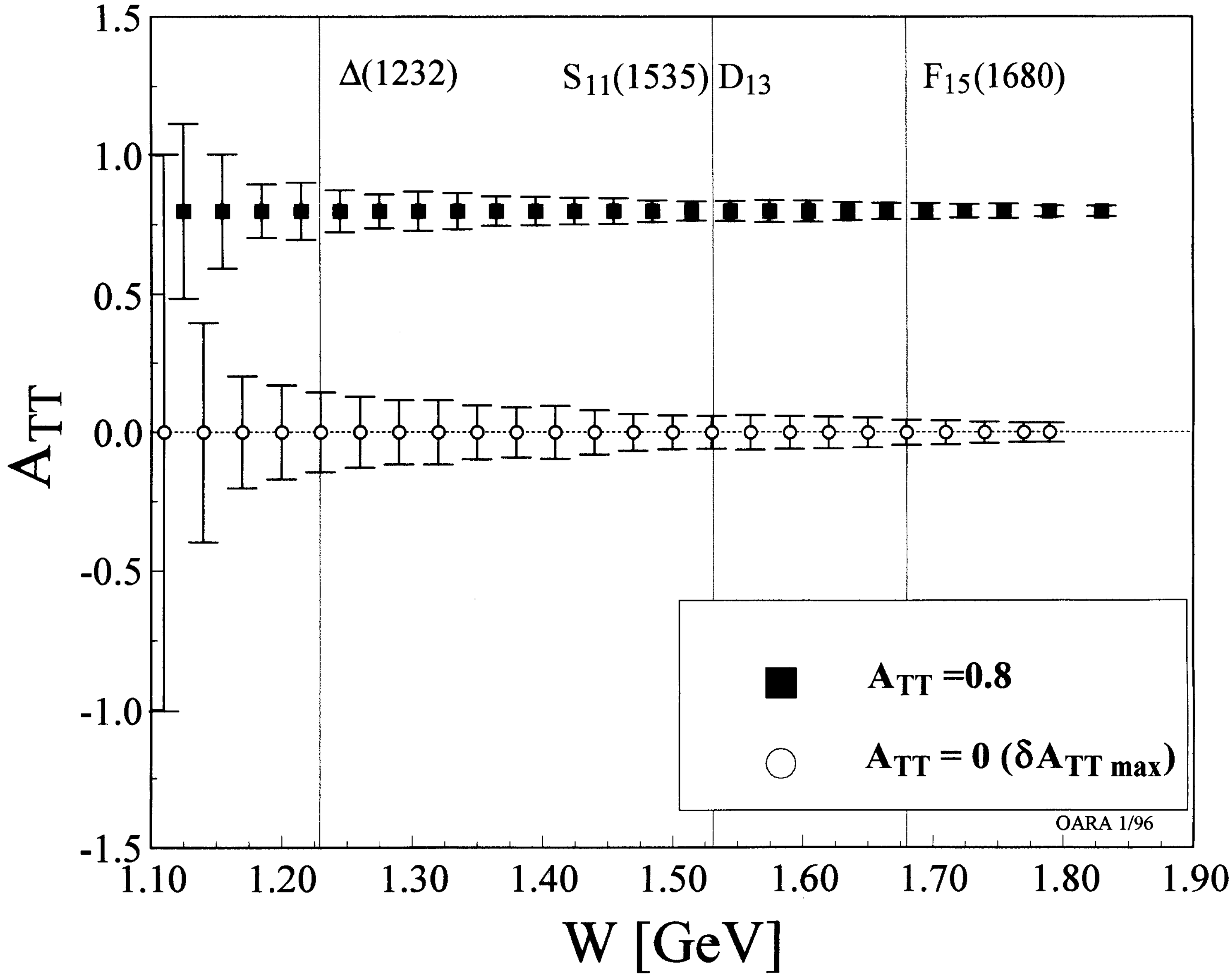
Time (W = 1230 GeV) = 150 hours

Systematics.

Nitrogen polarization	$^{14}NH_3$ correction $C \approx 1.5\%$
Radiative corrections	1%
Beam polarization	2%
Target polarization	2.5%
Dilution factor	2%
Pions, deadtime	1%
$\theta_N \neq \theta_q$	0.5% (cos 6.4° = 0.994)
Total systematics	4.5%



0.15
0.10
0.05
0.00
-0.05
-0.10
-0.15
-0.20
A|| proton
A|| E143
A|| E96-002
0.10
0.05
0.00
-0.05
-0.10
-0.15
A|| deuteron
OARA 1/00
1.00
1.20
1.40
1.60
1.80
2.00
2.20
W [GeV]



Δ(1232)
S11(1535) D13
F15(1680)
ATT =0.8
ATT = 0 (δATT max)
OARA 1/96
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
ATT
1.10
1.20
1.30
1.40
1.50
1.60
1.70
1.80
1.90
W [GeV]

Polarized Duality with 11 GeV at JLab

- Duality studies for SSF's are interesting with an 11 GeV beam at JLab because most of the available kinematic range is below the W = 2 GeV curve:

- Energy is too low for DIS.
- GDH sum rule does not need high energy.

Requirements (in addition to 11 GeV):

- Do good physics: comparable statistical and systematic errors
- Need good δW resolution to see any local duality:
  - very narrow $\Delta E'$:

$$\Delta E' = \frac{W}{M + 2E\sin^2(\frac{\theta}{2})}\Delta W$$

  - very good $\delta p/p$ (0.5% or better) - this is not easy to achieve with large radius (1 cm) rastered beams.
- Small angle measurements imply large final p: need Hall C type SHMS or equivalent (but SHMS small $\Delta\Omega \leq 3$ msr).
- Large angles are good for high Q^2: final $p < 7.5$ GeV (HMS OK)

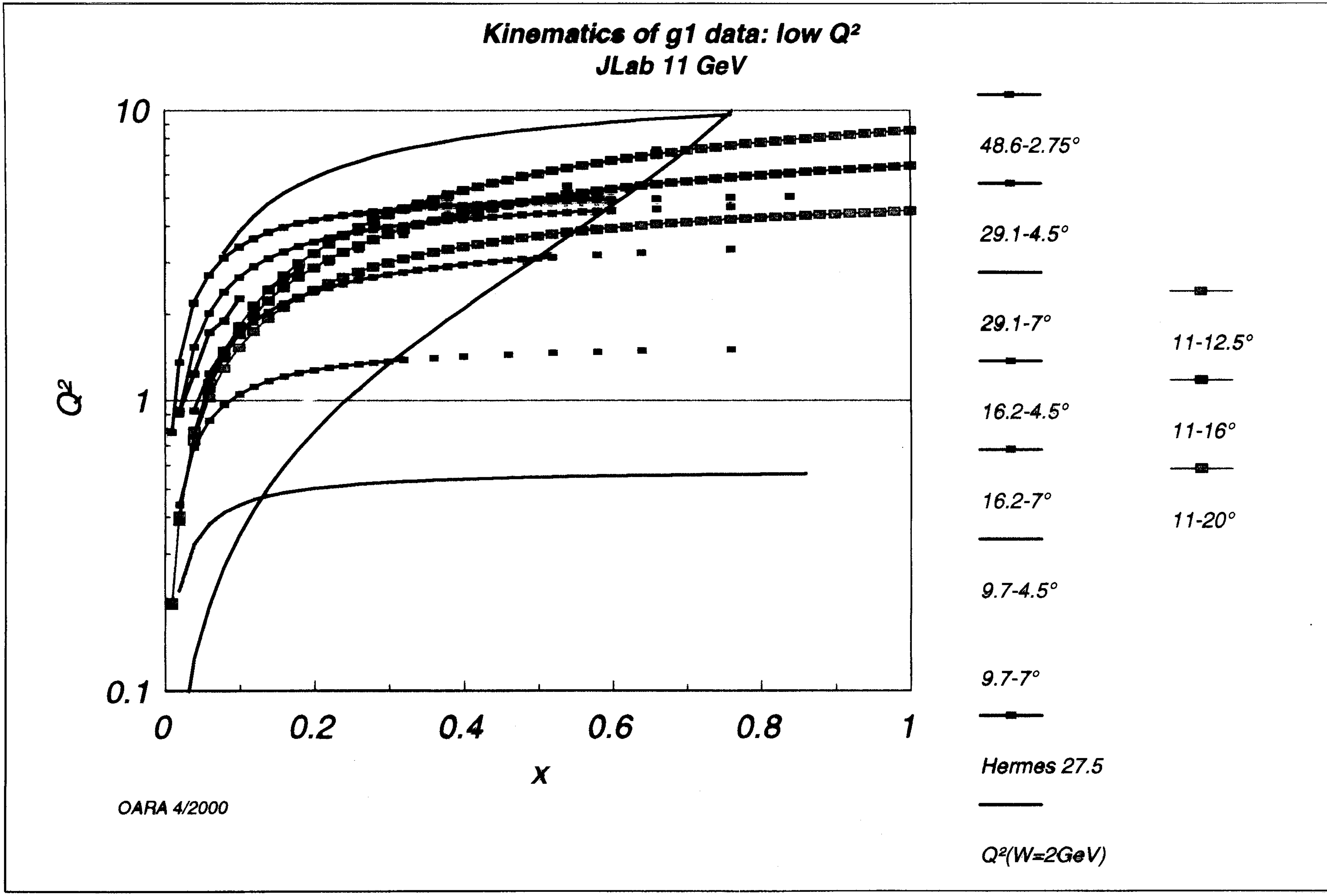
Possible Kinematics Choices

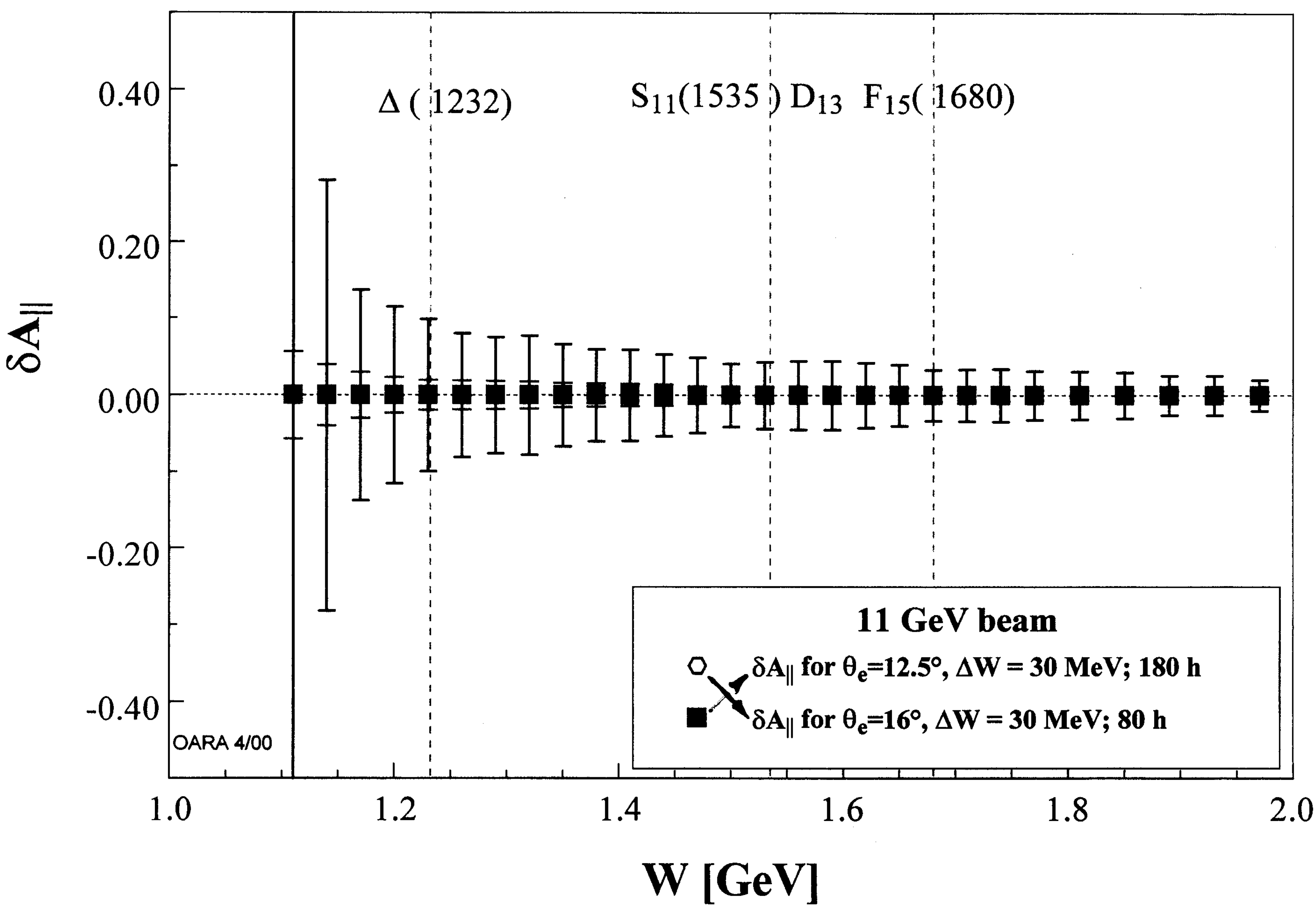
E GeV	θ	**Q^2** GeV^2	**ΔW** MeV	$\Delta E'(\Delta 1232)$ MeV	$E'(\Delta 1232)$ GeV	**Spectrometer**	**sigma Mott** nb/sr	***dp/p*** +/-
11	12.5°	4.2	30	31	8.34	SHMS (?)*	301	7.2%
	16°	6	30	27	7.33	HMS		7.2%
	20°	8	30	24	6.25	HMS		7.2%
	"	"	60	45	6.25	HMS		7.2%
9	16°	4.2	30	28	6.32	HMS	170	9.0%

*Solid angle < 3 msr

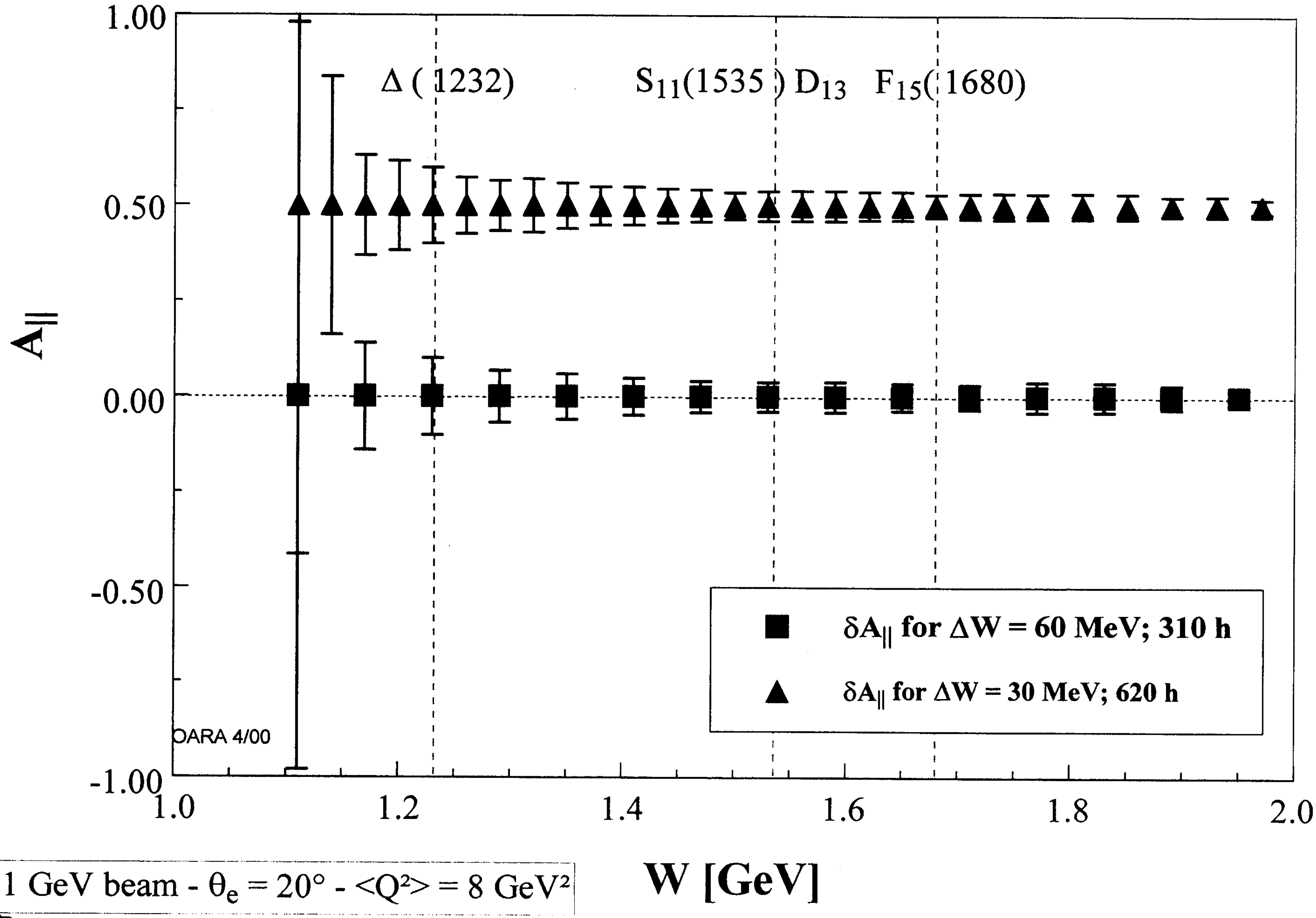
Assumptions and input parameters

NH3 Polarization	80%
Beam polarization	80%
Dilution factor	~0.22
Luminosity [Hz/nb]	100
Spectrometer solid angle [msr]	6.4
Invariant mass range W [GeV]	1.1 - 2.0


Kinematics of g1 data: low Q²
JLab 11 GeV
10
1
0.1
Q²
0
0.2
0.4
0.6
0.8
1
X
OARA 4/2000
48.6-2.75°
29.1-4.5°
29.1-7°
16.2-4.5°
16.2-7°
9.7-4.5°
9.7-7°
Hermes 27.5
Q²(W=2GeV)
11-12.5°
11-16°
11-20°



0.40
0.20
0.00
-0.20
-0.40
δA||
Δ (1232)
S11(1535) D13 F15(1680)
11 GeV beam
δA|| for θe=12.5°, ΔW = 30 MeV; 180 h
δA|| for θe=16°, ΔW = 30 MeV; 80 h
OARA 4/00
1.0
1.2
1.4
1.6
1.8
2.0
W [GeV]



11 GeV beam - $\theta_e = 20°$ - $<Q^2> = 8$ GeV^2

Additional considerations:

- Deuteron:
  - Need about 1.5 times longer for similar errors as for proton.
  - Possible targets are N^2H_3 or LiD, but Li nuclear structure is an issue.

- g_2 measurement requires about 50% additional time for each nucleon.

- Need significant momentum bite to measure entire region in one setting.

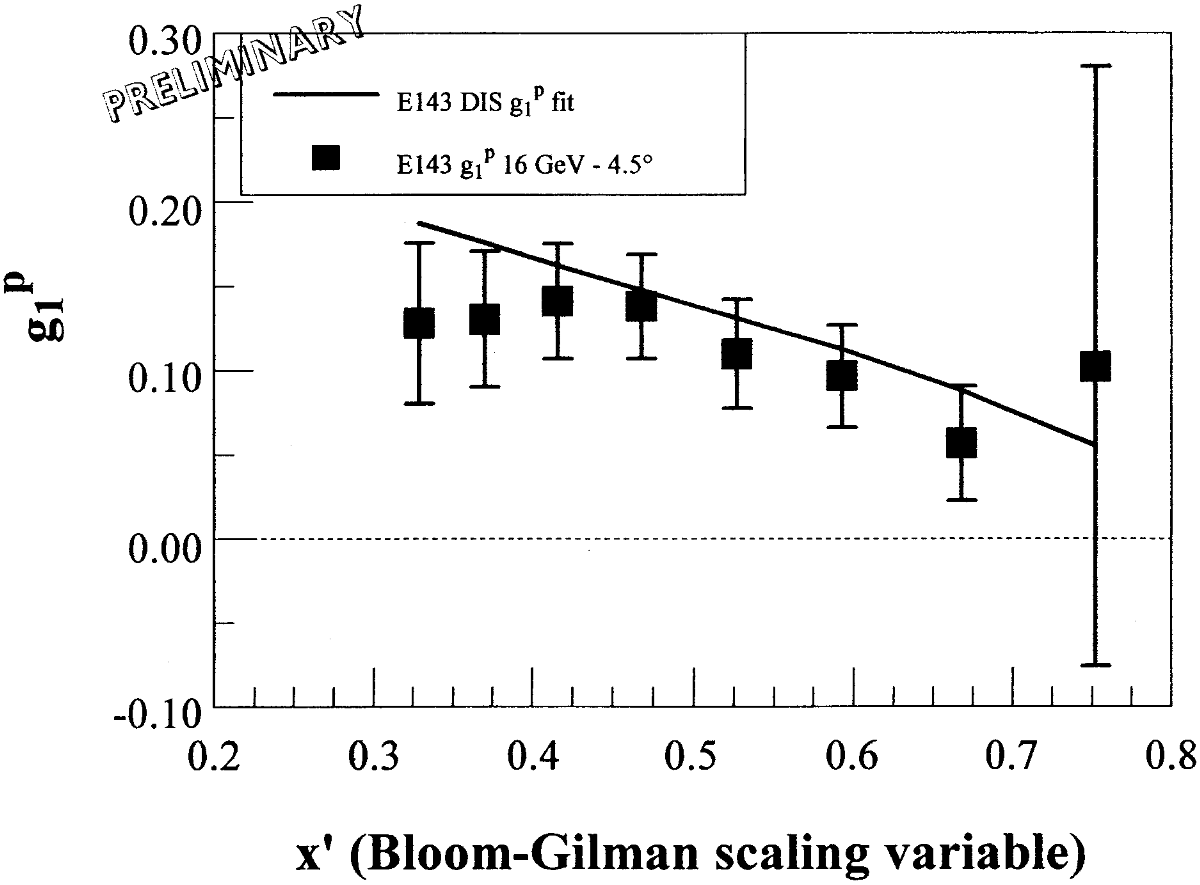
Questions
(mainly for theorists)

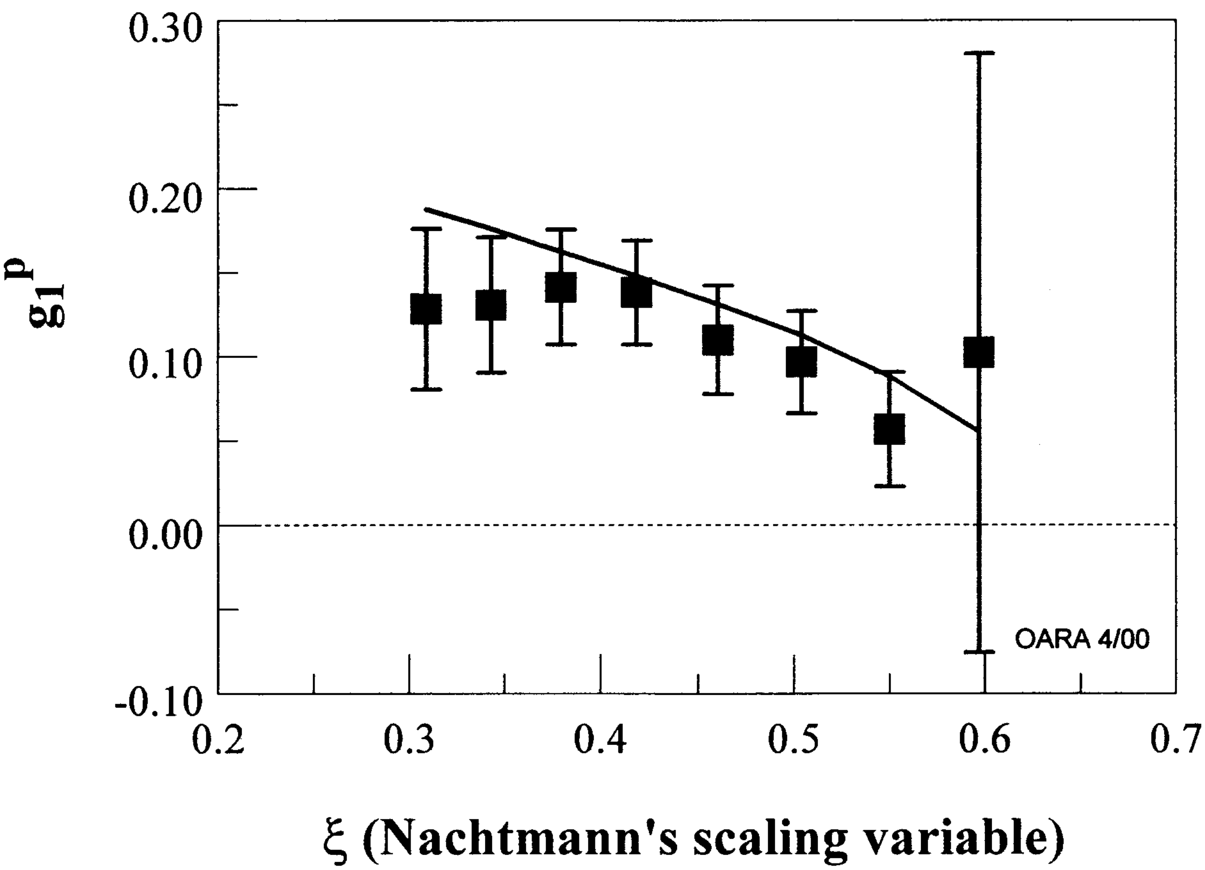
- So far duality seems mainly a proton s.f. property. How do we extract neutron structure functions in the resonances?

- What Q^2 dependence can be expected? What is the Q^2 upper limit? Resonances already are not prominent at all at 6 GeV^2. Some are already gone (D_{13}(1520)) or almost gone (P_{33}(1232)).

- What is dual to what in polarized scattering? We have seen $\boldsymbol{F_2}$ duality, but $\boldsymbol{g_1}$ is not the corresponding s.f. to $\boldsymbol{F_2}$, but to $\boldsymbol{F_1}$: is there any indication of $\boldsymbol{F_1}$ duality (at low Q^2 Callan-Gross is not valid).

- How about $\mathbf{A_1} \approx \boldsymbol{g_1} / \boldsymbol{F_1}$? Also, there is no unpolarized $\boldsymbol{g_2}$ analog. How about $\mathbf{A_2}$?


PRELIMINARY
E143 DIS g_1^p fit
E143 g_1^p 16 GeV - 4.5°
g_1^p
0.30
0.20
0.10
0.00
-0.10
0.2
0.3
0.4
0.5
0.6
0.7
0.8
x' (Bloom-Gilman scaling variable)


g_1^p
0.30
0.20
0.10
0.00
-0.10
0.2
0.3
0.4
0.5
0.6
0.7
OARA 4/00
ξ (Nachtmann's scaling variable)