THE SPIN STRUCTURE FUNCTIONS g_1 and g_2 FROM SLAC E155 and E155X

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REPRESENTING THE E155X COLLABORATION

Oct, 2000

- EXPERIMENT
- SOME THEORY
- g_1 AND A_1 FOR PROTON/DEUTERON
- g_2 AND A_2 FOR PROTON/DEUTERON
- Q^2 DEPENDENCE OF g_2 AND A_2
- TWIST-3 MATRIX ELEMENT d_2
- SUM RULES
- FUTURE?

E155/E155x Collaboration

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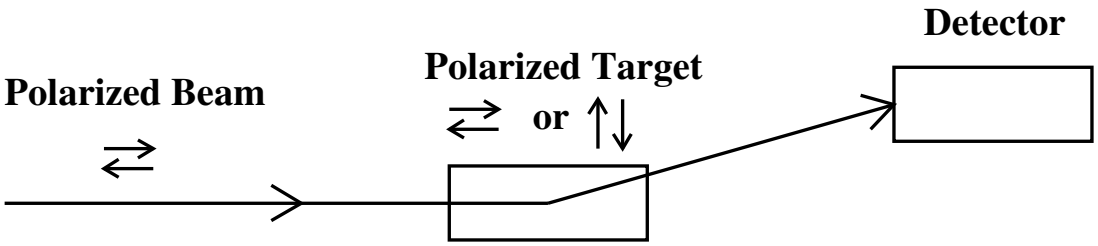
Polarized Deep Inelastic Scattering



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

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

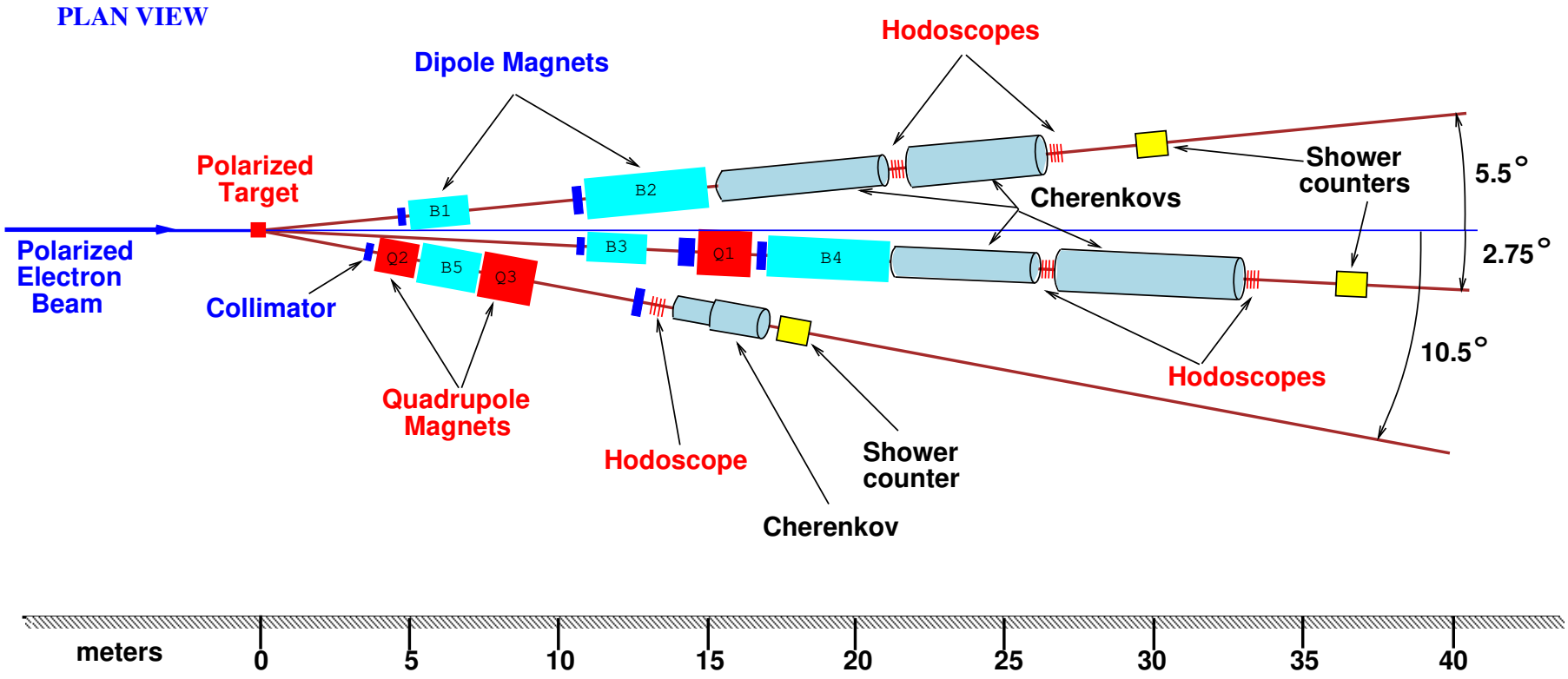
g_1 and g_2 are the polarized structure functions.

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

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

$\rightarrow$ f_k includes contribution from kinematics and unpolarized structure functions

E155 Spectrometers



EXPERIMENTAL OVERVIEW

- SLAC ELECTRON BEAM:
  - POLARIZATION $P_b = 0.83$
  - ENERGY: $E = 48.3 (g_1)$
  - ENERGY: $E = 29.1 (g_2)$ or $E = 32.3 (g_2)$
  - 120 HZ, 400 nsec SPILLS, 25 nA.
- POLARIZED TARGETS:
  - 1 K, 5 T, D.N.P
  - NH3 FOR PROTONS ($< P_t >= 0.75$).
  - LiD FOR DEUTERONS ($< P_t >= 0.22$).
- SCATTERED ELECTRONS DETECTED:
  - AT 2.75, 5.5, AND 10.5 DEGREES
  - CHERENKOV AND LEAD GLASS FOR PARTICLE I.D.
  - HODOSCOPES FOR TRACKS ($dP/P \approx 0.03$)
- PHOTOPRODUCED INCLUSIVE PIONS

Polarized Electron Beam

- Intense 48/29/32 GeV Beam
- Highly polarized : $P_b = 0.813 \pm 0.020$
- Helicity varied randomly from pulse to pulse (120 Hz)
- 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

POLARIZED TARGETS

- Solid cryogenic targets
  - Magnet at 5 T
  - Temperature 1K
- Dynamic nuclear polarization using microwaves
- Radiation Damage Limits $< P_t >$

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

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

→ Difficulty with NMR readout (E155 Proton Only)

- ^{6}LiD used for deuteron target

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

→ LiD 6 times as radiation resistant

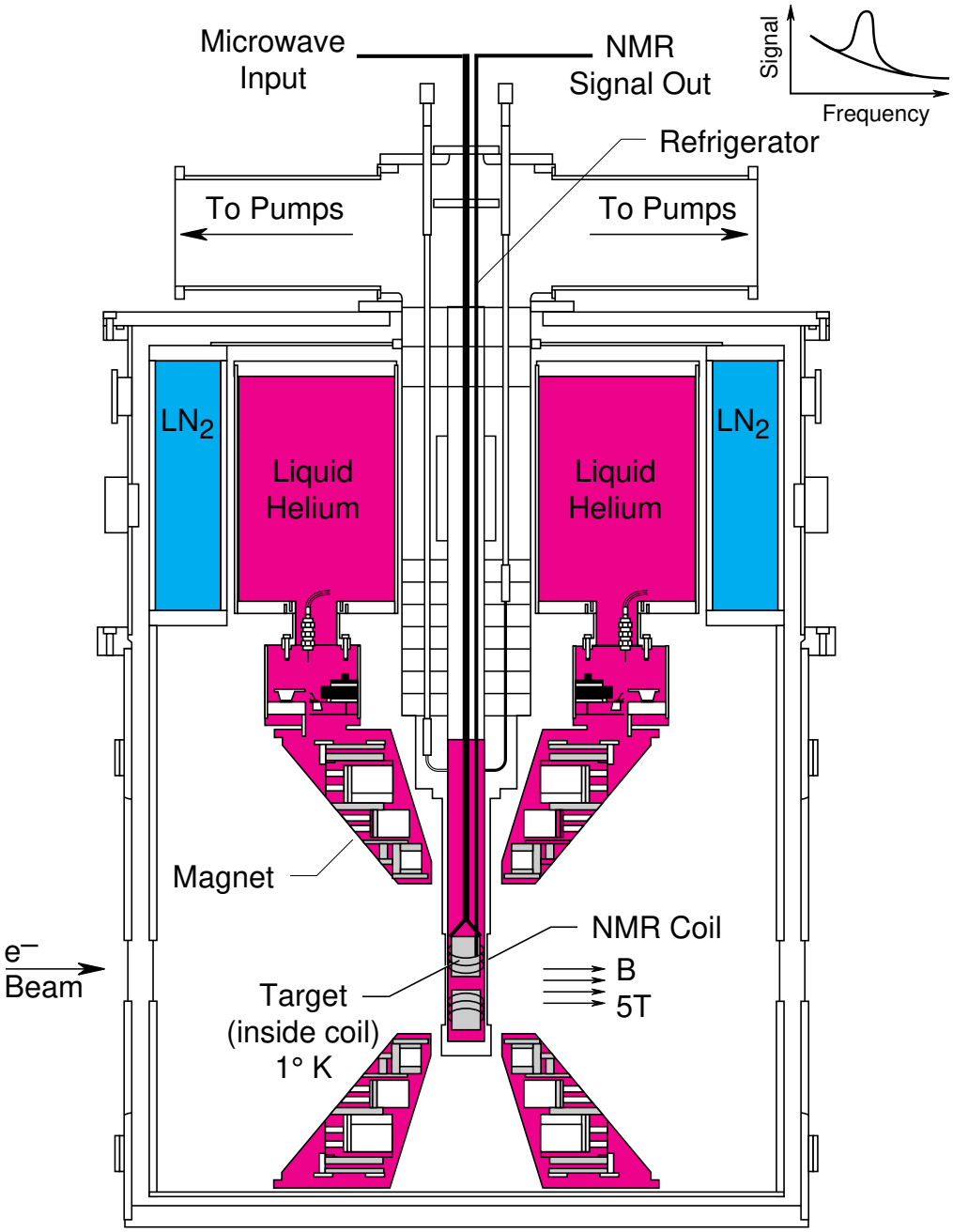
→ $< P_t > \approx$ 20%

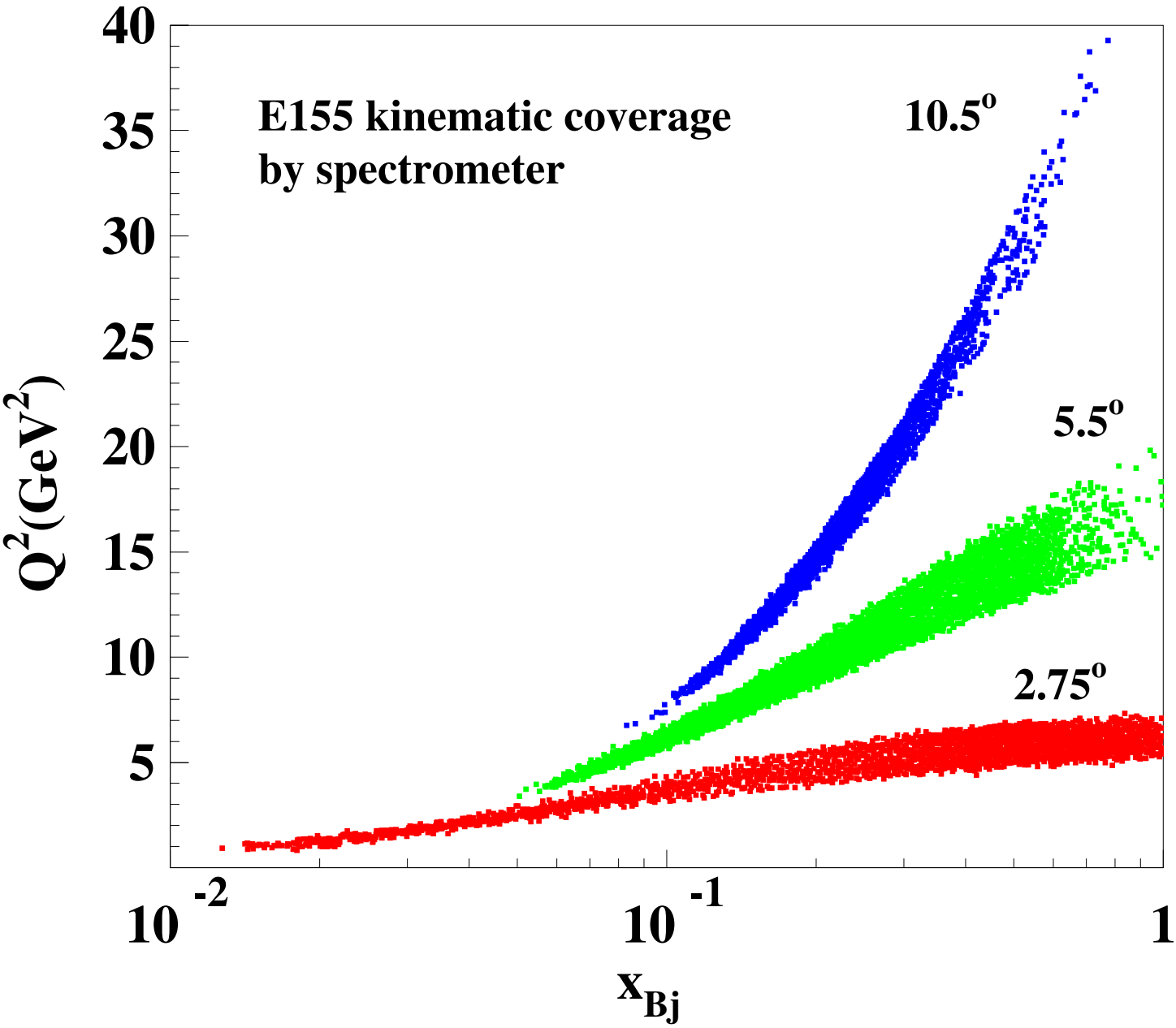
E155 PROTON TARGET NMR PROBLEMS

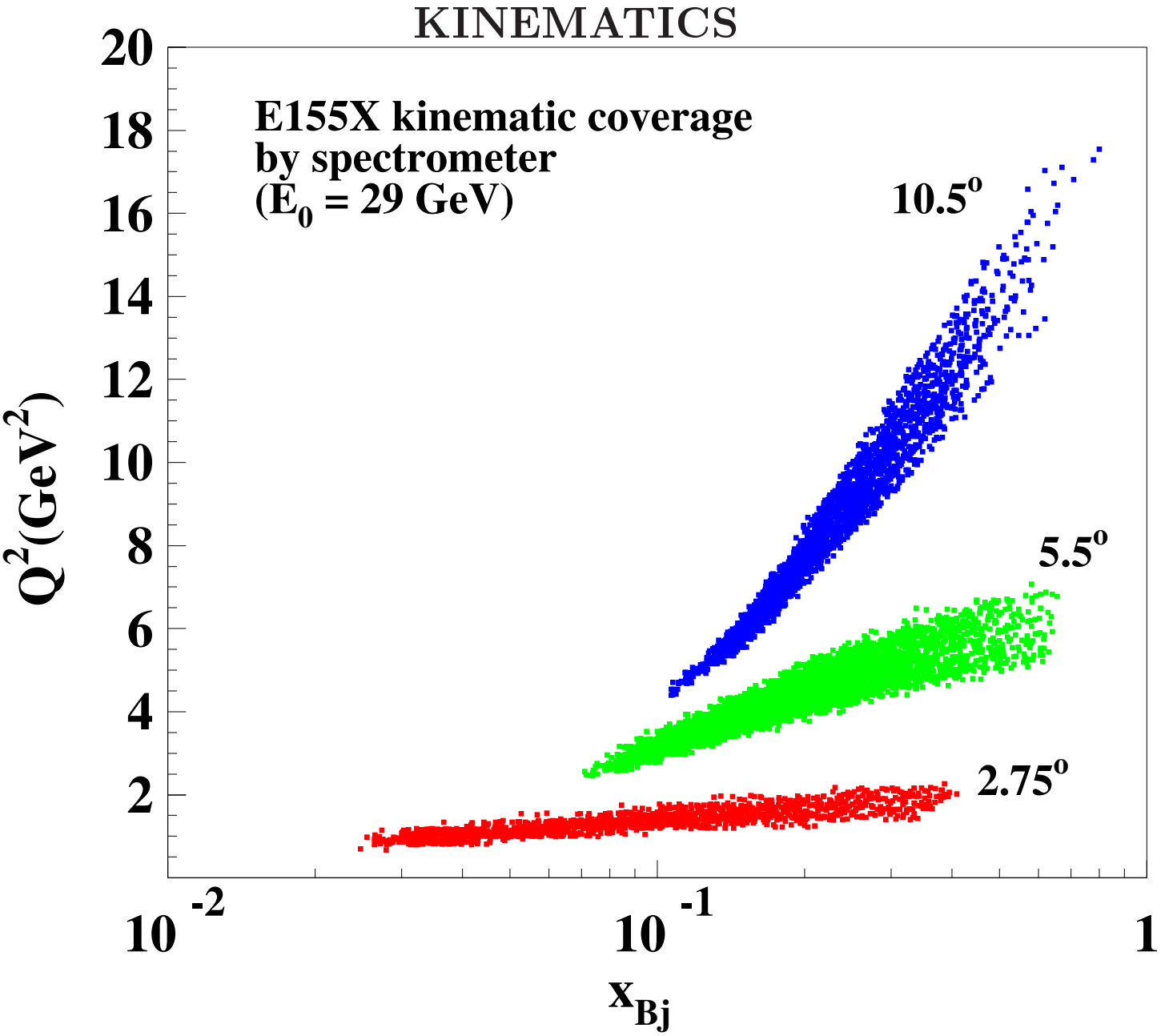
(NOT A PROBLEM FOR E155X)

- "Improved" Target Cell From E143
- Coupling between Target Cell and Cables
- Significant Non-Linear Behavior
- Qualitatively Understood, But Cannot Calculate Corrections.
- Determine Polarization from Beam Dose Effects Seen in E155X
- Other Methods Give Similar Results (^{15}N Polarization)
- Estimate Systematic Error of 7%

E143/E155/E155x Target




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


KINEMATICS
E155X kinematic coverage
by spectrometer
(E_0 = 29 GeV)
10.5°
5.5°
2.75°
Q^2(GeV^2)
x_{Bj}
20
18
16
14
12
10
8
6
4
2
10^{-2}
10^{-1}
1

SIMPLE FIT USED TO CALCULATE g_2^{WW}

$Q^2 > 1$

$$g_1^p/F_1^p = x^{.700}(.817+1.014x-1.489x^2)(1-.04/Q^2)$$
$$g_1^n/F_1^n = x^{-.335}(-.013-.330x+.761x^2)(1+.13/Q^2)$$

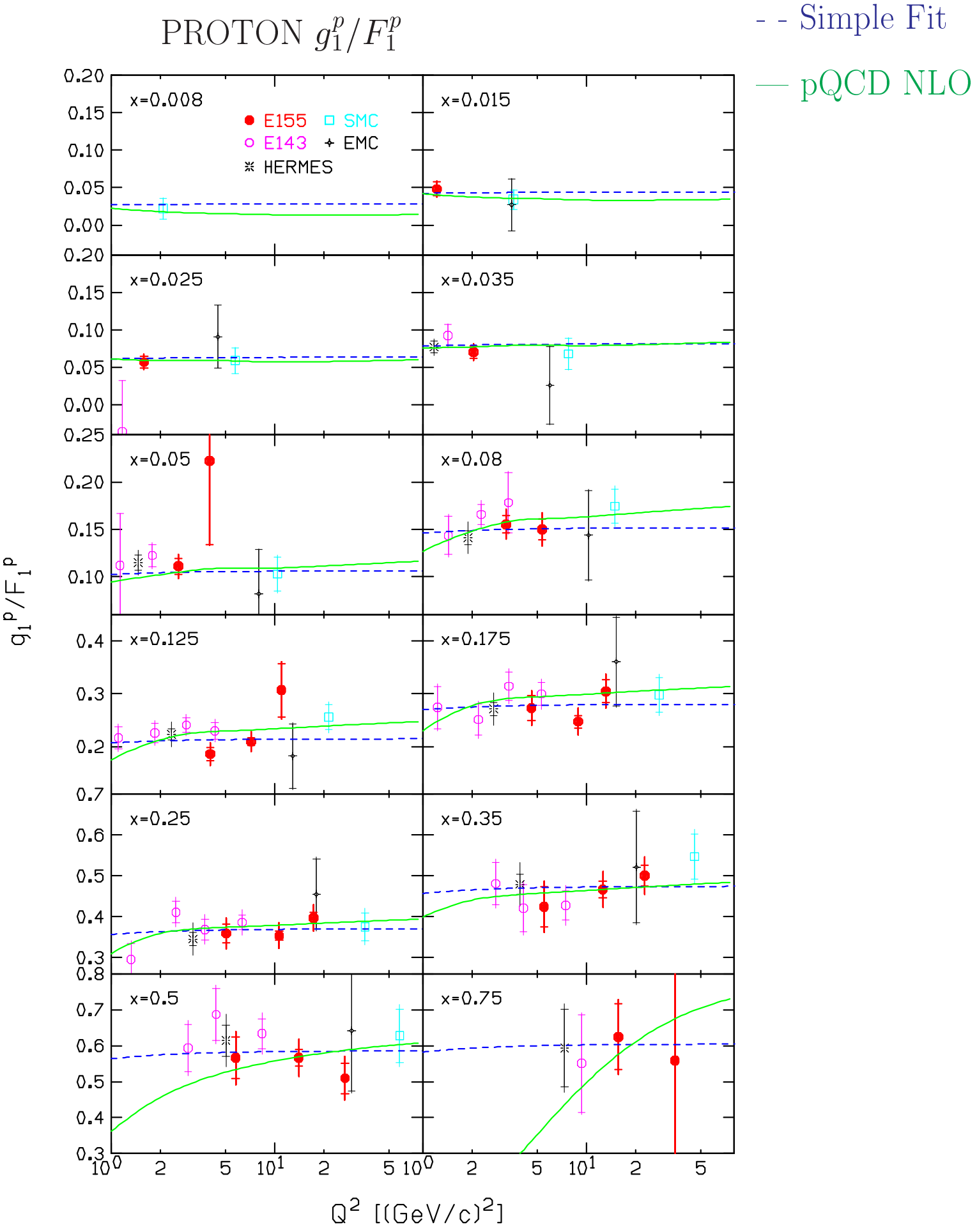
Q^2 DEPENDENCE

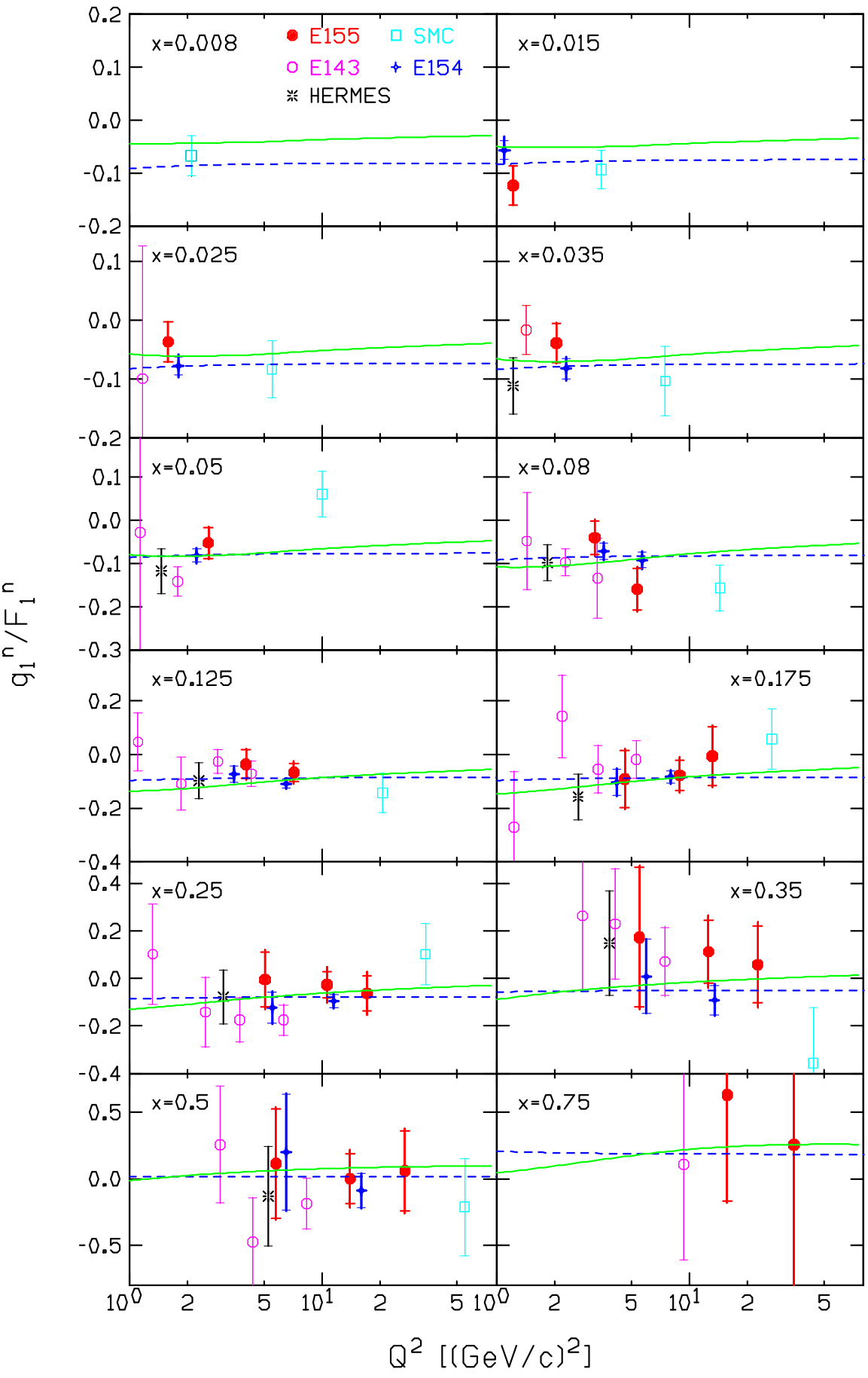
Proton -0.04 ± 0.06

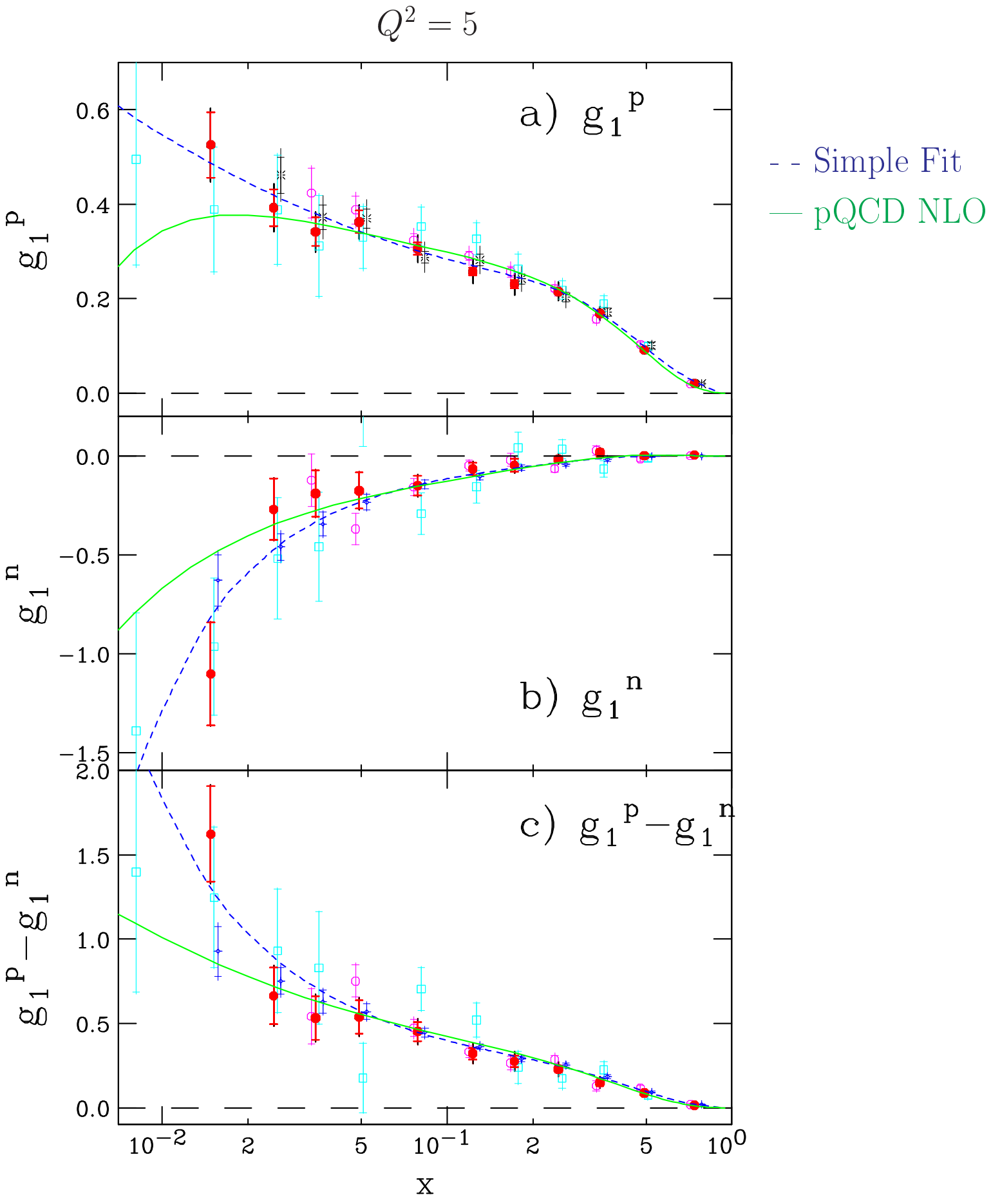
Neutron 0.13 ± 0.45

NLO pQCD $\overline{MS}$ FIT

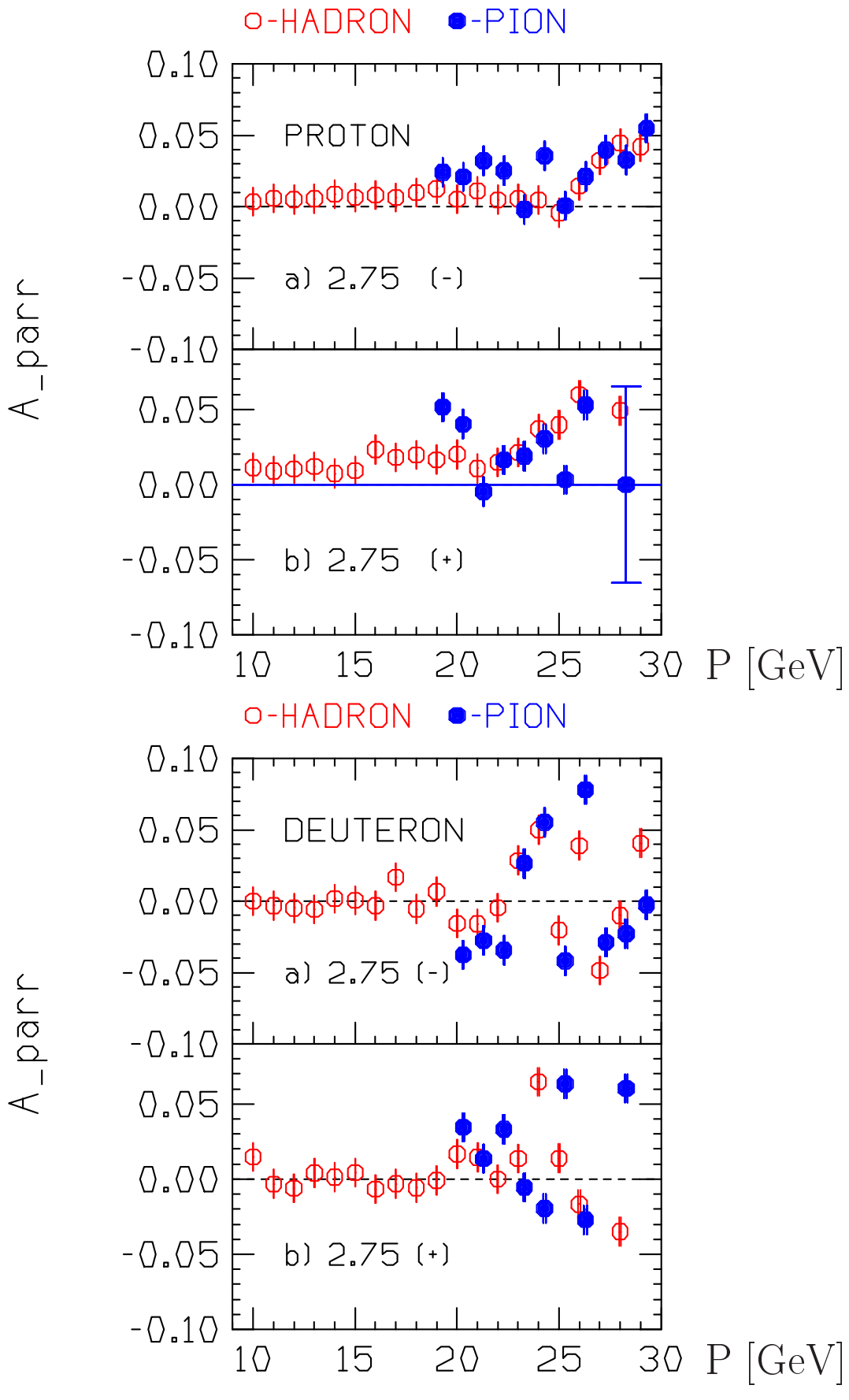
- Values at $Q^2 = 5$
- $\Delta\Sigma = 0.23 \pm 0.04 \pm 0.06$
- $\Gamma^{p-n} = 0.176 \pm 0.003 \pm 0.007$
- (Calculated 0.182 ± 0.005
- $\Delta G = 1.6 \pm 0.8 \pm 1.1$


PROTON g_1^p/F_1^p
- - Simple Fit
— pQCD NLO
x=0.008
E155
SMC
E143
EMC
HERMES
x=0.015
x=0.025
x=0.035
x=0.05
x=0.08
x=0.125
x=0.175
x=0.25
x=0.35
x=0.5
x=0.75
g_1^p/F_1^p
Q^2 [(GeV/c)^2]

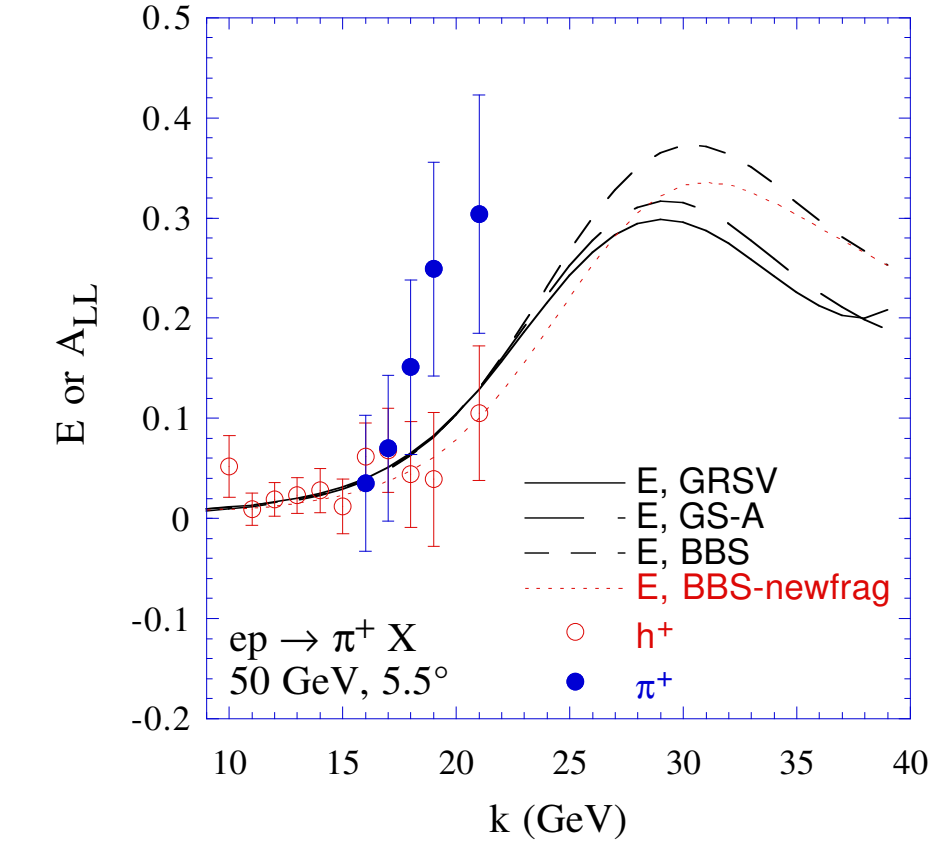

NEUTRON g_1^n/F_1^n
- - Simple Fit
— pQCD NLO
E155
SMC
E143
E154
HERMES
x=0.008
x=0.015
x=0.025
x=0.035
x=0.05
x=0.08
x=0.125
x=0.175
x=0.25
x=0.35
x=0.5
x=0.75
g_1^n/F_1^n
Q^2 [(GeV/c)^2]

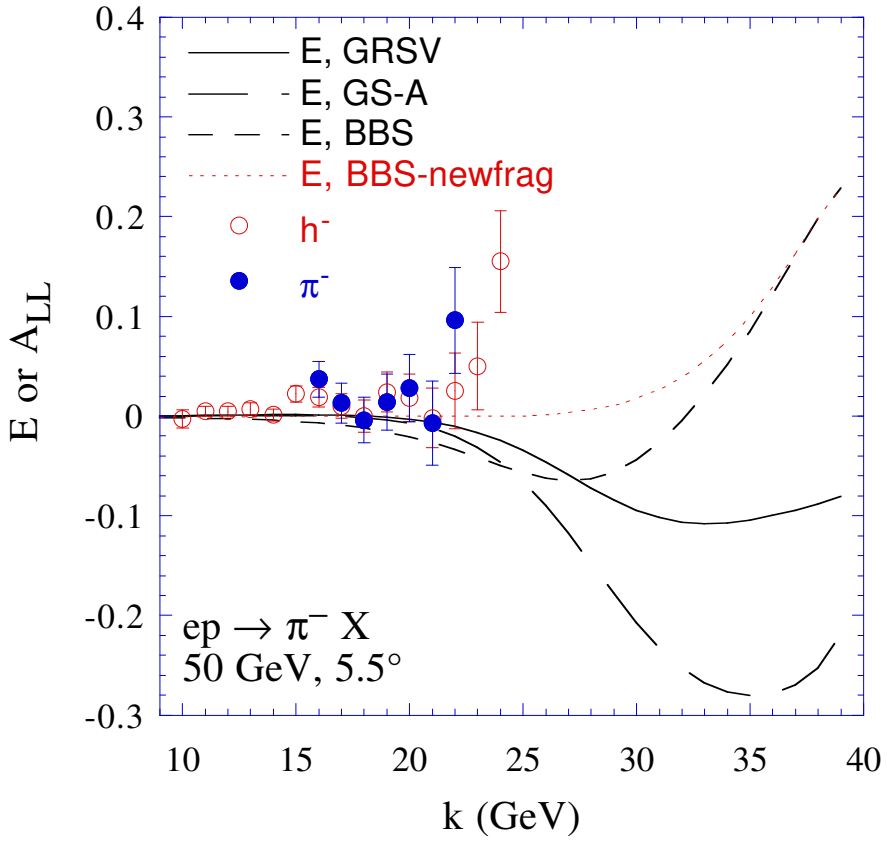

$Q^2 = 5$
a) g_1^p
b) g_1^n
c) $g_1^p - g_1^n$
g_1^p
g_1^n
$g_1^p - g_1^n$
x
- - Simple Fit
— pQCD NLO

INCLUSIVE HADRON ASYMMETRY: 2.75^O

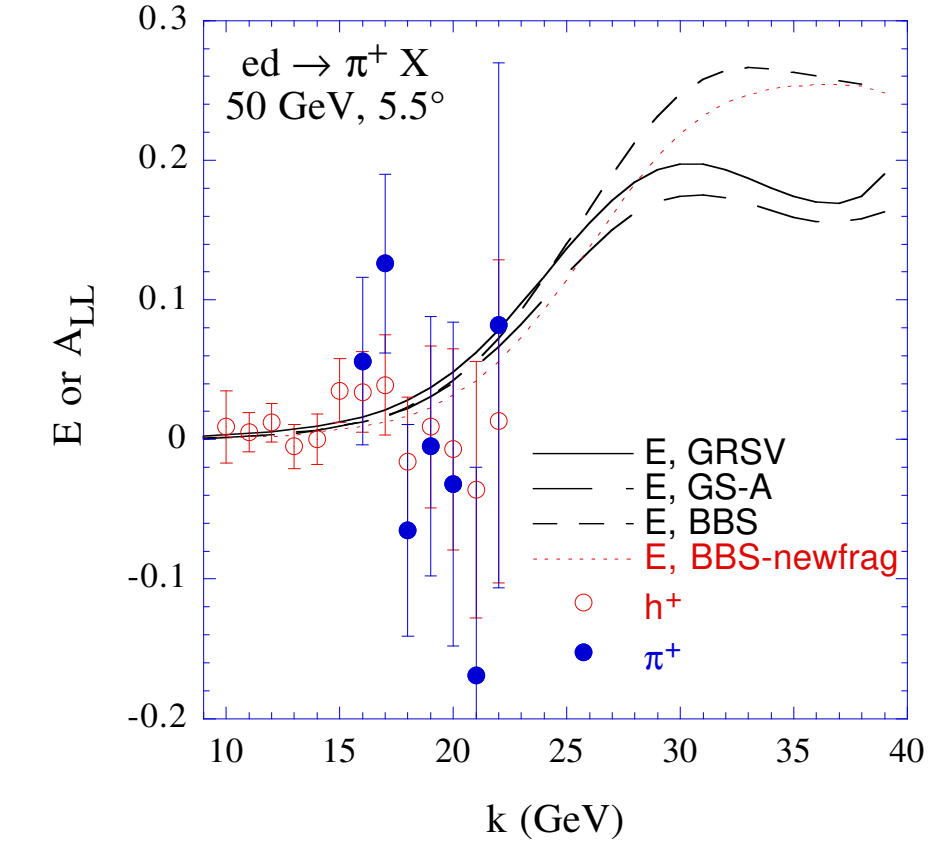


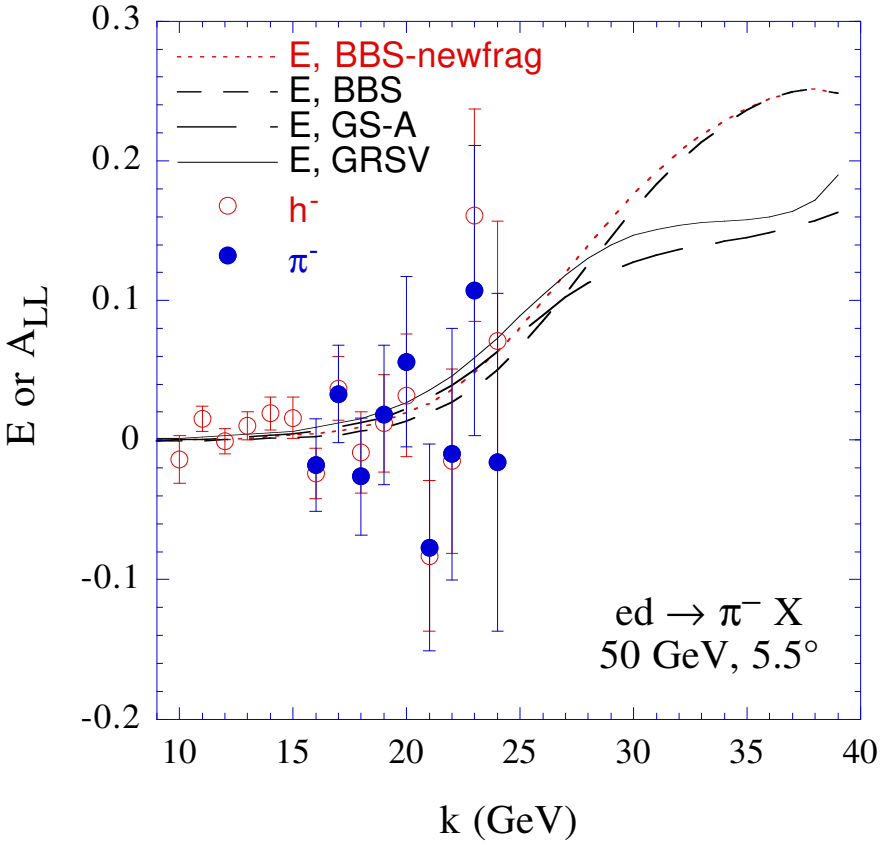
INCLUSIVE HADRON ASYMMETRY: PROTON





INCLUSIVE HADRON ASYMMETRY: DEUTERON





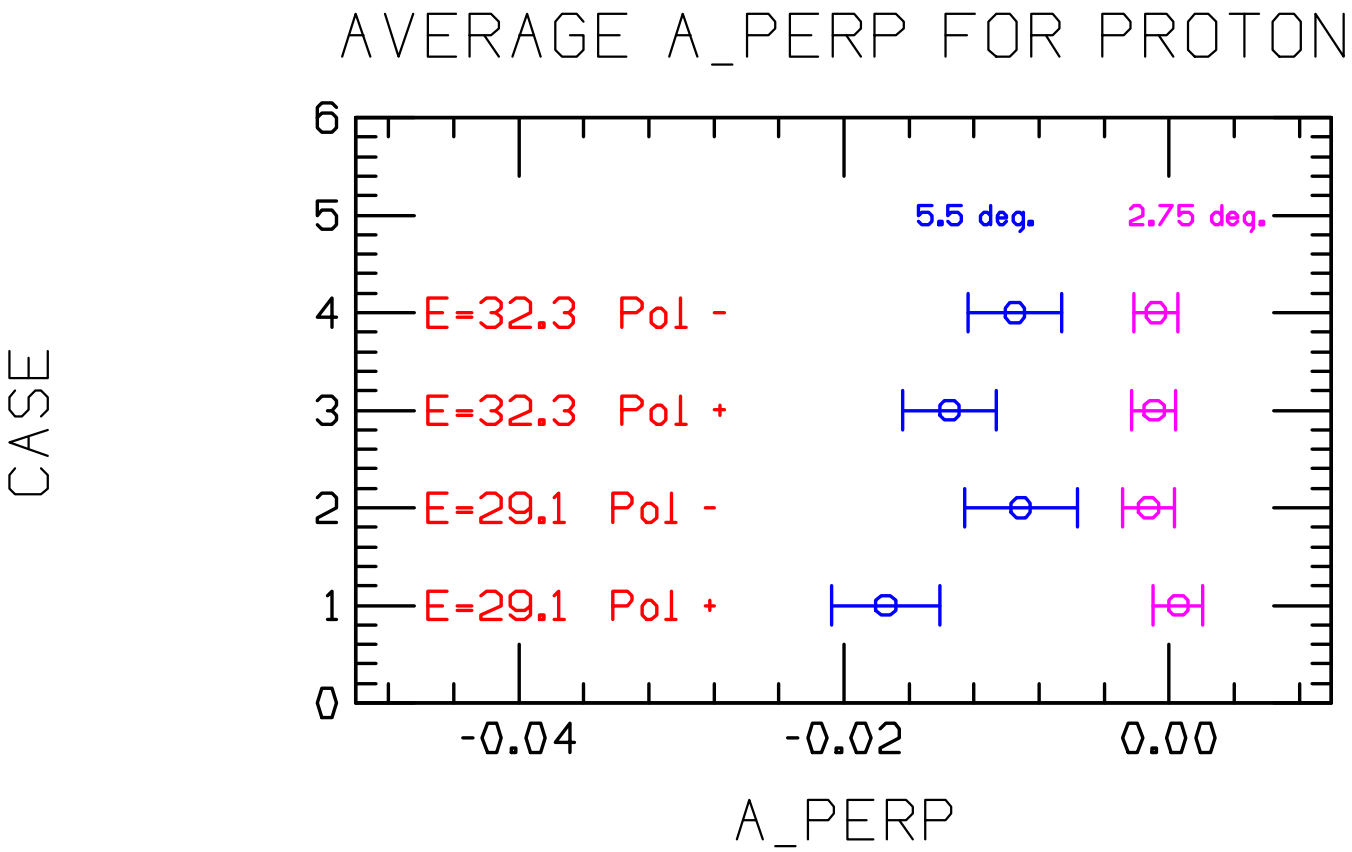
THE $A_\perp$ ASYMMETRY

$$A_\perp = \frac{C_1}{f P_t f_{RC} \cos(\phi)} \left(\left(\frac{N_L - N_R}{N_L + N_R} \right) \frac{1}{P_b} + A_{EW} \right) + A_{RC}$$

- N_L AND N_R ARE RATES FOR L AND R BEAM HELICITY, CORRECTED FOR PAIR-SYMMETRIC CONTRIBUTIONS (FEW PERCENT) AND PIONS MIS-IDENTIFIED AS ELECTRONS (FEW PERCENT)
- $C_1 \approx 1$ CORRECTS FOR POLARIZED ^{15}N or Li
- ADDITIONAL CORRECTION FOR ^{7}Li and LiH CONTAMINATION
- $\cos(\phi)$ IS THE ANGLE BETWEEN PLANE OF ELECTRON/PROTON SPINS AND PLANE OF ELECTRON SCATTERING.
- f IS DILUTION FACTOR (≈ 0.16 PROTON)
- A_{EW}: ELECTROWEAK ASYMMETRY ($\approx 8 \times 10^{-5} Q^2$)
- f_{RC} AND A_{RC} ARE FOR RADIATIVE CORRECTIONS, PRESENTLY MADE USING g_2^{ww} MODEL AND E155 FIT TO g_1. THIS WILL BE REFINED IN FUTURE, LIKELY RESULTING IN REDUCTION OF STATISTICAL ERRORS AT LOWEST x OF EACH SPECTROMETER.

SYSTEMATIC CHECKS

- TARGET POLARIZATION ALIGNED (+) OR ANTI-ALIGNED (-) WITH B FIELD
- BEAM ENERGY CHANGED BY 3.2 GeV TO PRECESS SPIN BY π IN TRANSPORT LINE.
- CORRECT FOR EW ASYMMETRY (DEPENDS ONLY ON BEAM HELICITY)
- ANY REMAINING FALSE ASYMMETRIES (I.E. HELICITY-DEPENDENT BEAM POSITION) WOULD SHOW UP AS A DIFFERENCE IN AVERAGE $A_\perp$. NONE SEEN.



DETERMINATION OF g_2 and A_2

- WE USE MEASURED $A_\perp$ and E155 g_1 FIT TO OBTAIN g_2 USING:

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

- WE CAN COMPARE g_2 TO THE SIMPLE TWIST-2 MODEL OF WANDZURA-WILCZEK

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

- WE CAN ALSO EXTRACT VIRTUAL PHOTON-NUCLEON ASYMMETRY

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

- COMPARE TO POSITIVITY LIMIT $A_2 < \sqrt{R(x,Q^2)}$
- COMPARE TO SOFFER LIMIT $A_2 < \sqrt{R(1+A_1)/2}$

$g_2(x, Q^2)$ 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.

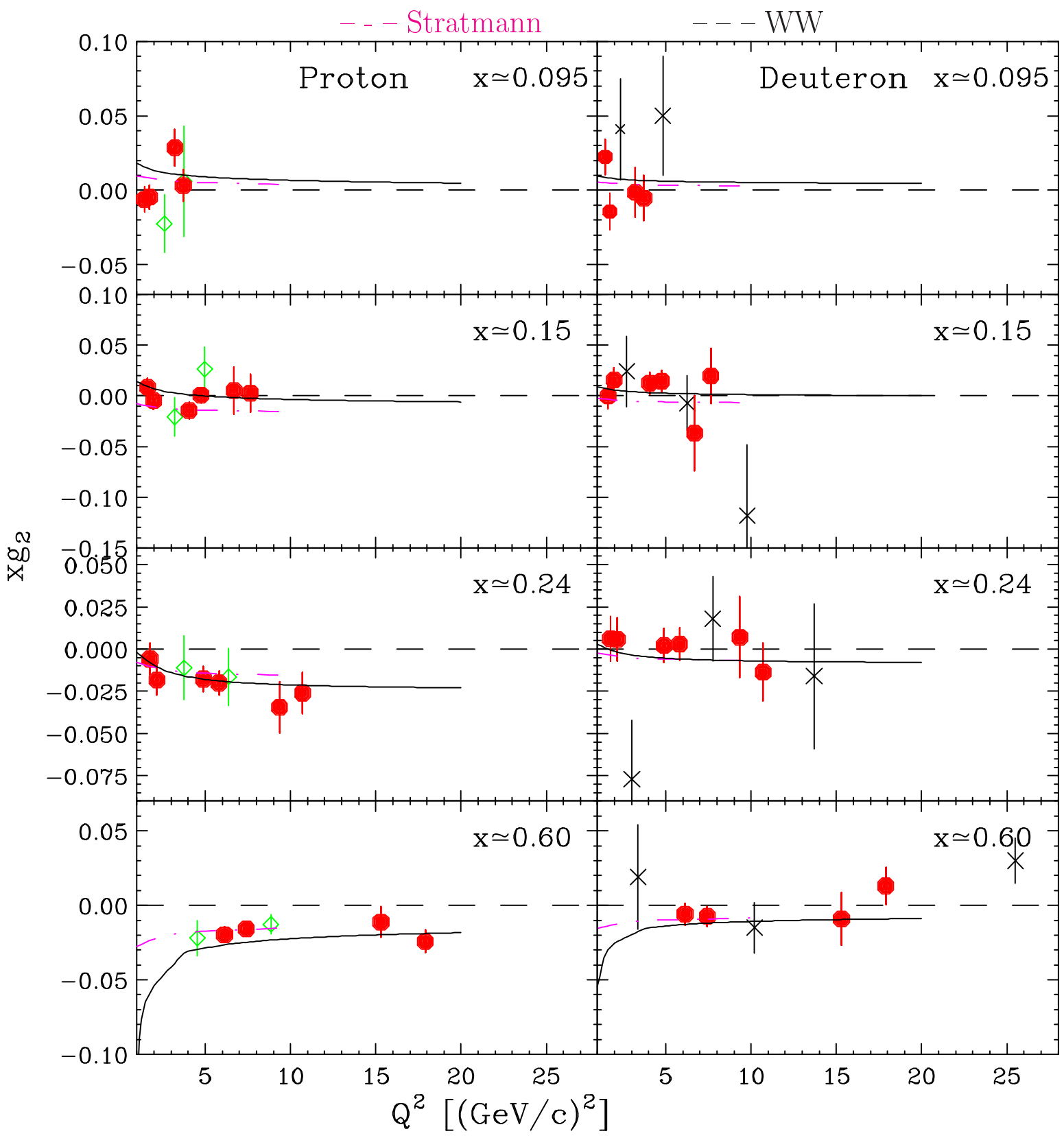
$$g_2(x, Q^2) = g_2^{WW}(x, Q^2) - \int_x^1 \frac{\partial}{\partial y}\left(\frac{m}{M} h_T(y, Q^2) + \xi(y, Q^2)\right)\frac{dy}{y}$$

(twist-2 $\Downarrow$ twist-2 $\Downarrow$ twist-3 $\Downarrow$)

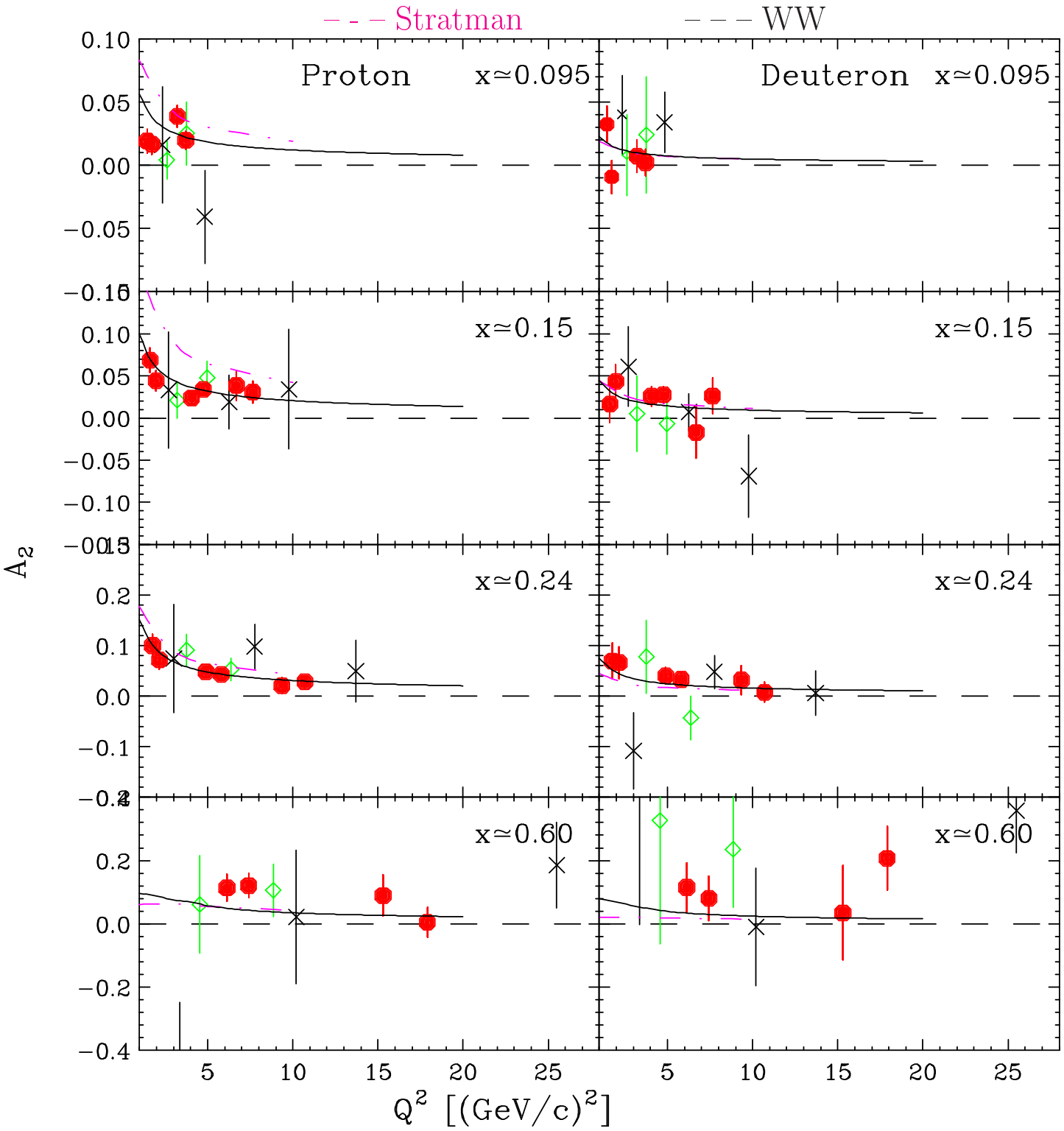
$$= g_2^{WW}(x, Q^2) + \overline{g_2}(x, Q^2)$$

- $\overline{g_2}$ 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:

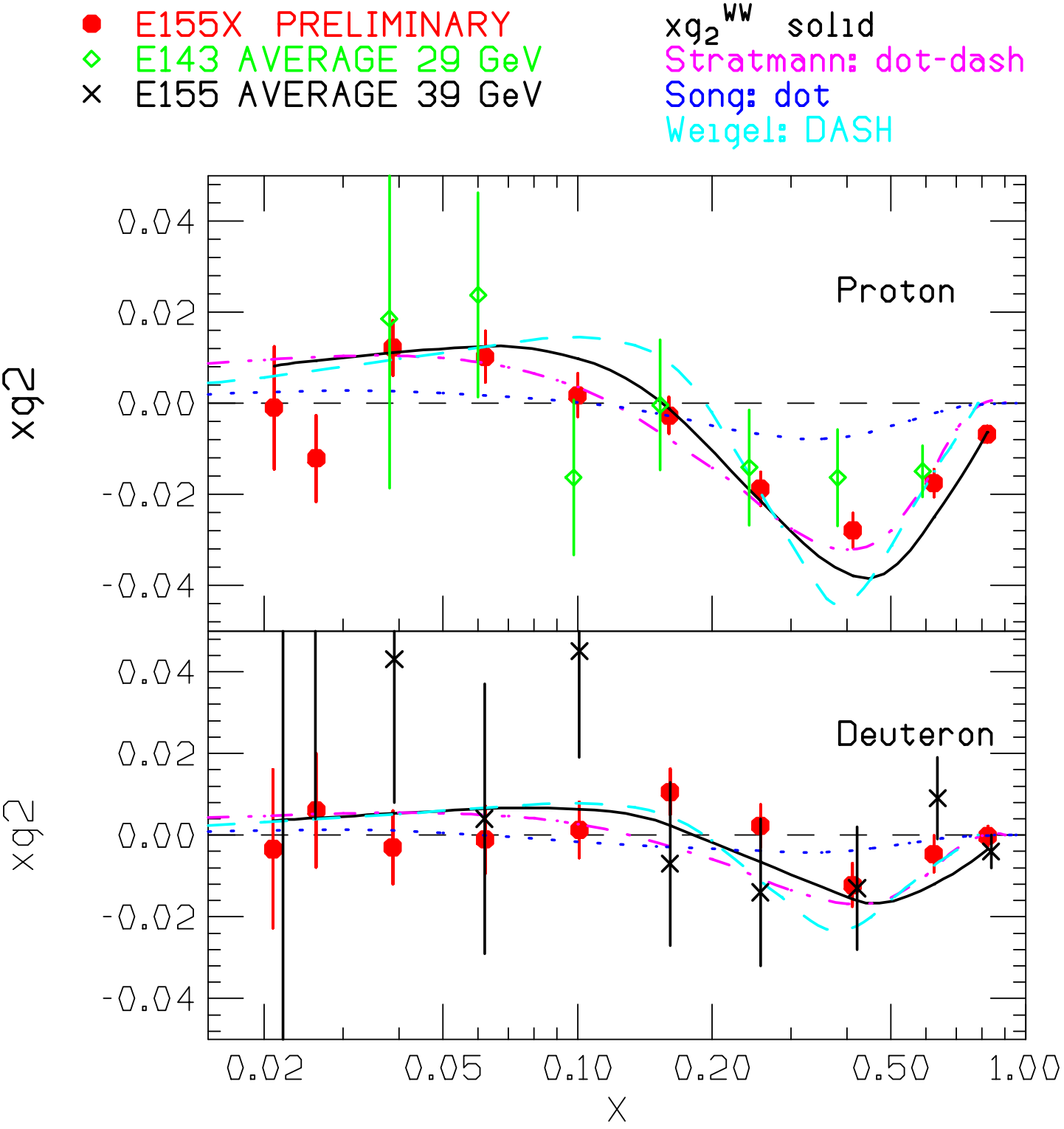
$$\int_0^1 g_2(x, Q^2) dx = 0$$


Q^2-DEPENDENCE OF xg_2
Stratmann
WW
Proton
Deuteron
x≃0.095
x≃0.15
x≃0.24
x≃0.60
xg_2
Q^2 [(GeV/c)^2]

Q^2-DEPENDENCE OF A_2

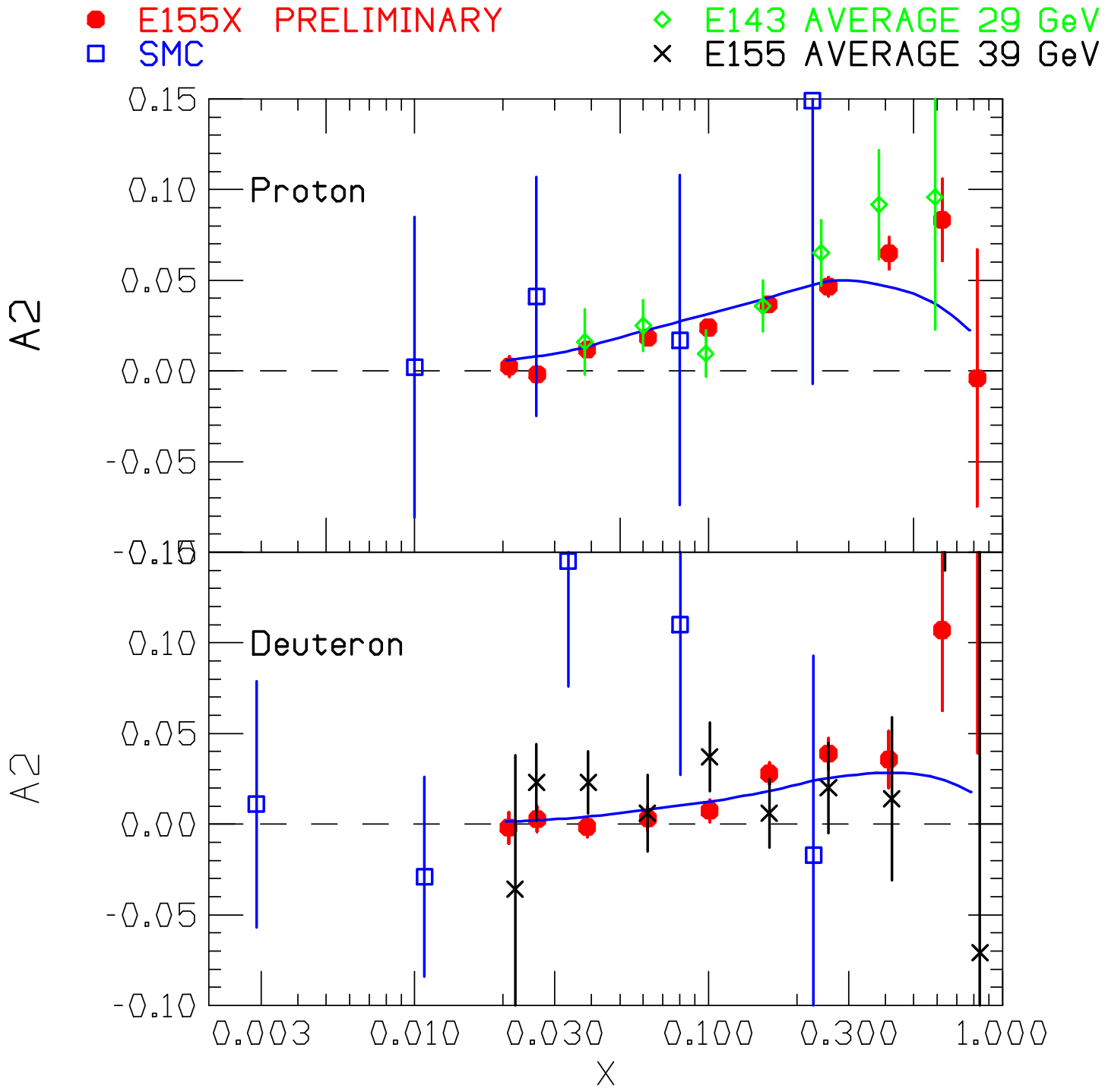


RESULTS FOR Q^2-AVERAGED xg_2



χ^2/df agreement with $g_2^{WW} = 2.5(\mathrm{p}) \quad 1.2(\mathrm{d})$

RESULTS FOR Q^2-AVERAGED A_2



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).

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

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

n=2,4,...

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

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

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

d_2^n

$$\Gamma_1^{(2)} = \int_0^1 x^2 g_1(x,Q^2)dx$$

$$\Gamma_2^{(2)} = \int_0^1 x^2 g_2(x,Q^2)dx$$

$$\overline{\Gamma_2^{(2)}} = \int_0^1 x^2 \overline{g_2}(x,Q^2)dx$$

$$d_2 = 2\Gamma_1^{(2)} + 3\Gamma_2^{(2)} = 3\overline{\Gamma_2^{(2)}}$$

FOR TWIST-2 ONLY: $\quad d_2 = 0$

OTHER TWIST-2 RELATIONS

$$n\Gamma_1^{(n)} + (n+1)\Gamma_2^{(n)} = 0$$

Q^2 DEPENDENCE

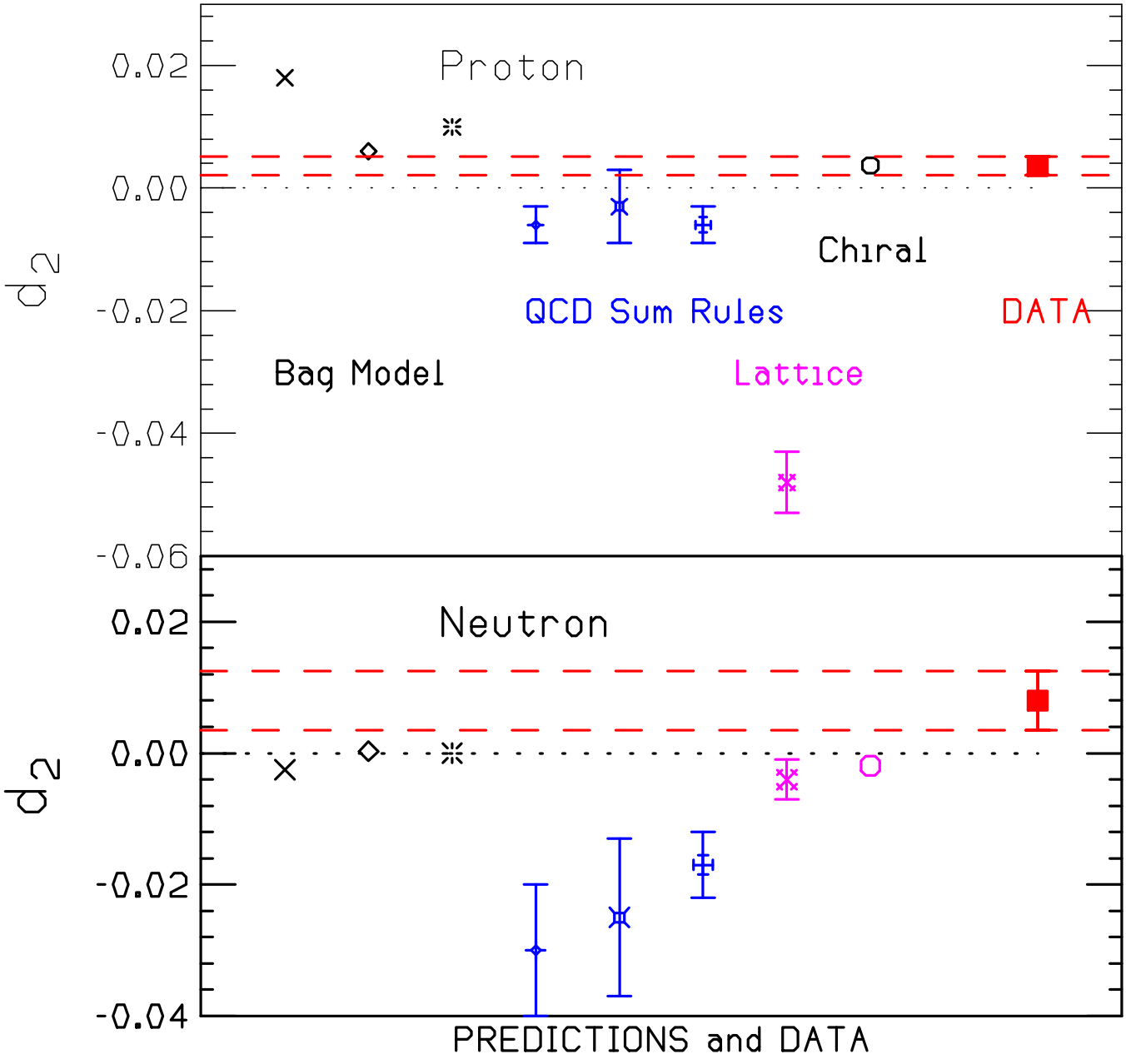
- d_2 depends logarithmically on Q^2.
- All the Integrals are at FIXED Q^2 whilst the Measurements have Q^2 and x correlated.
- For g_1 integrals, we have 'evolved' to fixed Q^2 using Q^2 dependent fits to g_1/F_1
- For g_2 we use:

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

  and ASSUME that the Q^2 dependence of $\overline{g_2}(x, Q^2)$ is negligible.
- To calculate g_2^{WW} we utilize a global Q^2 dependent fit to A_1.

THE TWIST-3 d_2 MATRIX ELEMENT

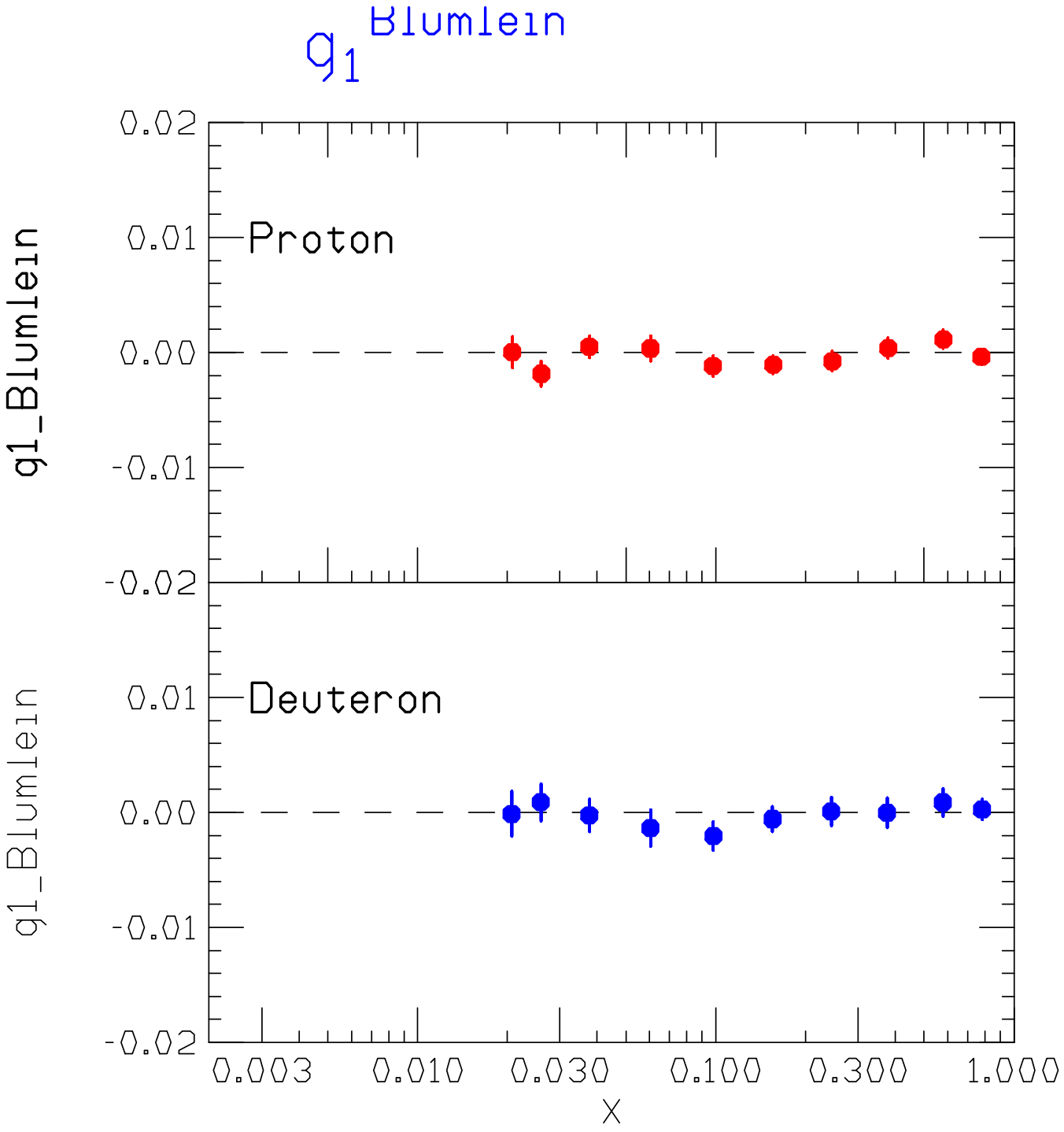
$$d_2 = 3\int_0^1 x^2[g_2(x,Q^2) - g_2^{WW}(x,Q^2)]dx$$



THE TWIST-3 SUM RULE

Blumlein and Tkabadze

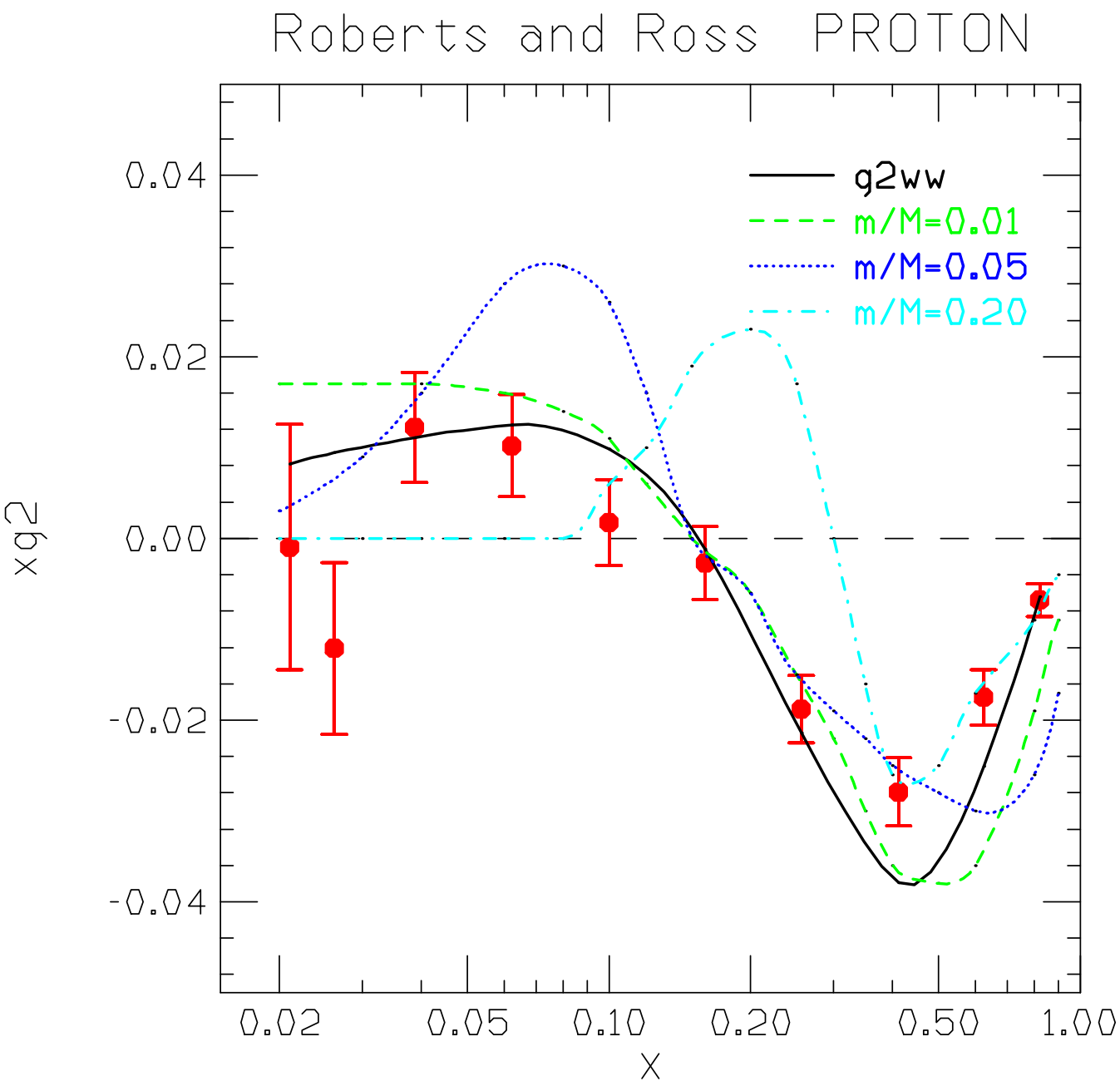
$$g_1(x,Q^2) = \frac{4M^2x^2}{Q^2}\left[\bar{g}_2(x,Q^2) - 2\int_x^1 \frac{dy}{y}\bar{g}_2(y,Q^2)\right]$$



QUARK MODEL WITH TRANSVERSE MOMENTUM

Roberts and Ross

$$A_2F_1 \propto \; g_1+g_2 \; = \int_x^{k_T^2 max} dk_T^2 \tilde{h}(x+\frac{k_T^2}{xM^2})$$



SUM RULES

Burkhardt-Cottingham

$$\int_0^1 g_2(x)dx = 0$$

	p	d
EXPERIMENT:	-0.005 ± 0.012	0.001 ± 0.017

Efremov-Teryaev-Leader

$$\int_0^1 x[g_1^V(x) + 2g_2^V(x)]dx = 0$$

IF SEA QUARKS EQUAL IN PROTON AND NEUTRON $\Rightarrow$

$$\int_0^1 x[g_1^p(x)+2g_2^p(x)-g_1^n(x)-2g_2^n(x)]dx = 0$$

EXPERIMENT (at $Q^2 = 3$) : $\quad -0.0077 \pm 0.0079$

SUMMARY

- **E155x ERRORS $\approx$ 3x SMALLER THAN PREVIOUS RESULTS.**
- **NORMALIZATION SYSTEMATIC ERROR SMALL COMPARED TO STATISTICAL ERRORS.**
- **RADIATIVE CORRECTIONS AND RESOLUTION SMEARING CORRECTIONS STILL NEED STUDY.**
- **g_2^p IS POSITIVE FOR $x < 0.1$, NEGATIVE FOR $x > 0.2$.**
- **ROUGH AGREEMENT SEEN WITH g_2^{ww} MODEL, BAG MODEL OF STRATMANN AND CHIRAL MODEL OF WEIGEL**
- **PROTON A_2 IS POSITIVE FOR ALL x, APPROACHING 0 FOR $x \to 0$.**
- **d_2 SMALL**
- **SUM RULES VALID**

FUTURE?

3 PHOTOPRODUCTION EXPERIMENTS

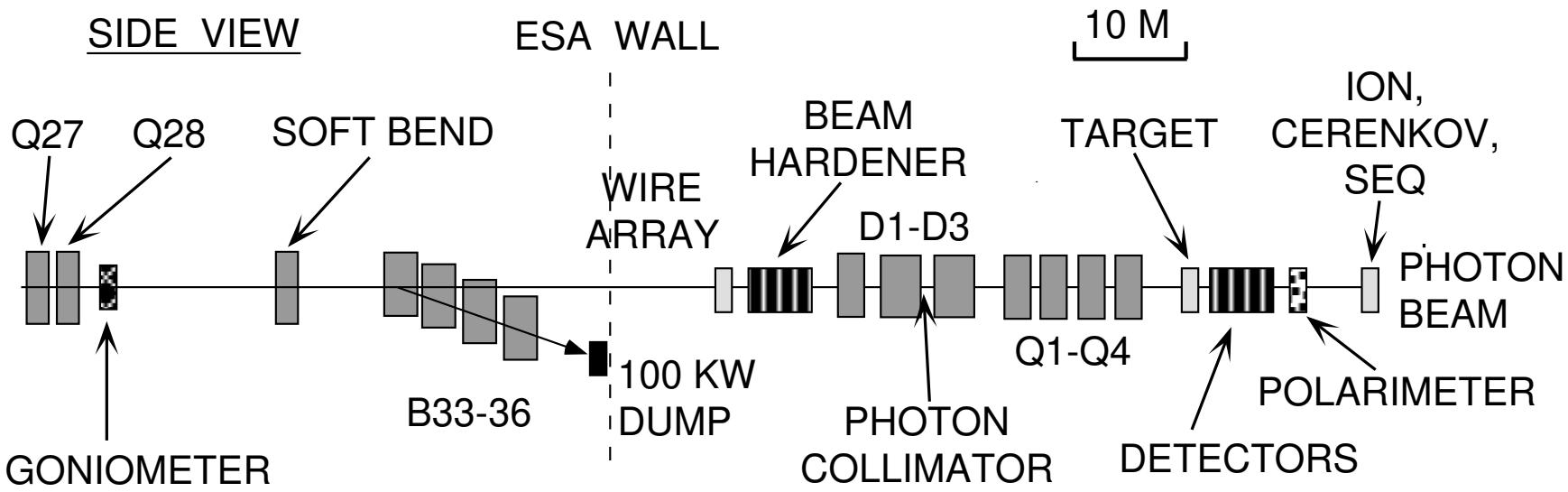
POLARIZED QUASI-MONOENERGIC PHOTON BEAM

- GLUON POLARIZATION FROM OPEN CHARM
  - 35-50 GeV
  - Polarized LiD Target 60%
  - Single Muon Spectrometer
- GDH SUM RULE
  - Total Hadronic Cross Section Asymmetry

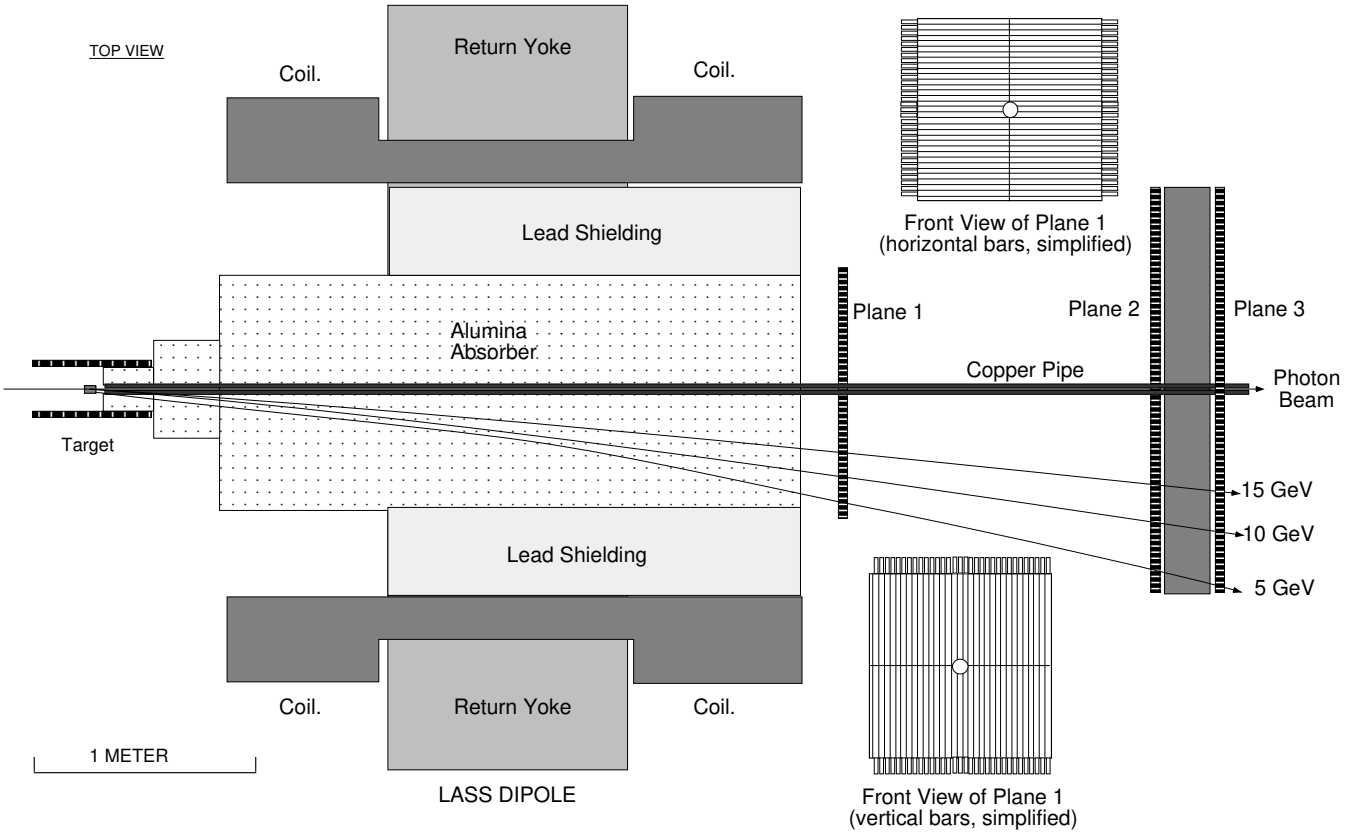
$$\int_{k_\pi}^{\infty} \frac{dk}{k} \Delta\sigma^{\gamma N}(k) = \frac{2\pi^2 \alpha \kappa^2}{M^2} \qquad (1)$$

  - 10-45 GeV
  - LOWER ENERGIES AT JLAB, MAMI, LEGS, GRAAL, ELSA
  - NH_3 and ND_3 Targets
- A DEPENDENCE OF J/ψ and ψ'
  - J/ψ-NUCLEON CROSS SECTION FOR QUARK-GLUON PLASMA
  - COLOR TRANSPARENCY

POLARIZED QUASI-MONOENERGIC PHOTON BEAM

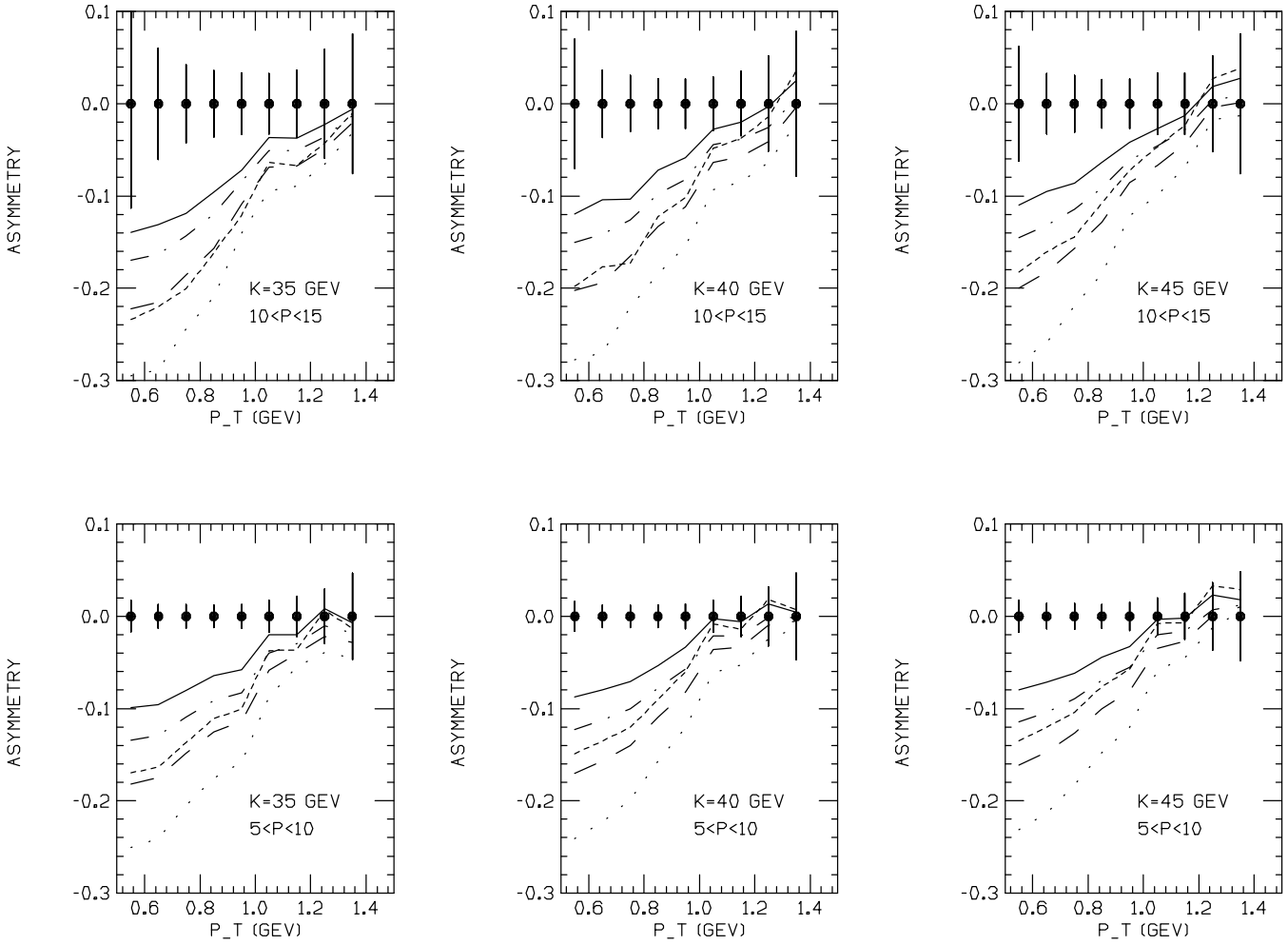


DETECTOR FOR OPEN CHARM



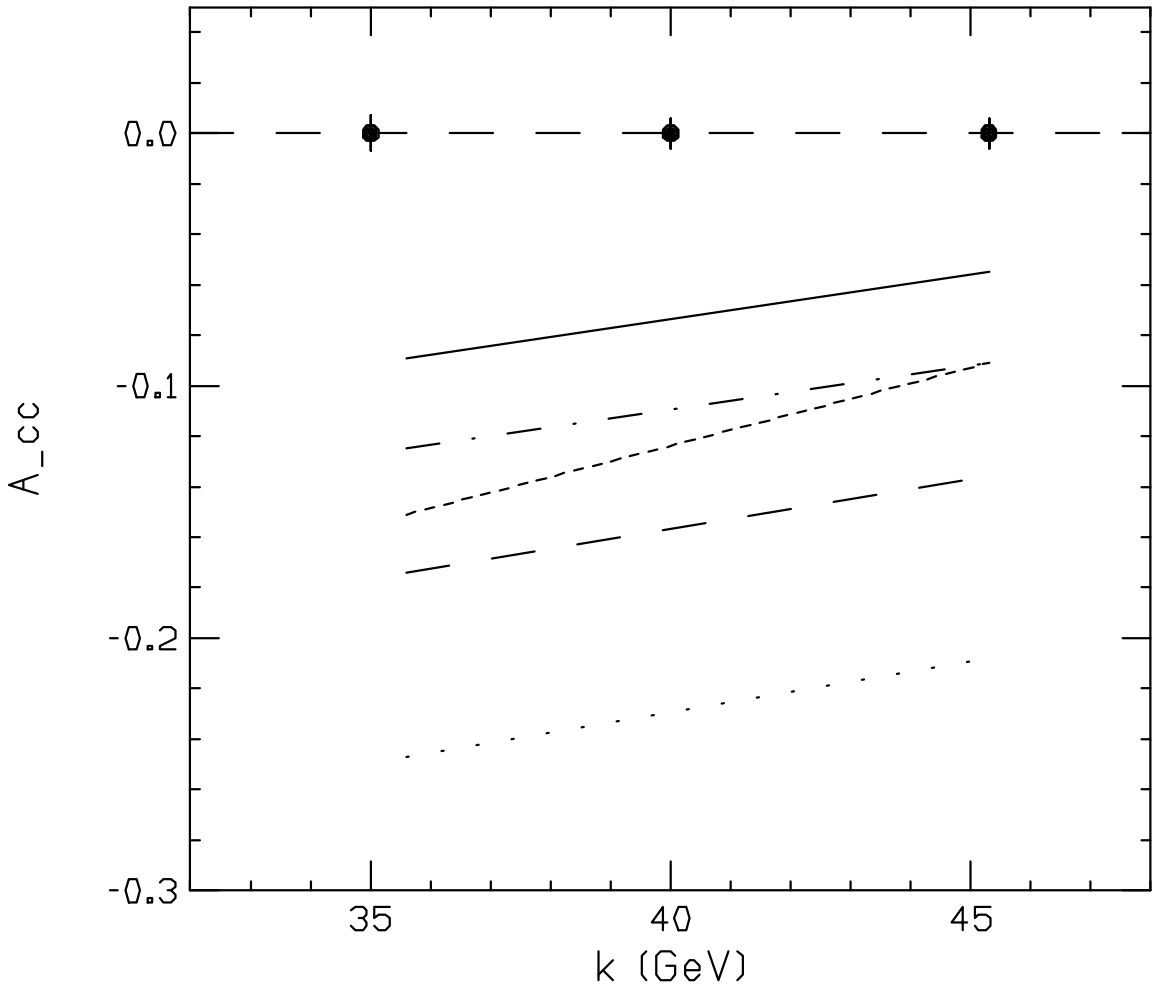
Overall plan view of the main components of the spectrometer. The absorber fills most of the gap of the LASS dipole, and also extends into the warm bore of the target magnet. A thick evacuated copper beam pipe contains the photon beam. The three detector planes are made from scintillator hodoscopes. Two simplified front views of the front plane are shown. The dashed curves are typical trajectories for muons with $p_t = 0.7$ and $P = 5$, 10, and 15 GeV.

EXPECTED ERRORS



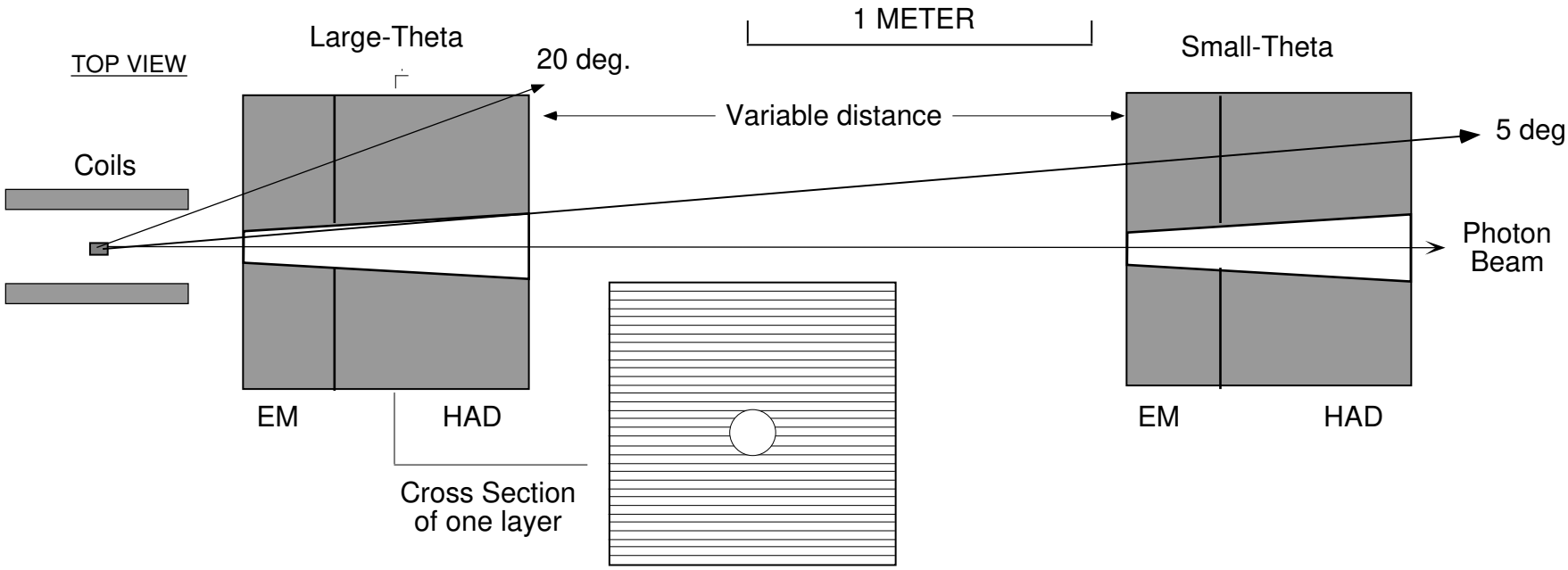
Asymmetries for the five fits to the gluon polarization as a function of p_T^μ of the detected muon. The top row is for $10 < P_\mu < 15$ GeV and the bottom row for $5 < P_\mu < 10$. The three columns correspond to peak beam energies of 35, 40 and 45 Gev. The points indicate the projected statistical errors. Experimental systematic errors will be highly correlated from point-to-point, and will be approximately 0.10 of the measured asymmetries.

AVERAGE EXPECTED ERRORS

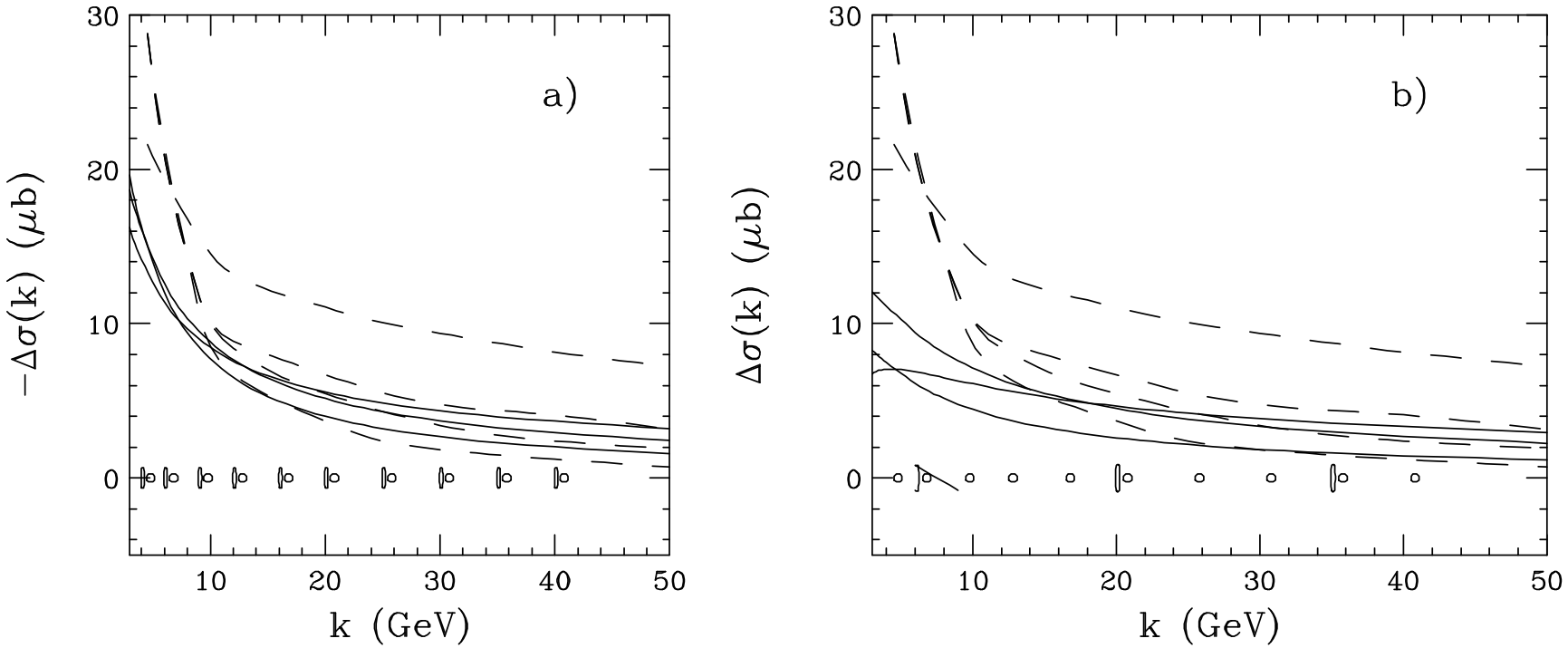


Asymmetries for the five fits to the gluon polarization as a function of beam energy. The points, arbitrarily placed at zero asymmetry, indicate the projected statistical errors for the running conditions given in the text, averaged over p_T.

GDH SUM RULE DETECTOR



GDH: ASYMMETRY ERRORS



Estimated a)proton b) neutron errors for $\Delta\sigma^{\gamma p}(k)$ for this proposal as a function of photon energy for the counting mode (rectangles) and flux integration mode (circles). The symbol heights represent the expected statistical errors in the more conservative analysis. Systematic errors are not shown, but are expected to be 6% to 8% of the measured values of $\Delta\sigma^{\gamma N}(k)$. The dashed curves are representative models.