

# The Hall C Spin Program at Jlab

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Topics

Resonant Spin Structure

SANE

Semi-SANE

# Resonant Spin Structure (RSS) of the Proton and Deuteron

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(UVA)

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## Analysis

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Frank Wesselmann, Junho Yun, Hongguo Zhu  
(Eric Christy, Peter Bosted)*

## E01-006 Collaboration

*Univ. Basel, Florida International Univ., Hampton Univ., Univ. of Massachusetts, Univ. of Maryland,  
Mississippi State Univ., North Carolina A&T Univ., Univ. of N. C. at Wilmington,  
Norfolk State Univ., Old Dominion Univ., S.U. at New Orleans, Univ. of Tel-Aviv,  
Jefferson Lab, Univ. of Virginia, Virginia P. I. & S.U., Yerevan Physics Institute*

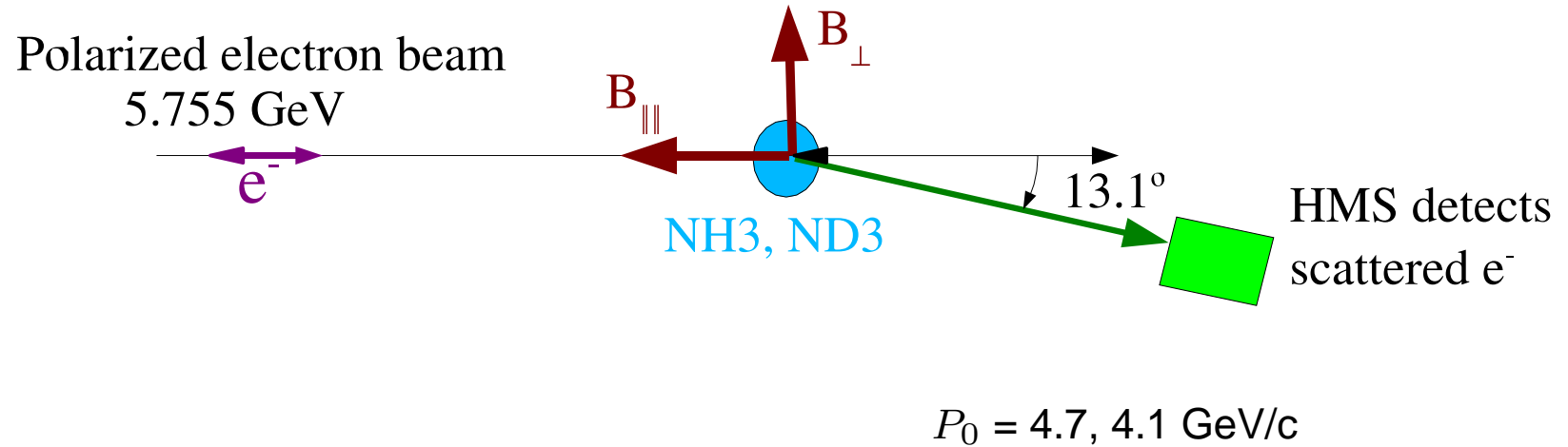
# Goals

Measure proton and deuteron  $A_1(W, Q^2)$  and  $A_2(W, Q^2)$  in the resonance region at moderate  $Q^2$ .

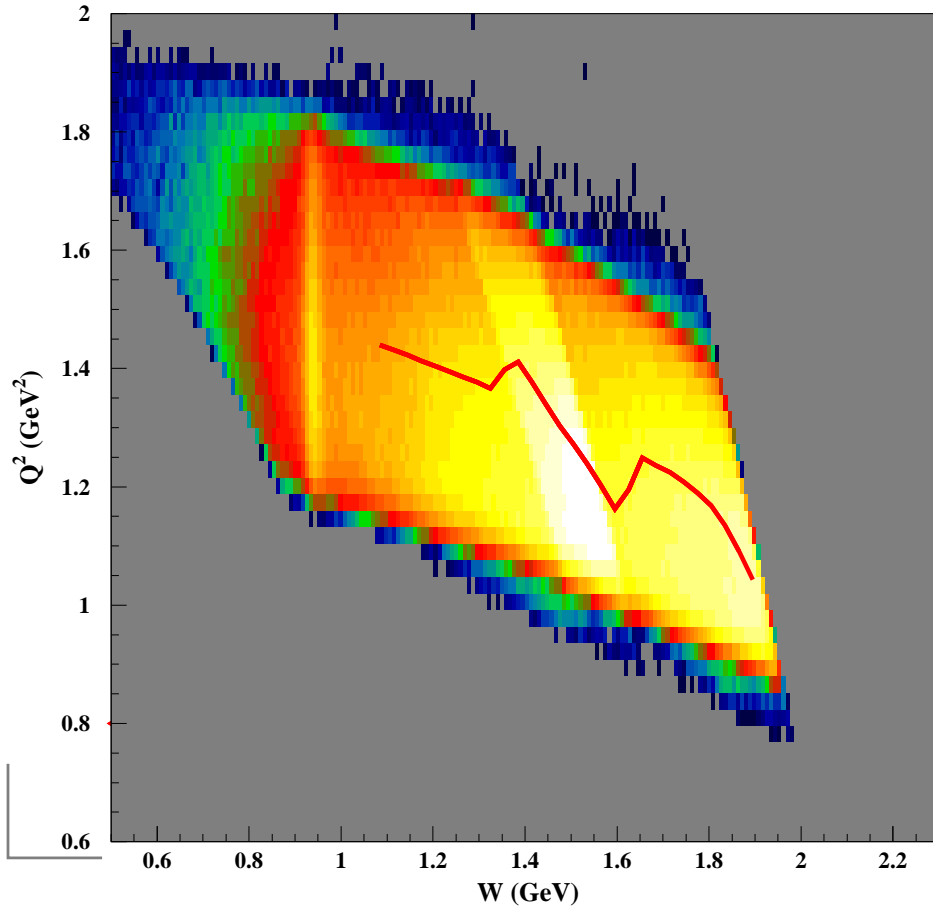
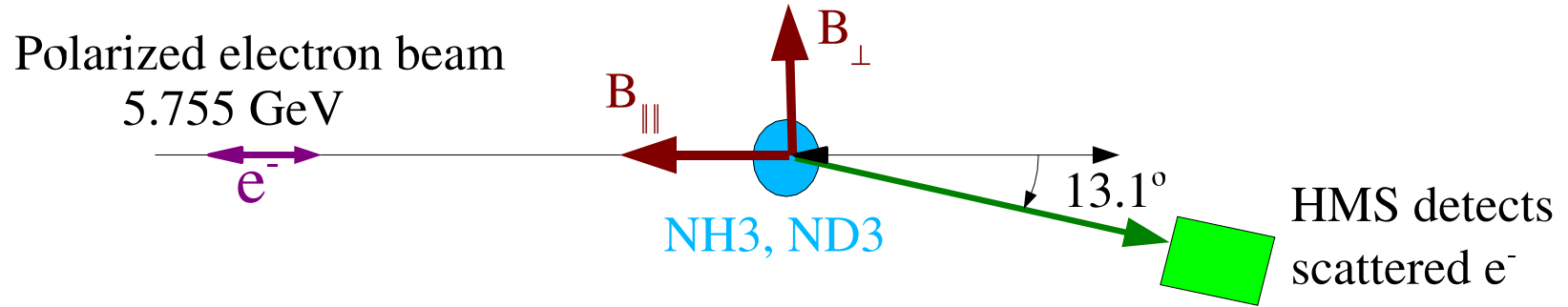
Extract  $g_1$  and  $g_2$  structure functions and study:

- $W$ -dependence
- Onset of polarized local duality
- twist-3 effects in  $d_2$  matrix element

# Experimental set-up in Hall C



# Experimental set-up in Hall C



$$P_0 = 4.7, 4.1 \text{ GeV}/c$$

$$Q^2 \approx 1.3 \text{ GeV}^2$$

$$W : 0.8 - 2.0 \text{ GeV}$$

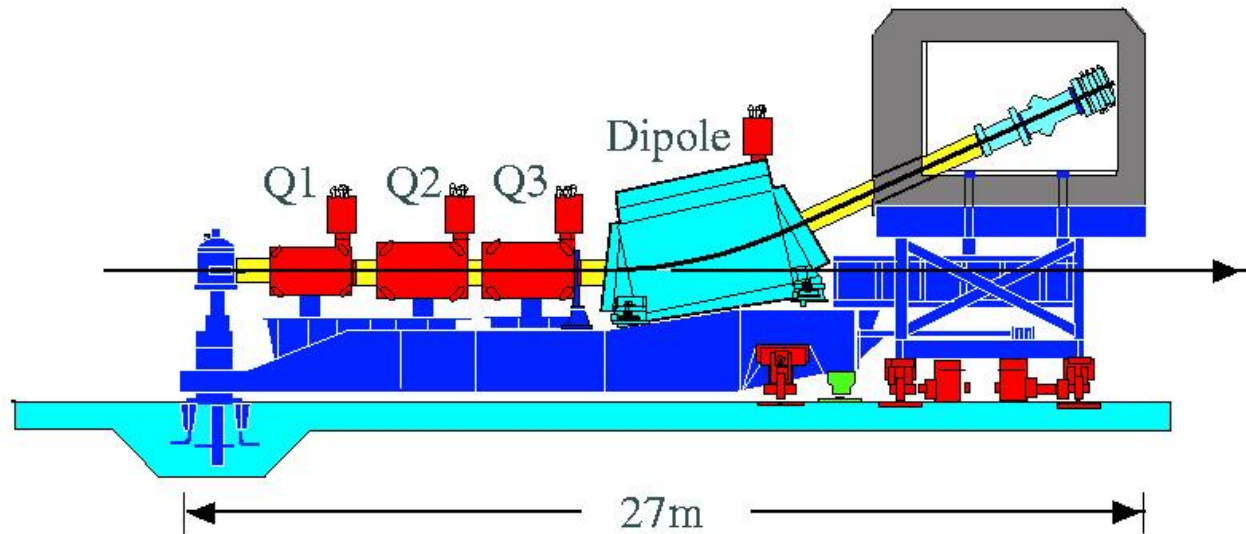
$$P_b = 65.6 \pm 2.6 \text{ for } B_{\parallel}$$

$$P_b = 70.9 \pm 1.7 \text{ for } B_{\perp}$$

$$I \approx 100 \text{ nA}$$

$$\text{Beam charge asym.} < 0.1\%$$

# High Momentum Spectrometer

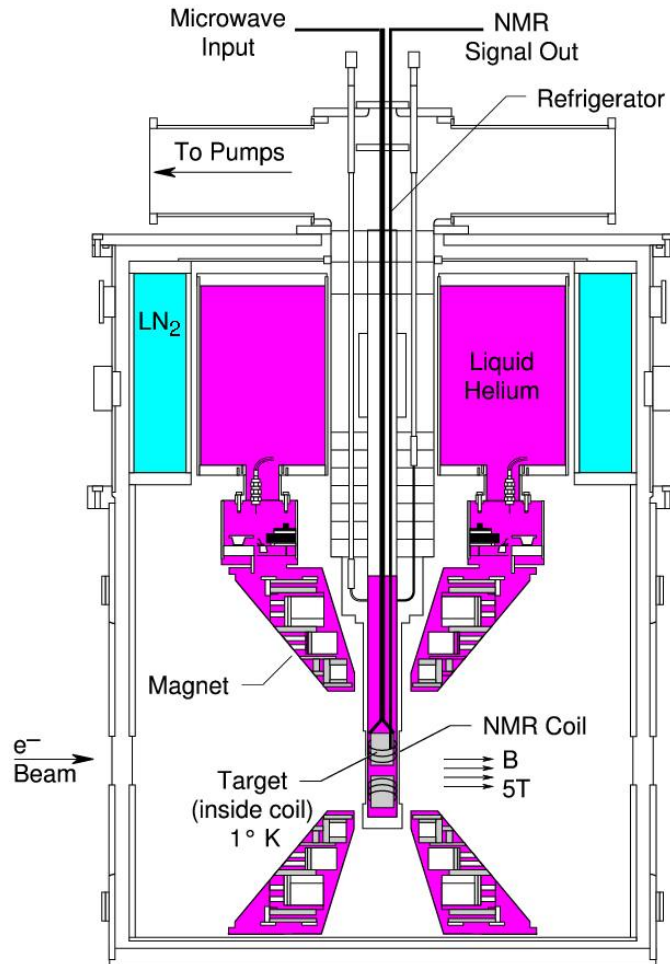


- $12.5^\circ < \Theta < 90^\circ$
- 1 dipole, 3 quadrupoles
- $\pm 9\%$  acceptance
- Shielded detector package

Scintillator hodoscopes, wire drift chambers

Gas cherenkov, segmented Pb glass calorimeter

# Polarized Target



## Target Ladder

- 2  $\text{NH}_3$  cups
- 2  $\text{ND}_3$  cups
- 1 Carbon (7mm)

## Target Field

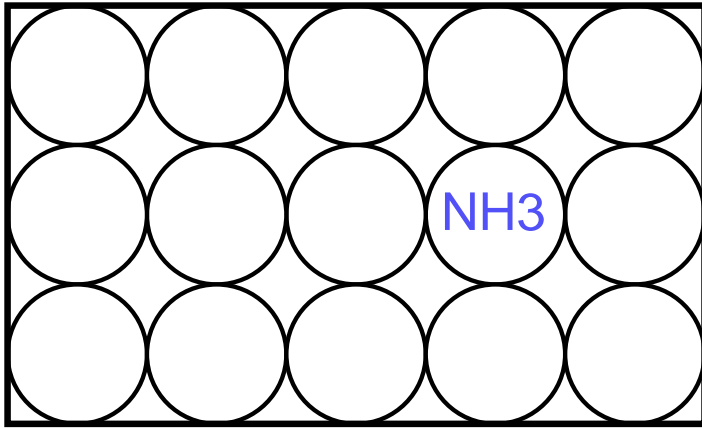
- 5 Tesla
- Para & perpendicular fields.
- Polarization can be flipped by  $180^\circ$ . Ran  $\pm$  for equal times.

## Target Polarization

- $\text{NH}_3 : P_t \approx 0.68 \pm 0.017$
- $\text{ND}_3 : P_t \approx 0.18 \pm 0.007$

# Packing fractions

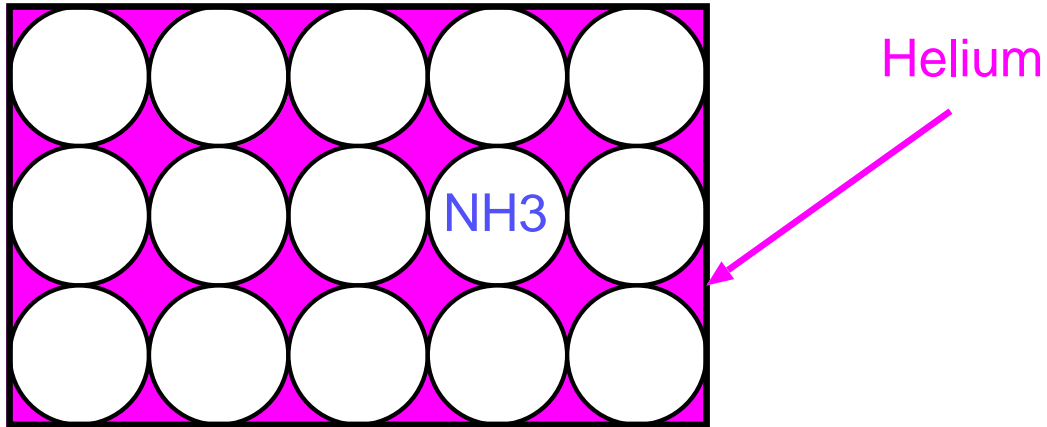
Packing fraction is ratio of  $\text{NH}_3$





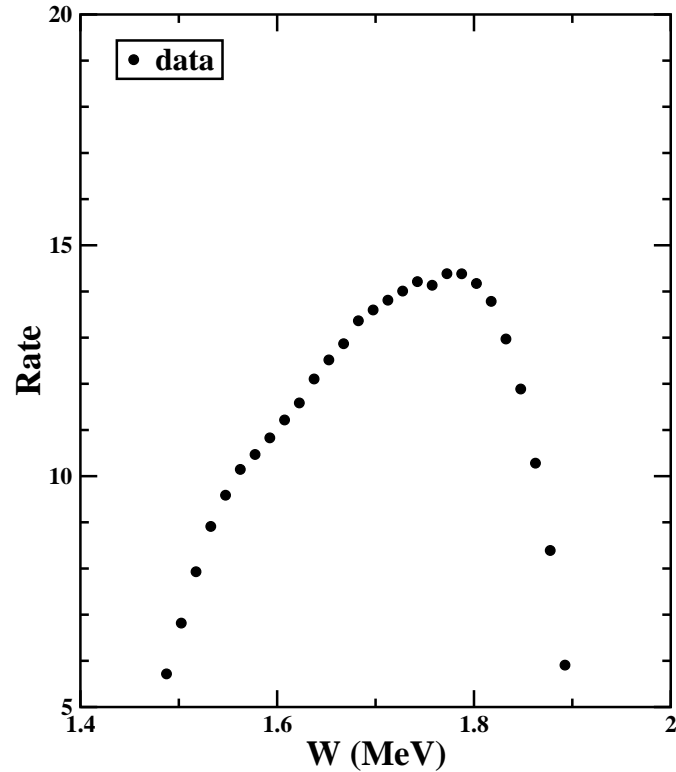
# Packing fractions

Packing fraction is ratio of  $\text{NH}_3$  to  $(\text{NH}_3 + \text{He})$ .



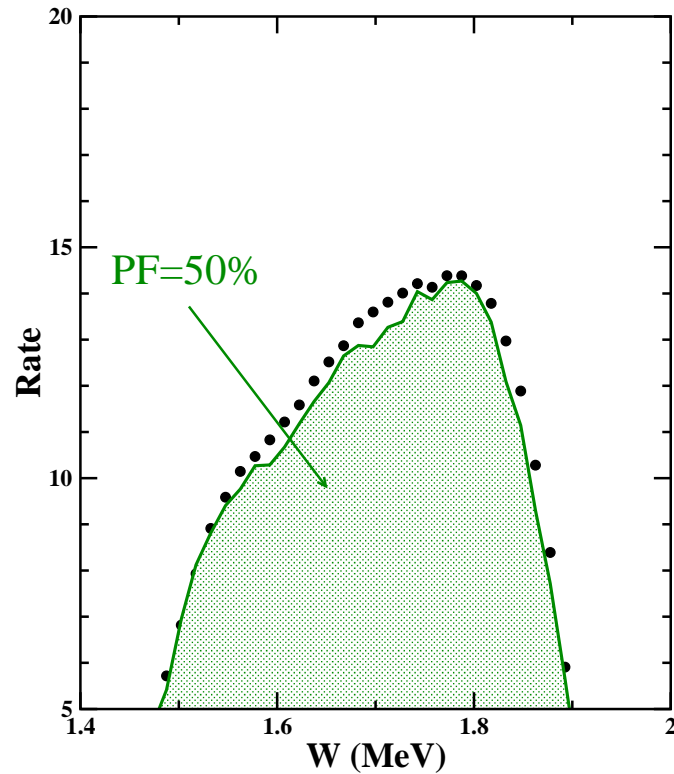
# Packing fractions

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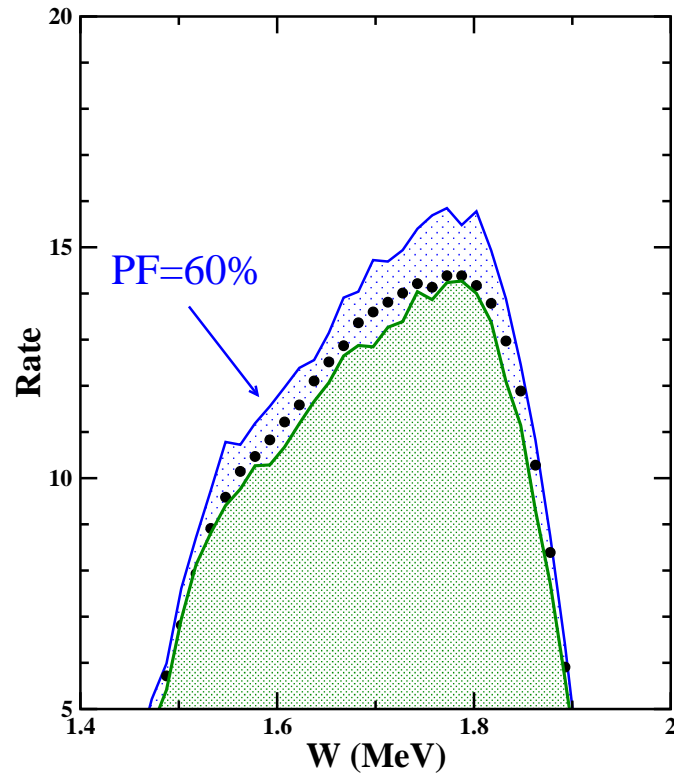
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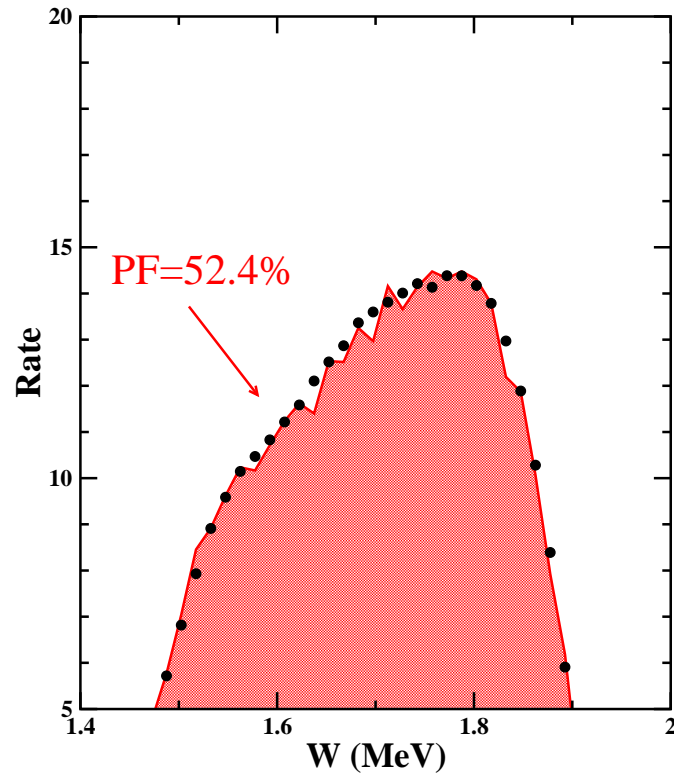
# Packing fractions

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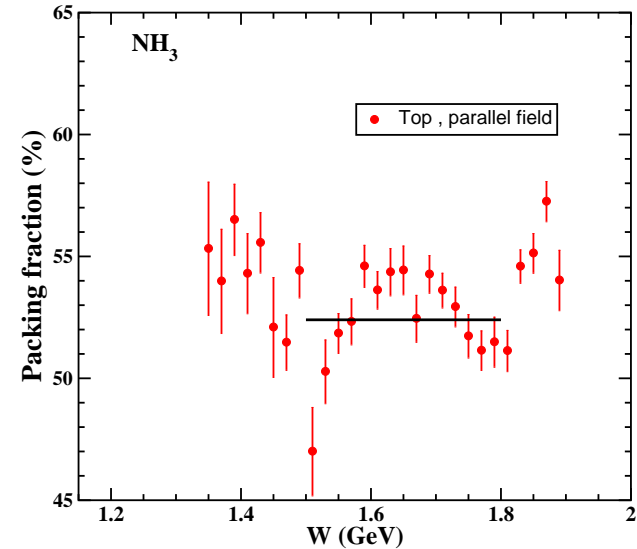
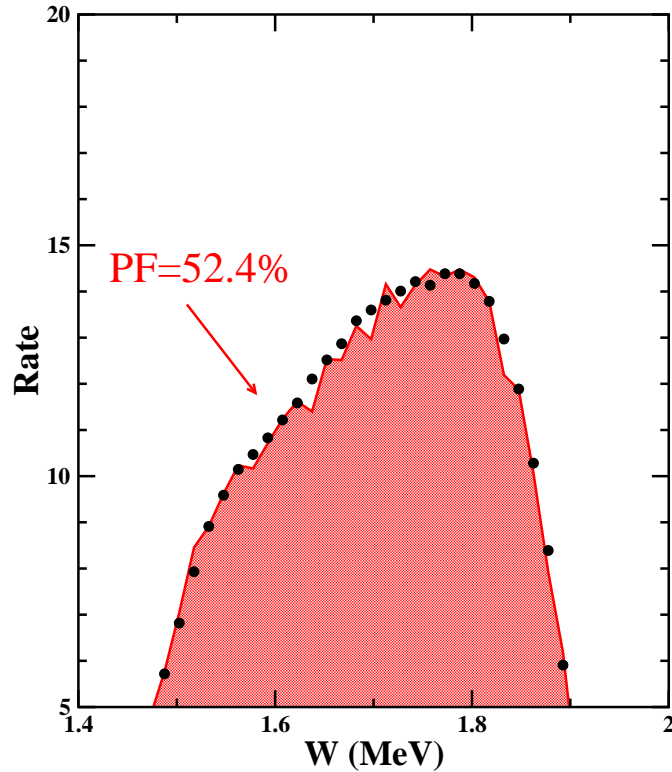
# Packing fractions

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## Packing Fractions

	$\text{NH}_3$		$\text{ND}_3$	
	$B_{\parallel}$	$B_{\perp}$	$B_{\parallel}$	$B_{\perp}$
Top	52.4%	58.9	55.2	—
Bottom	53.2	60.7	56.0	62.1

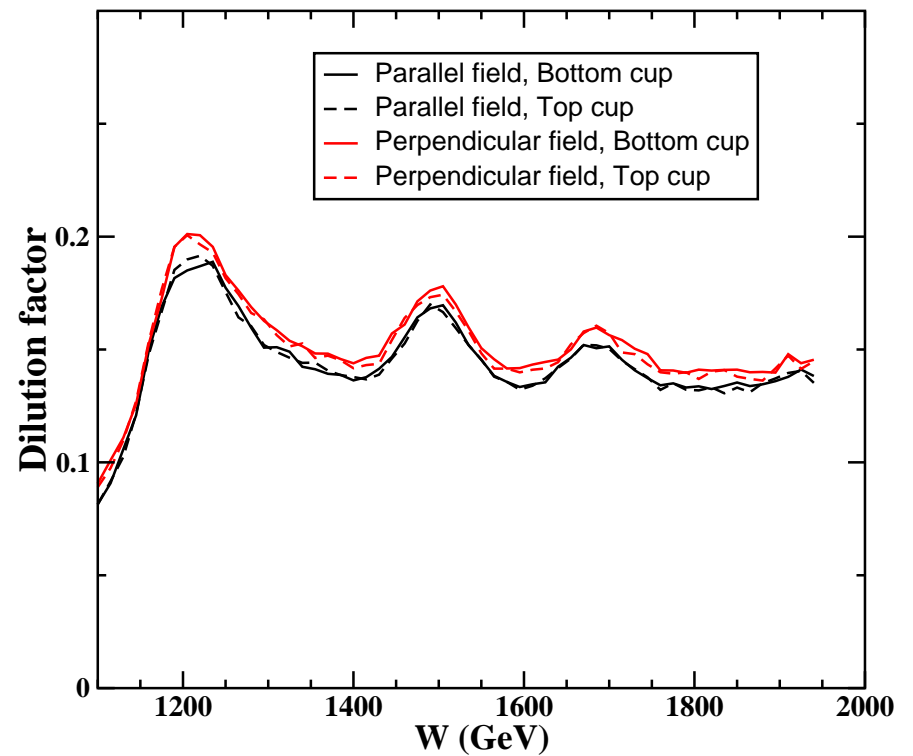
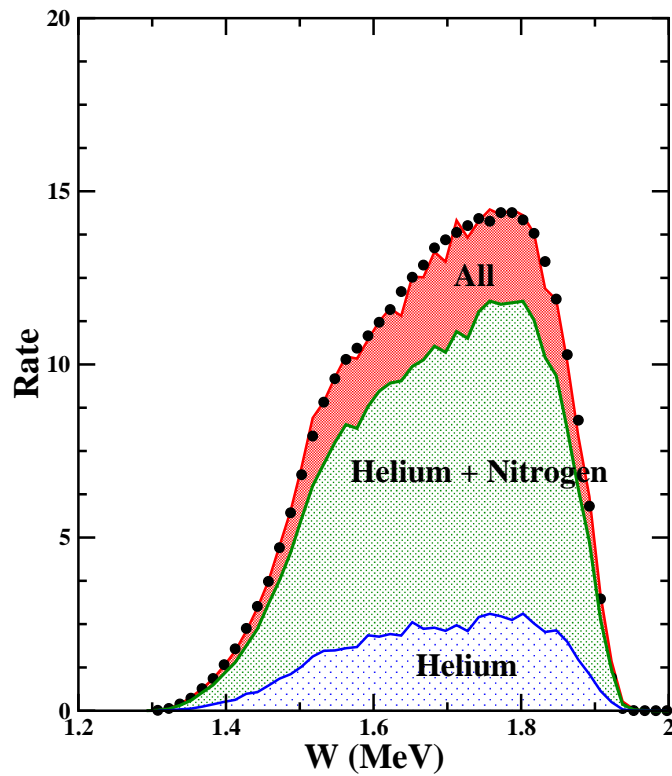
# Dilution factors

$$f = \frac{\dot{N}_{\text{Pol}}}{\dot{N}_{\text{Tot}}}$$

NH<sub>3</sub>

Hall C fit for F<sub>2</sub> and R. (*M. E. Christy*)

QFS for A > 2

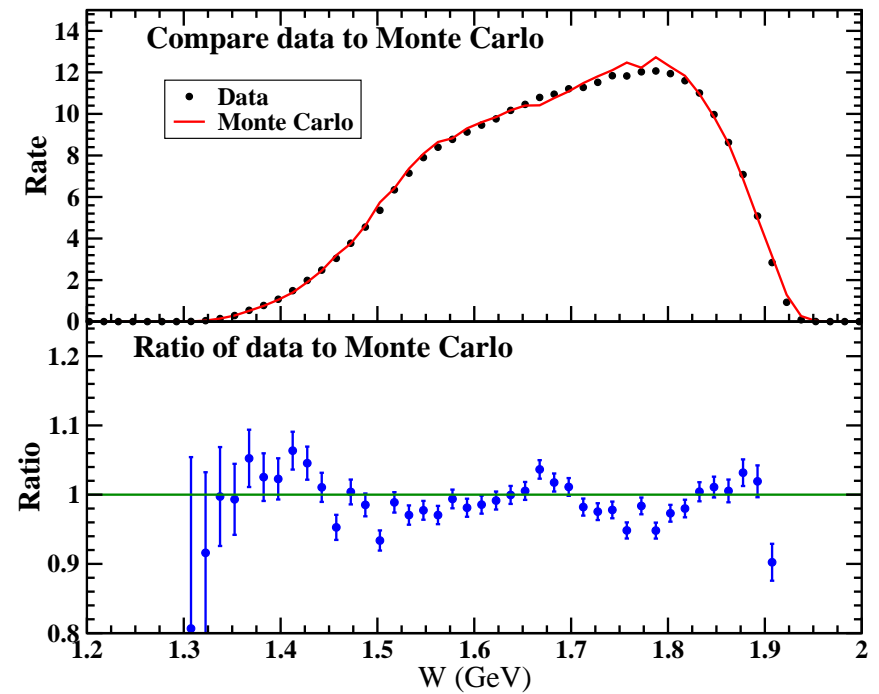
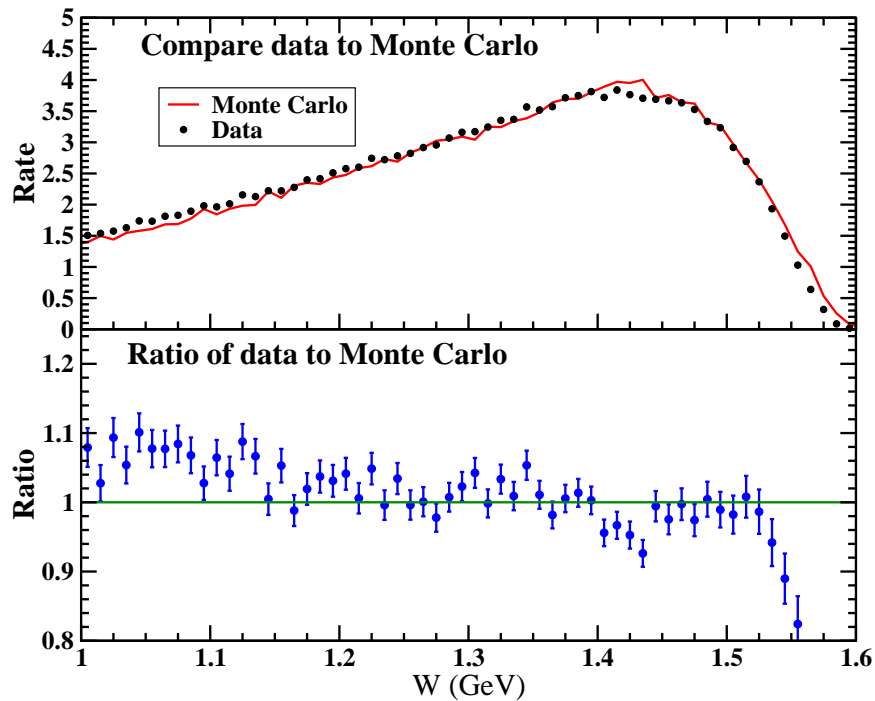


# Comparisons to carbon data

Carbon data used to fit QFS model.

$P_0 = 4.7 \text{ GeV}/c$

$P_0 = 4.1 \text{ GeV}/c$





# Extracting Asymmetry

- Raw Asymmetries

$$A_{raw} = \frac{N^+ - N^-}{N^+ + N^-}$$

$N^+, N^-$  : Helicity gated counts, normalized by the charge and deadtime

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- Raw Asymmetries

$$A_{raw} = \frac{N^+ - N^-}{N^+ + N^-}$$

- Physics Asymmetries

$$A_{\parallel, \perp} = \frac{1}{C f_{rc}} \frac{1}{f P_b P_t} A_{raw} + A_{rc}$$

$f$  : ratio of rates from polarized nucleons to all nucleons.

$P_b, P_t$  : beam and target polarizations.

$C$  : corrections for  $^{15}\text{N}$  asymmetry (not applied yet).

$f_{rc}, A_{rc}$  : radiative corrections

POLRAD (Akusevich *et al.*) modified to include our data as input.

# Proton Elastic Asymmetry

$$A_{el} = \frac{K_1 \cos \theta^* + K_2 \frac{G_E}{G_M} \sin \theta^* \cos \phi^*}{G_E^2 / G_M^2 + \tau / \epsilon}$$

$\theta^*, \phi^*$  = polar and azimuthal angles  
between  $\vec{q}$  and target spin

$K_1, K_2$  = kinematic factors

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Sensitivity		⊥
$\frac{\Delta A_{el} / A_{el}}{\Delta \frac{G_E}{G_M} / \frac{G_E}{G_M}}$	0.02	1

- $A_{||}$  used to determine  $P_b P_t$
- $A_{\perp}$  measure  $\frac{G_E}{G_M}$

# Proton Elastic Asymmetry

$$A_{el} = \frac{K_1 \cos \theta^* + K_2 \frac{G_E}{G_M} \sin \theta^* \cos \phi^*}{G_E^2/G_M^2 + \tau/\epsilon}$$

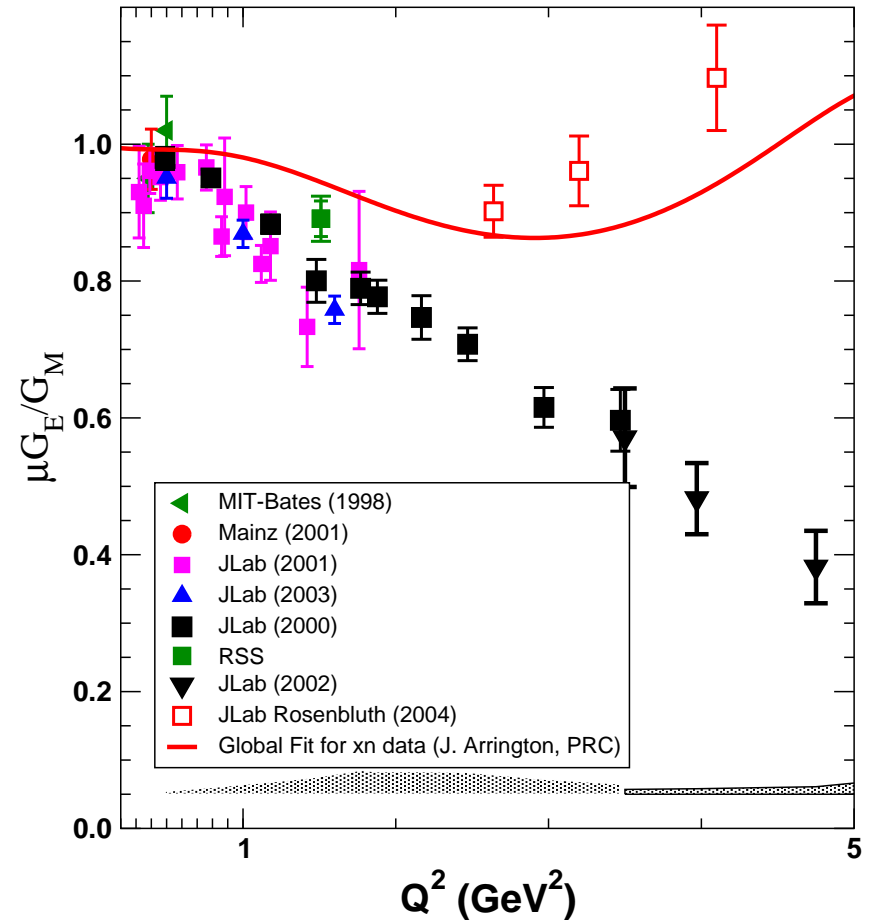
$\theta^*, \phi^*$  = polar and azimuthal angles  
between  $\vec{q}$  and target spin

$K_1, K_2$  = kinematic factors

Sensitivity	$\parallel$	$\perp$
$\frac{\Delta A_{el}/A_{el}}{\Delta \frac{G_E}{G_M} / \frac{G_E}{G_M}}$	0.02	1

●  $A_{\parallel}$  used to determine  $P_b P_t$

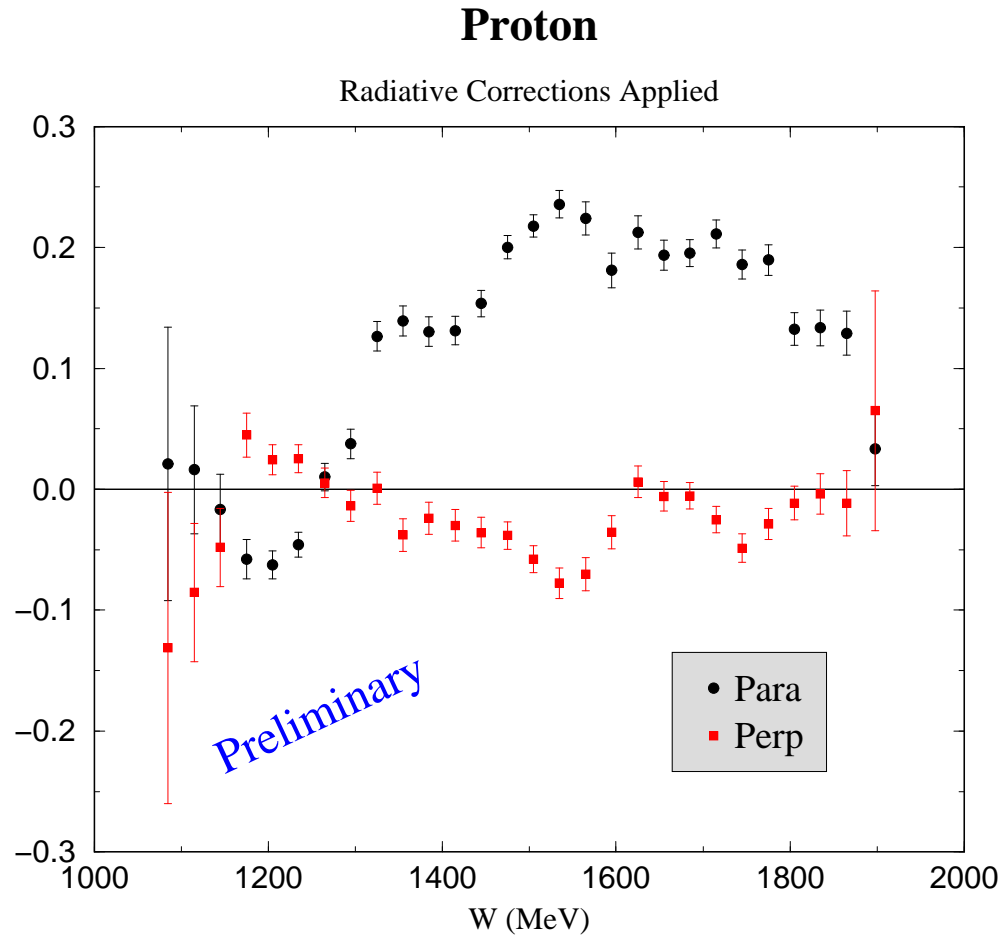
●  $A_{\perp}$  measure  $\frac{G_E}{G_M}$



# Inelastic Asymmetries

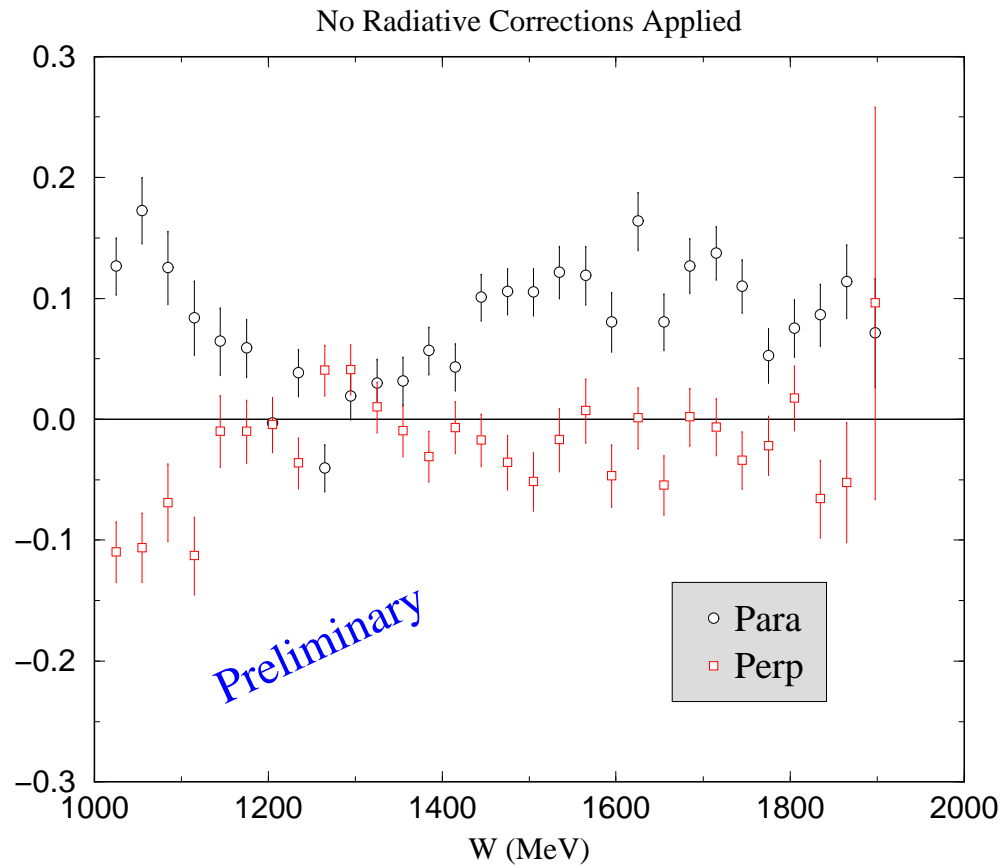
- $^{15}\text{N}$  asymmetry correction ( $\approx 1.02$ ) not applied yet.
- Radiative corrections have been applied to proton data.  
Work on radiative correction for deuteron in progress.
- Expected systematic errors:
  - $\text{NH}_3$  : 6% (relative)
  - $\text{ND}_3$  : 8% (relative)
- $A_{\parallel}$  and  $A_{\perp}$  transformed to  $A_1$  and  $A_2$  using Hall C  $F_2$  and  $R$  fit (M. E. Christy)

# Asymmetries



# Asymmetries

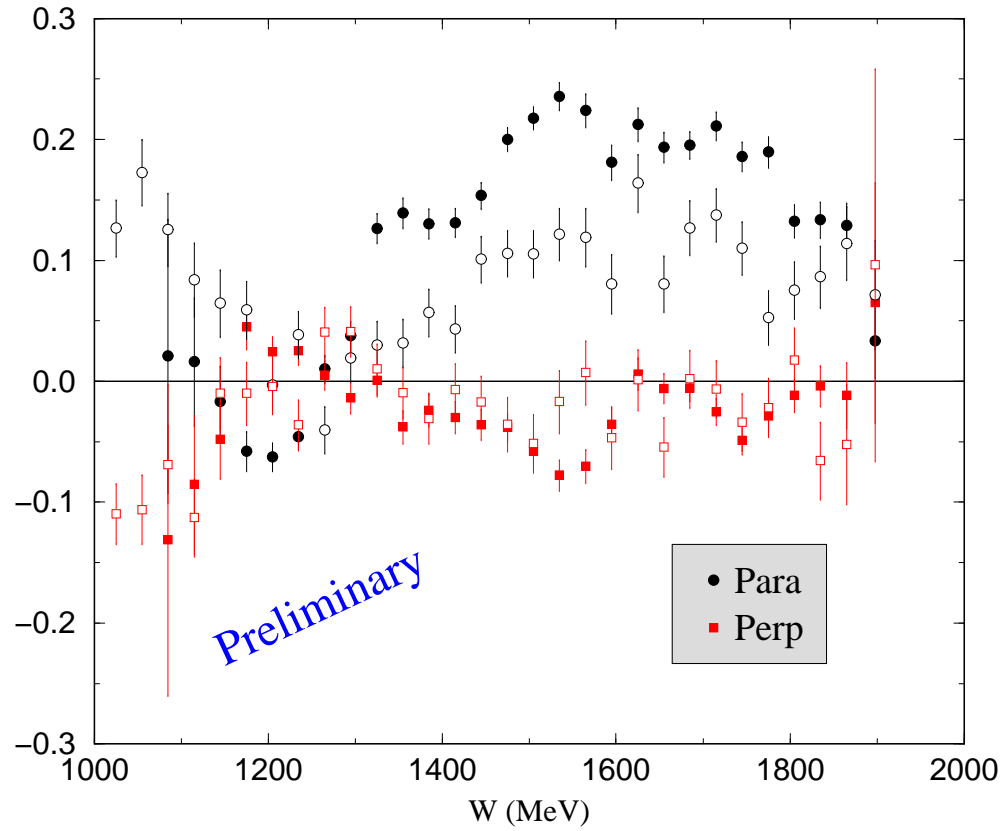
## Deuteron



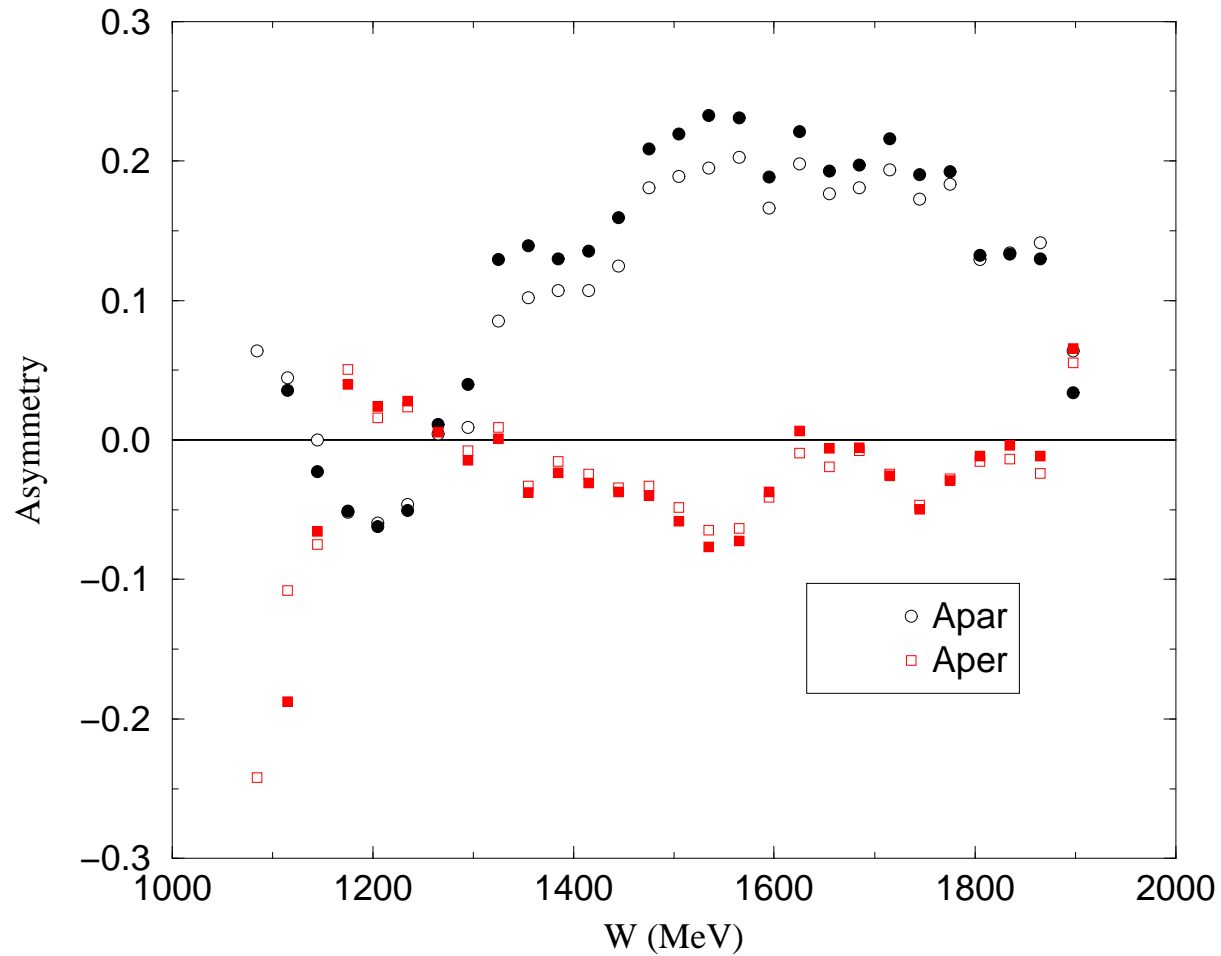


# Asymmetries

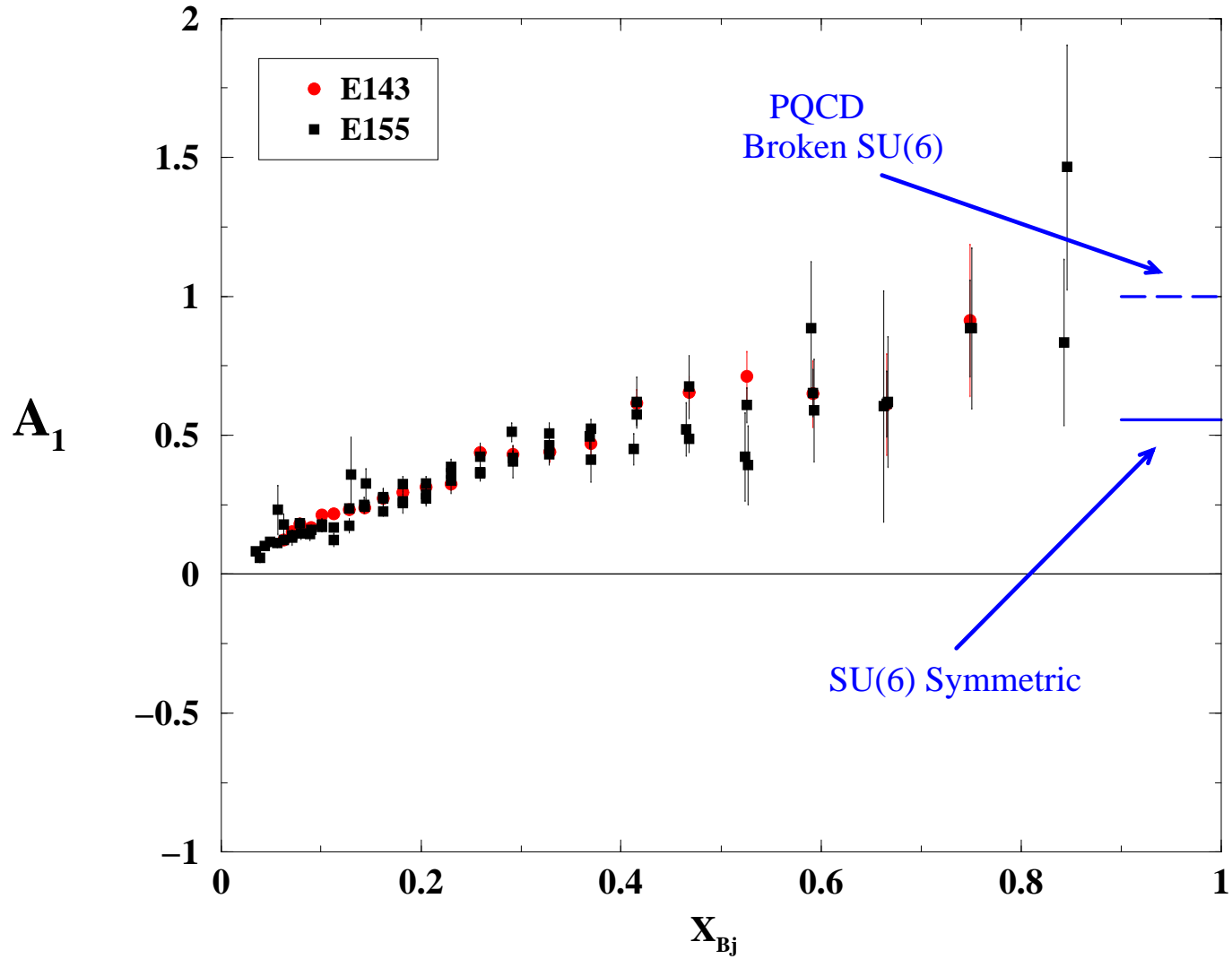
## Proton and Deuteron



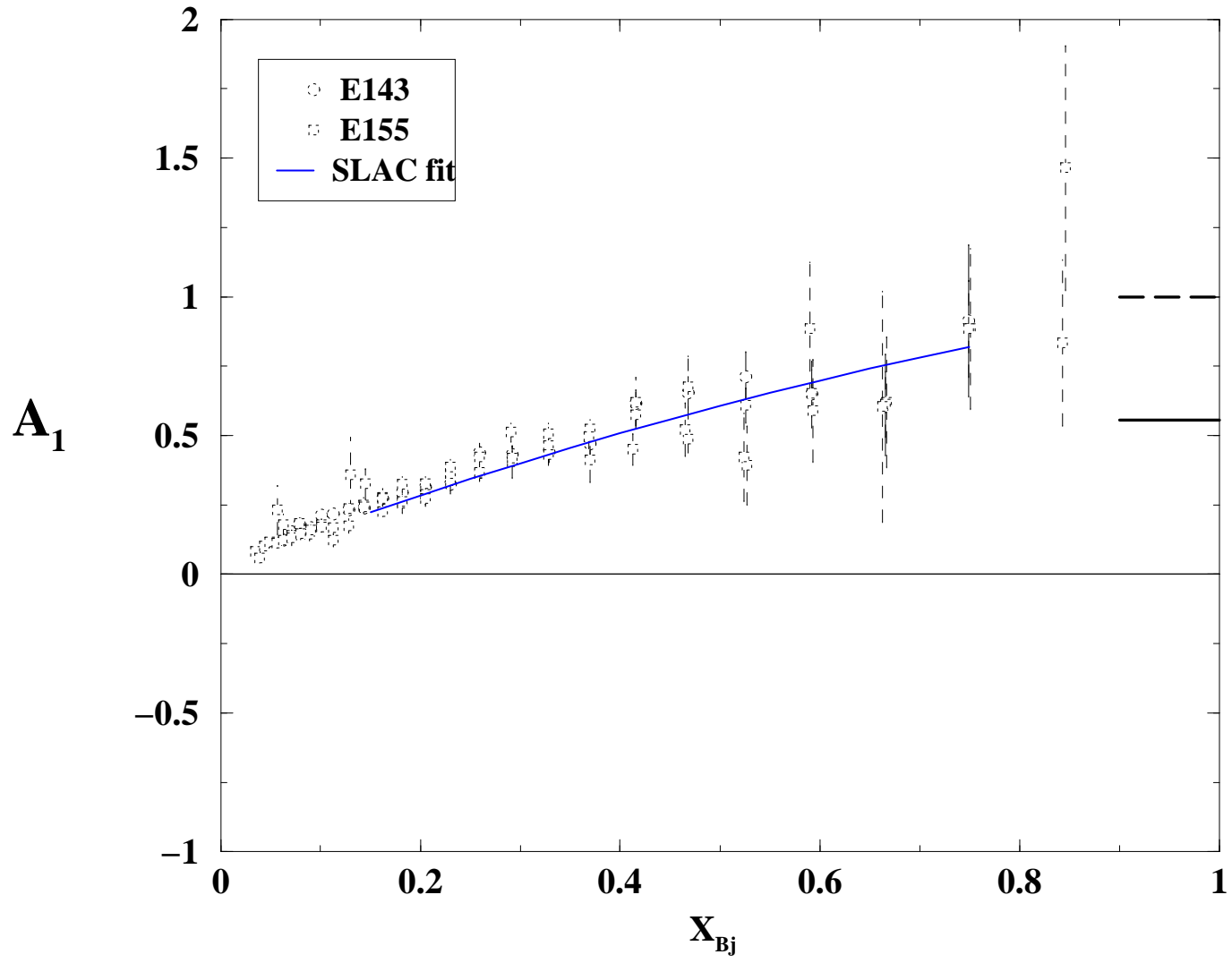
# Radiative Corrections



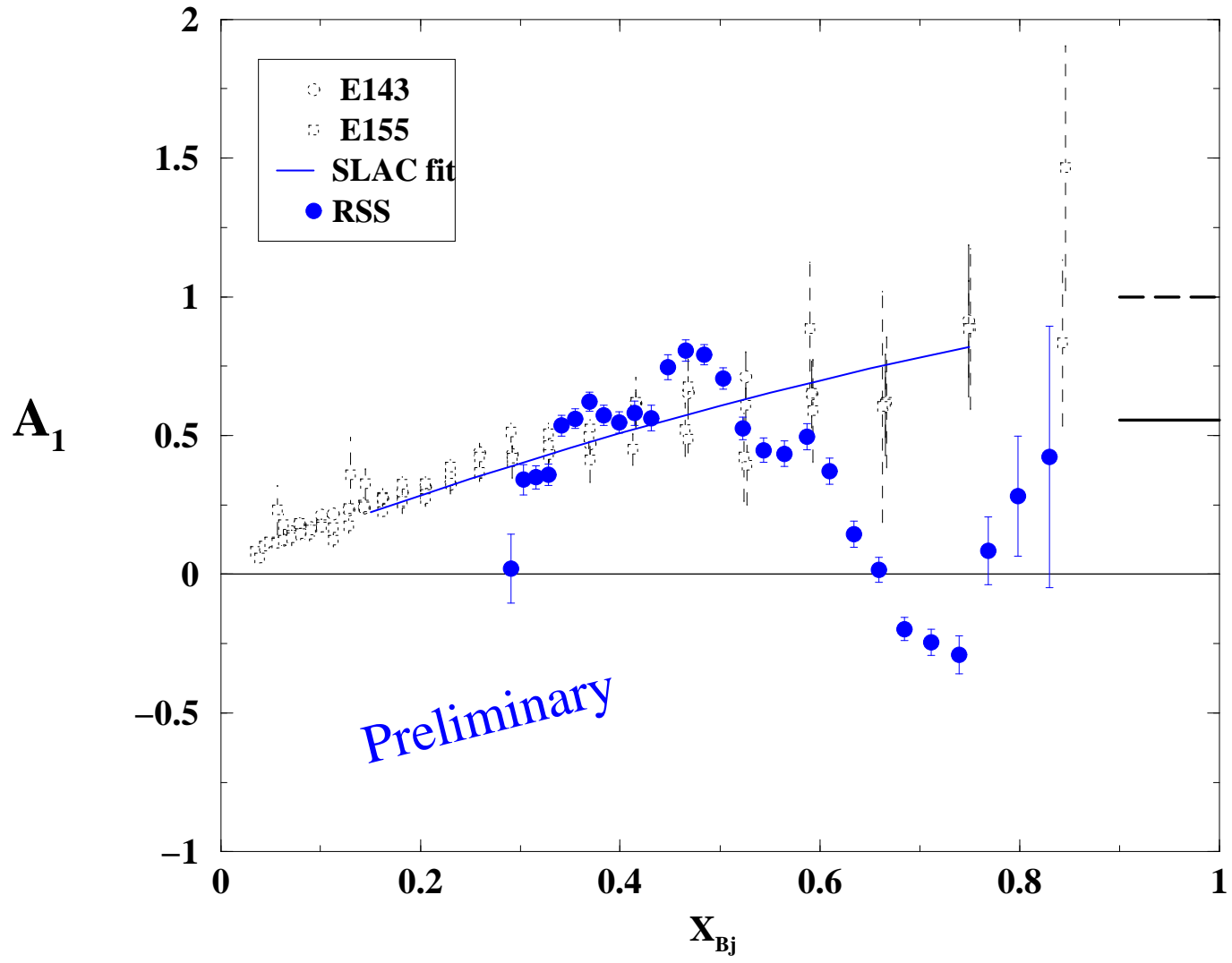
# Proton $A_1$



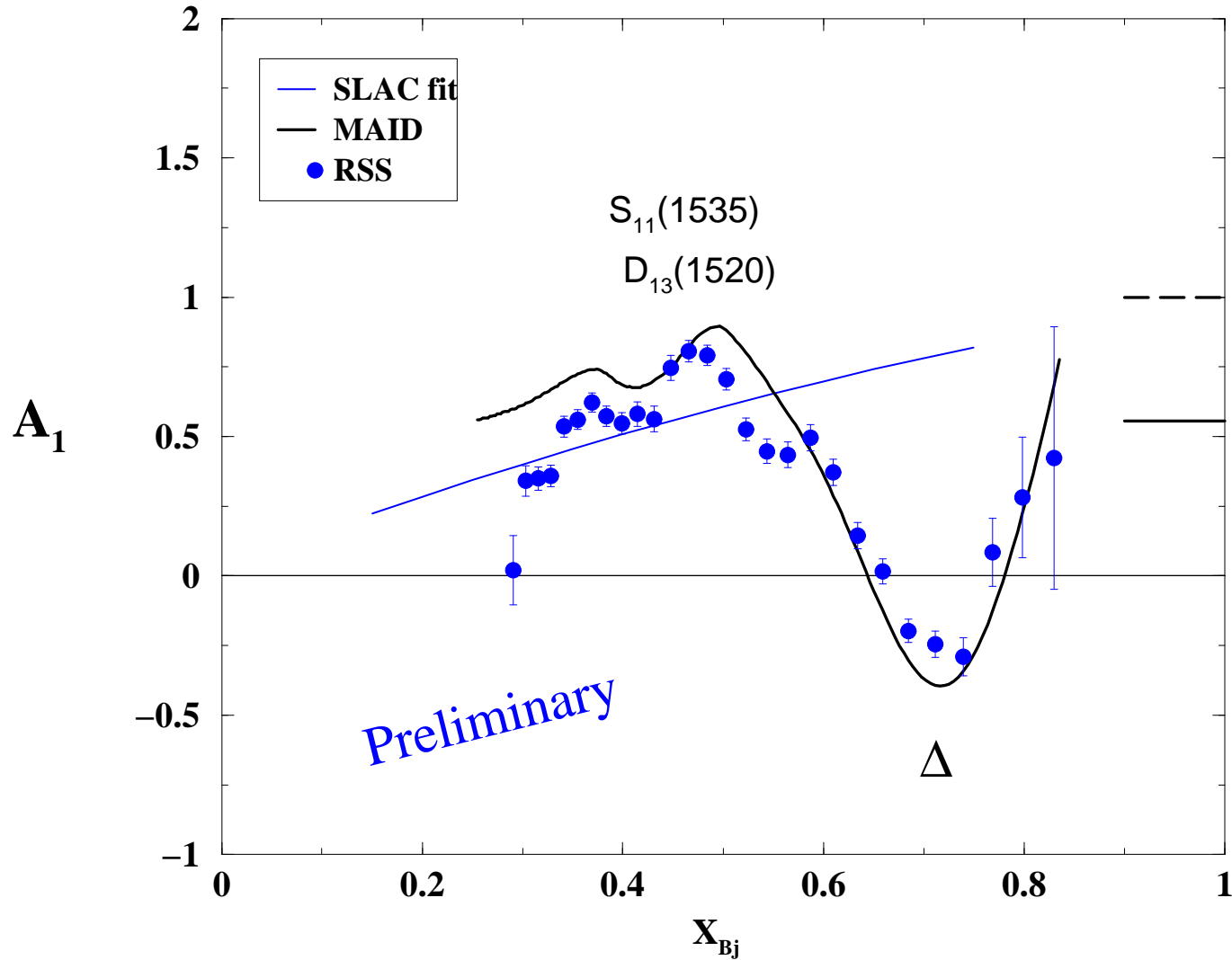
# Proton $A_1$



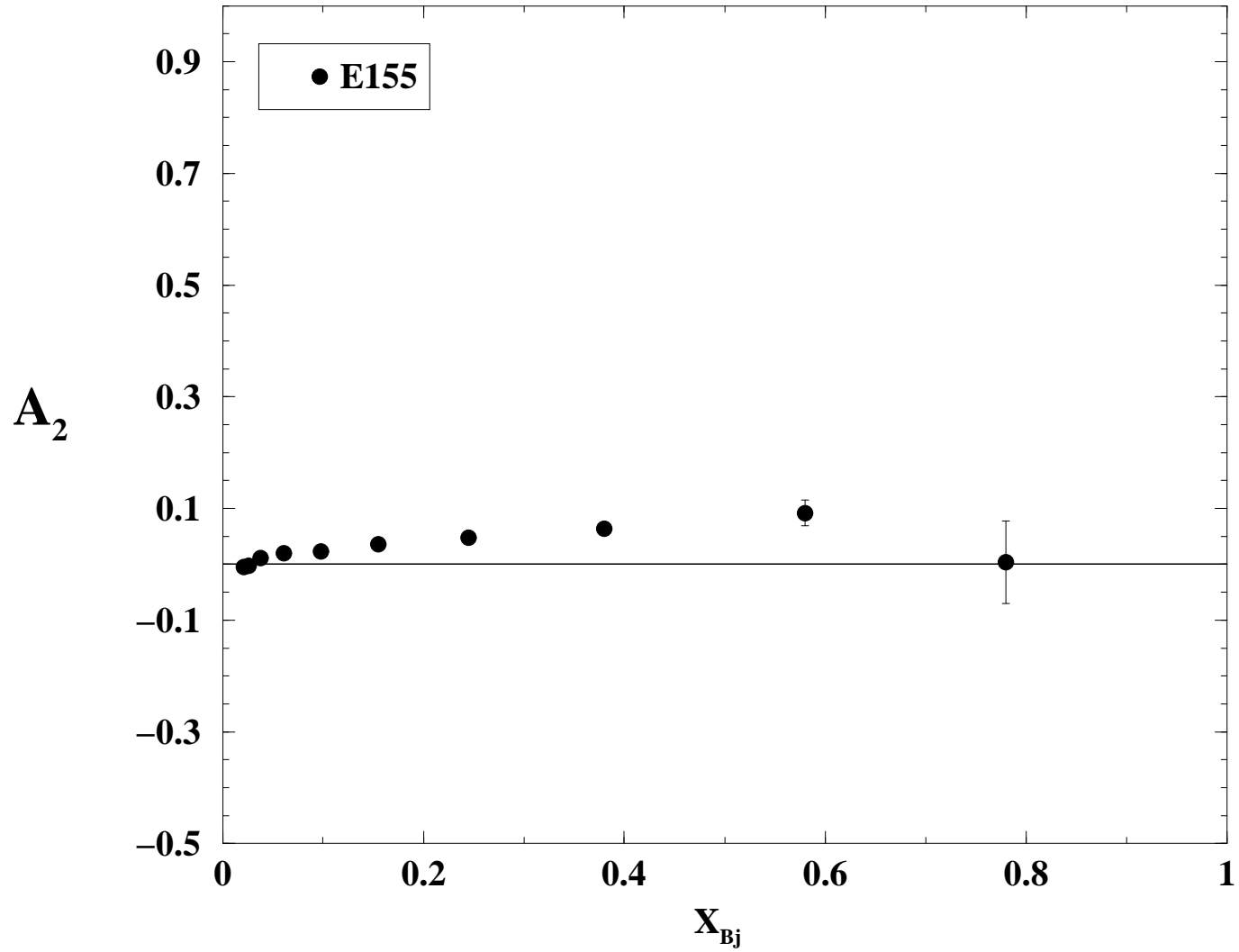
# Proton $A_1$



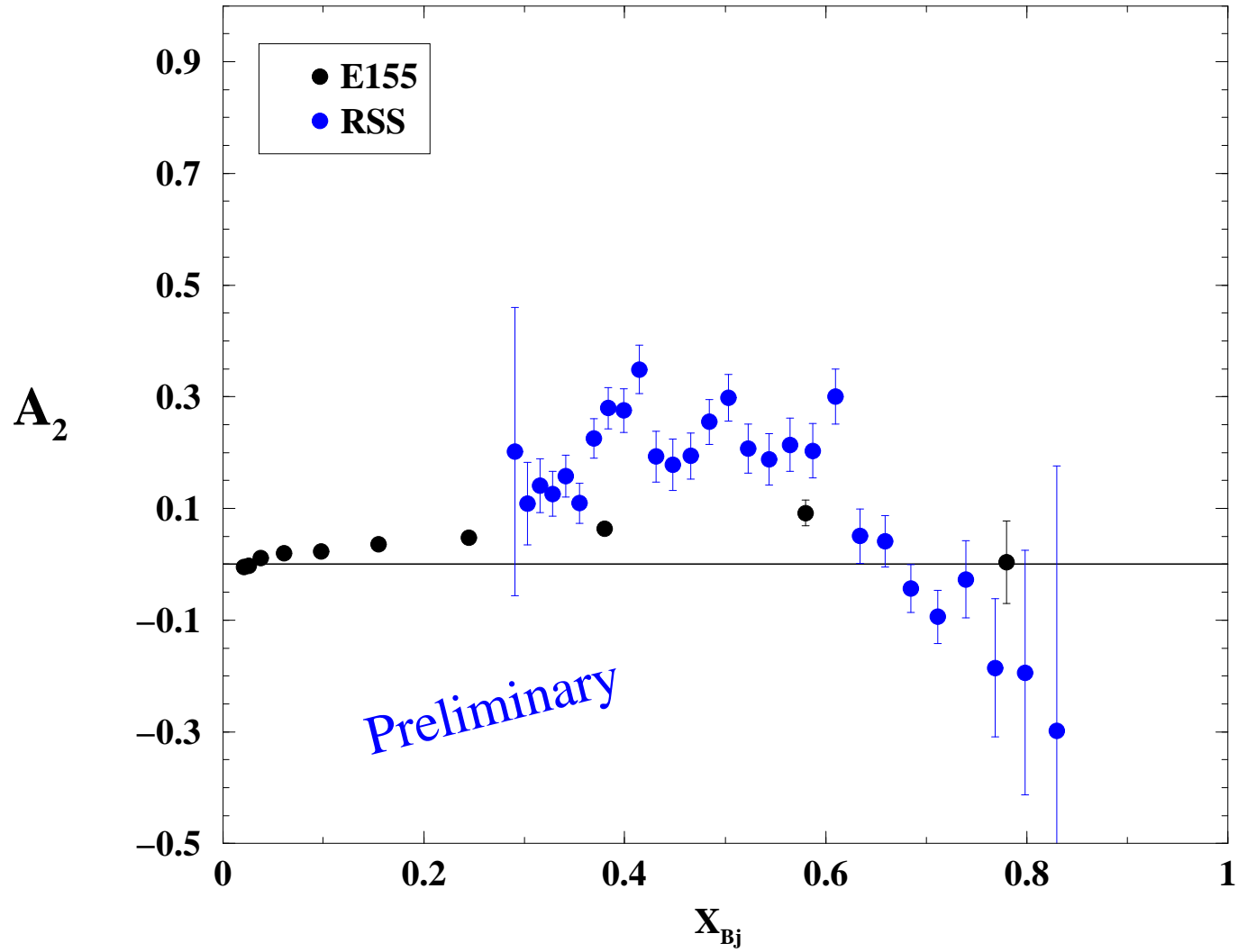
# Proton $A_1$



# Proton $A_2$

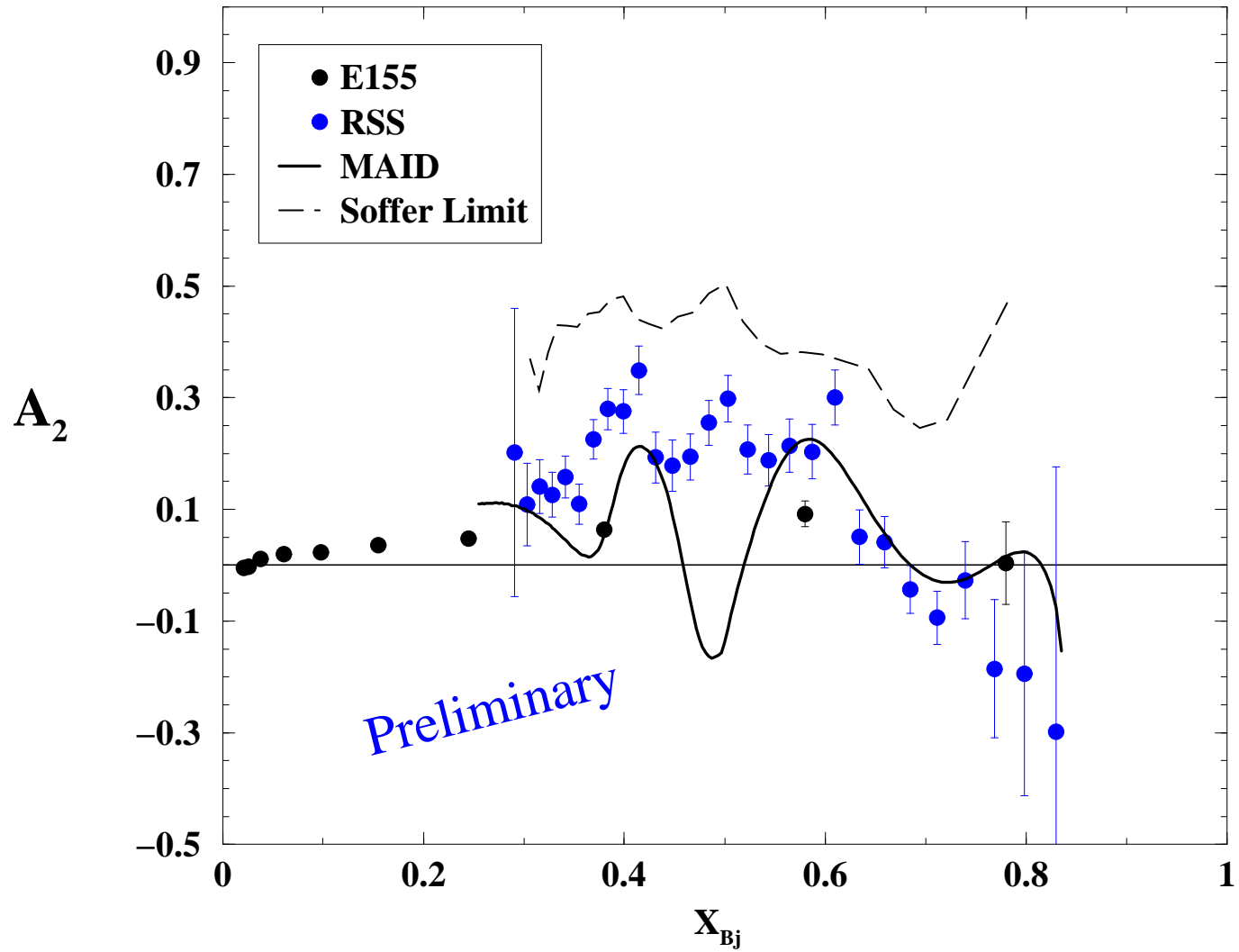


# Proton $A_2$

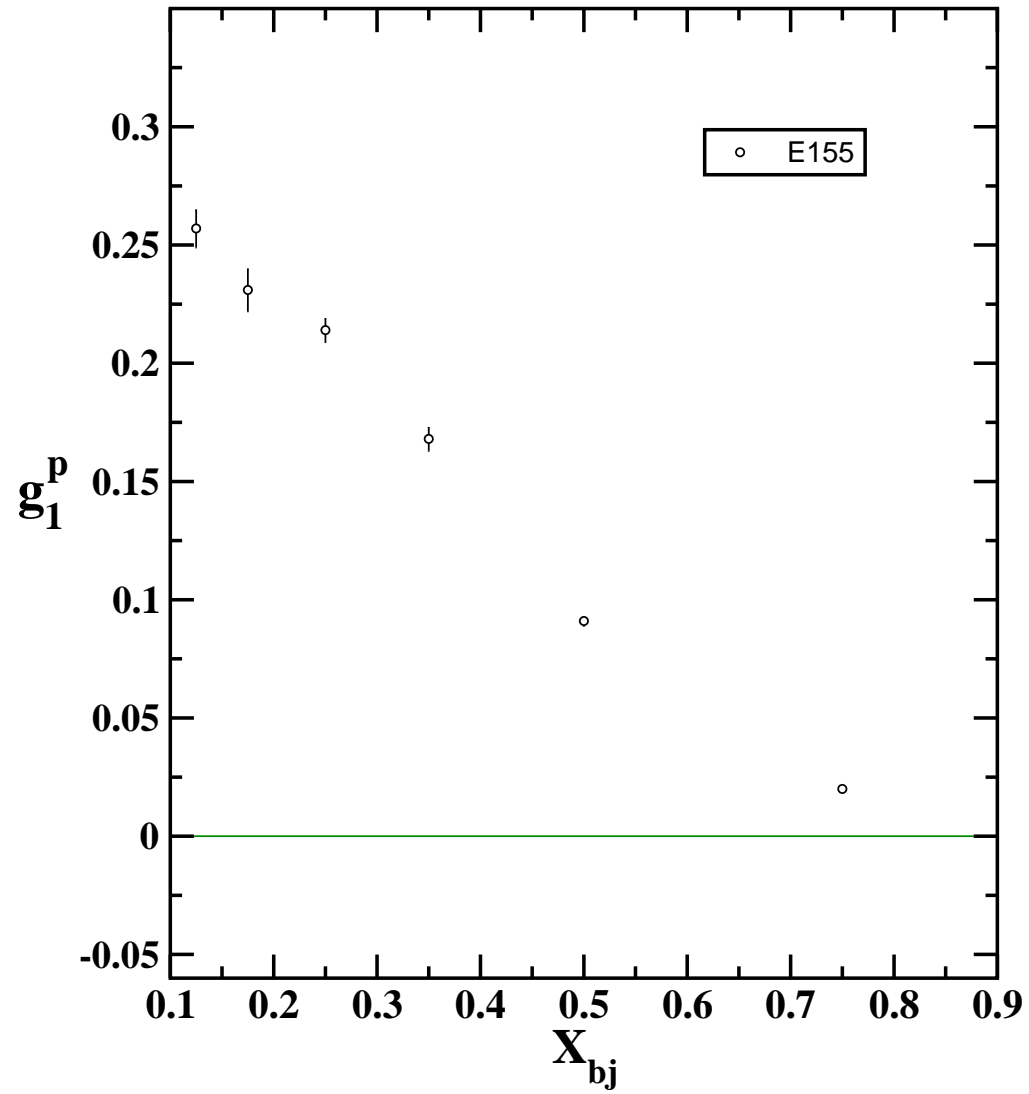




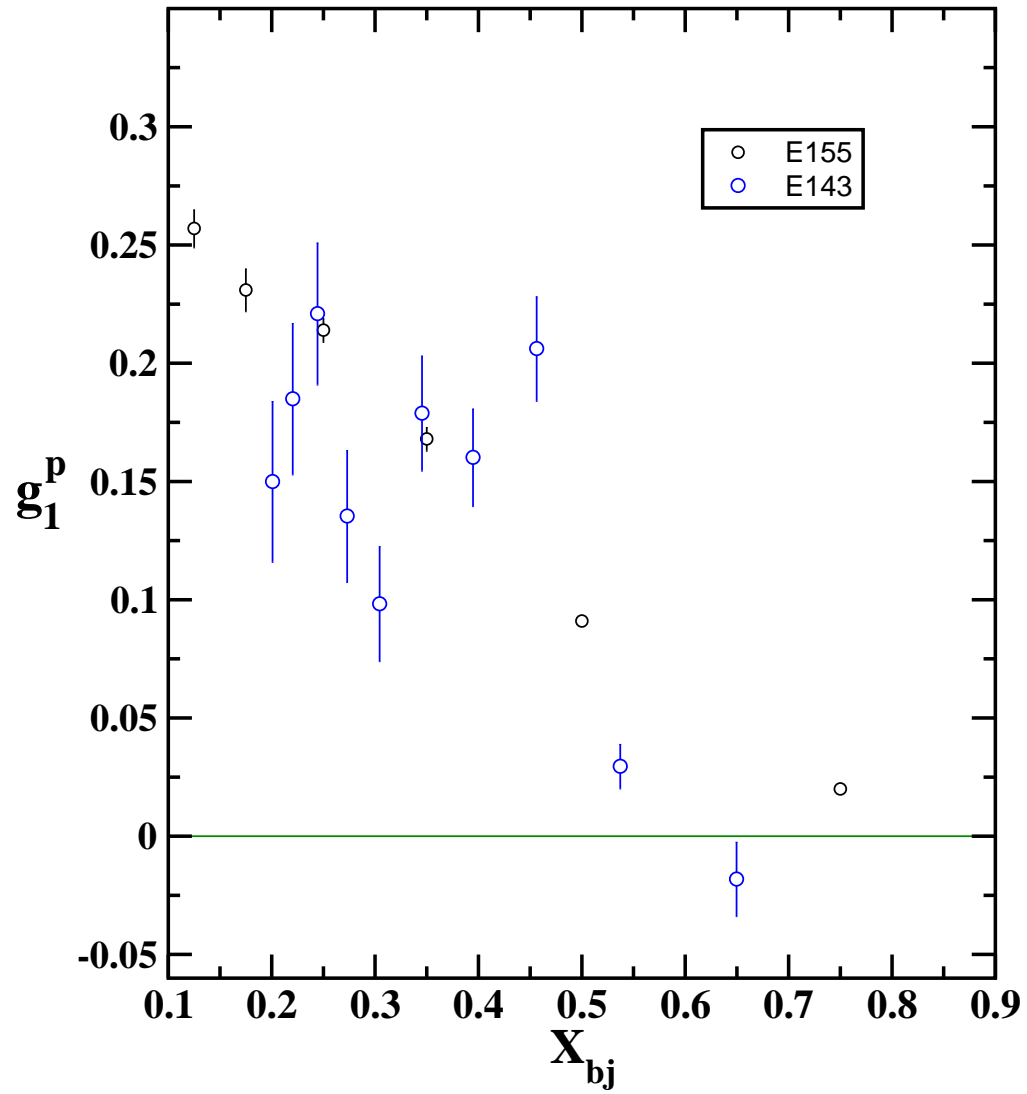
# Proton $A_2$



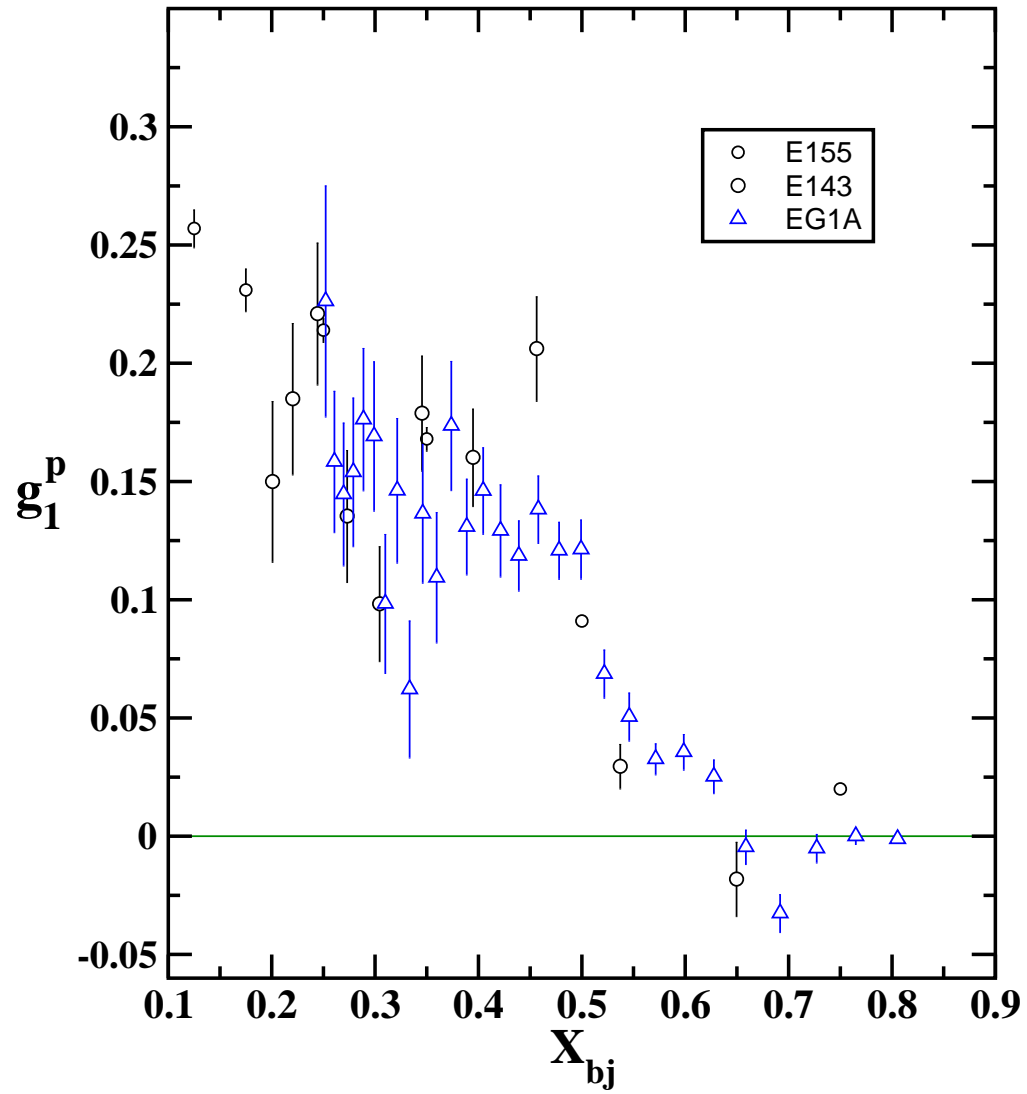
# Proton $g_1$



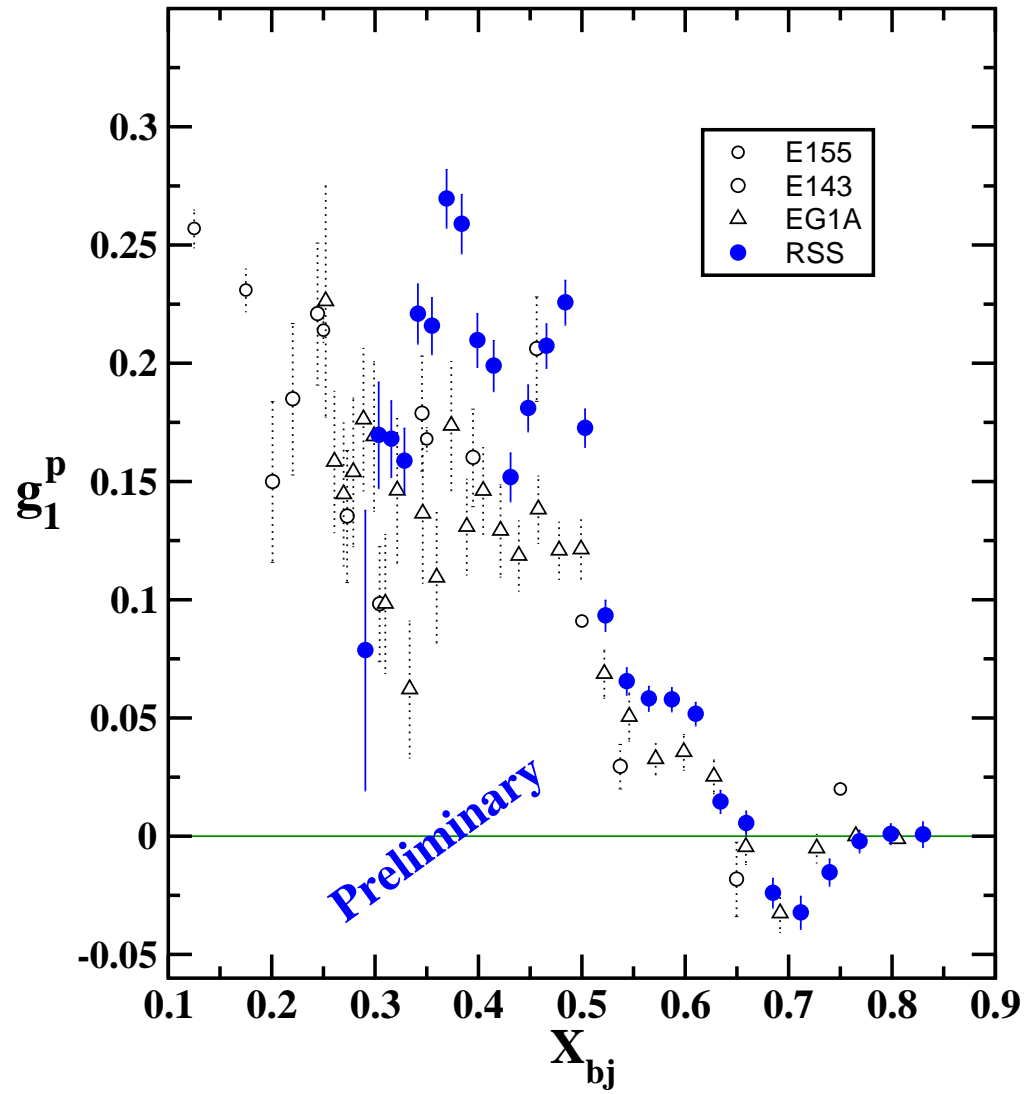
# Proton $g_1$



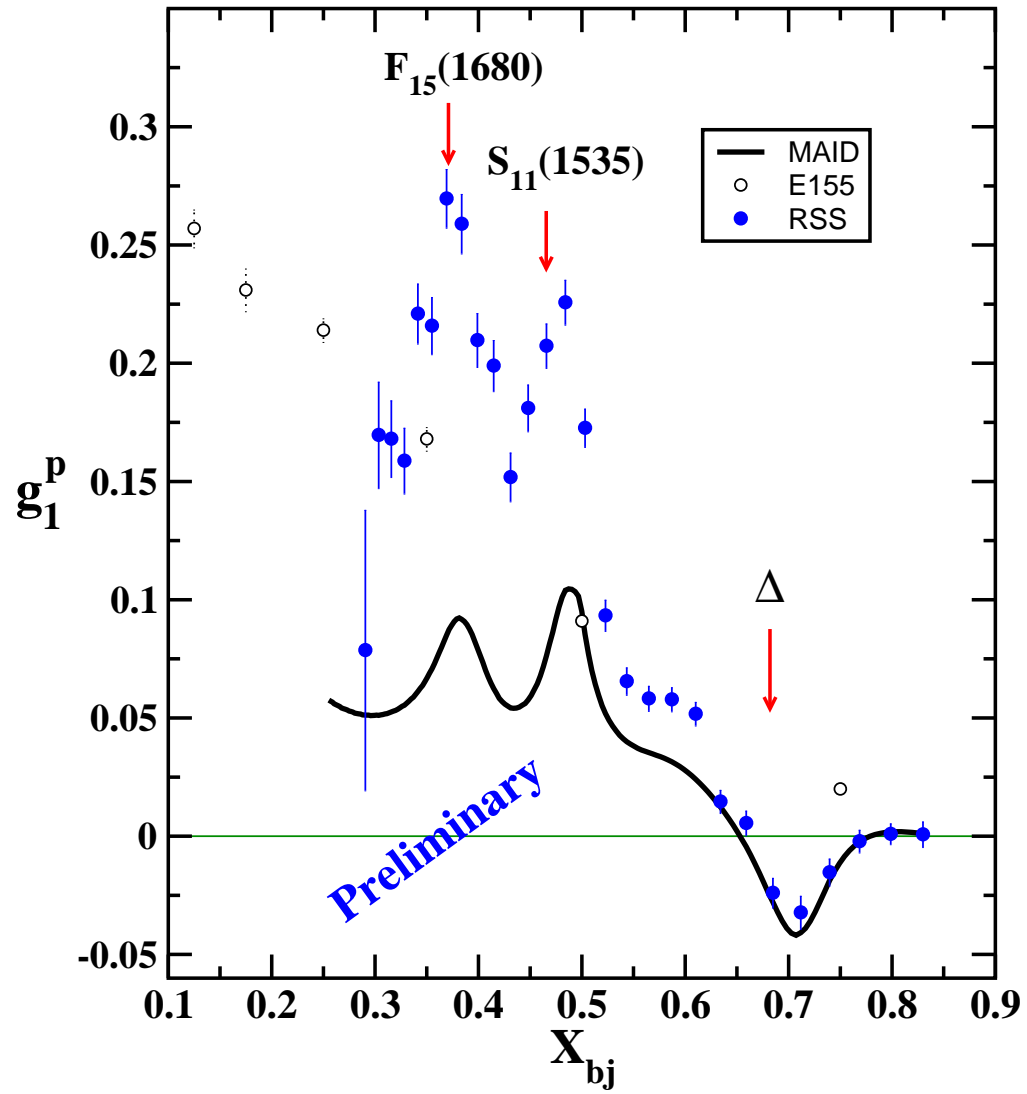
# Proton $g_1$



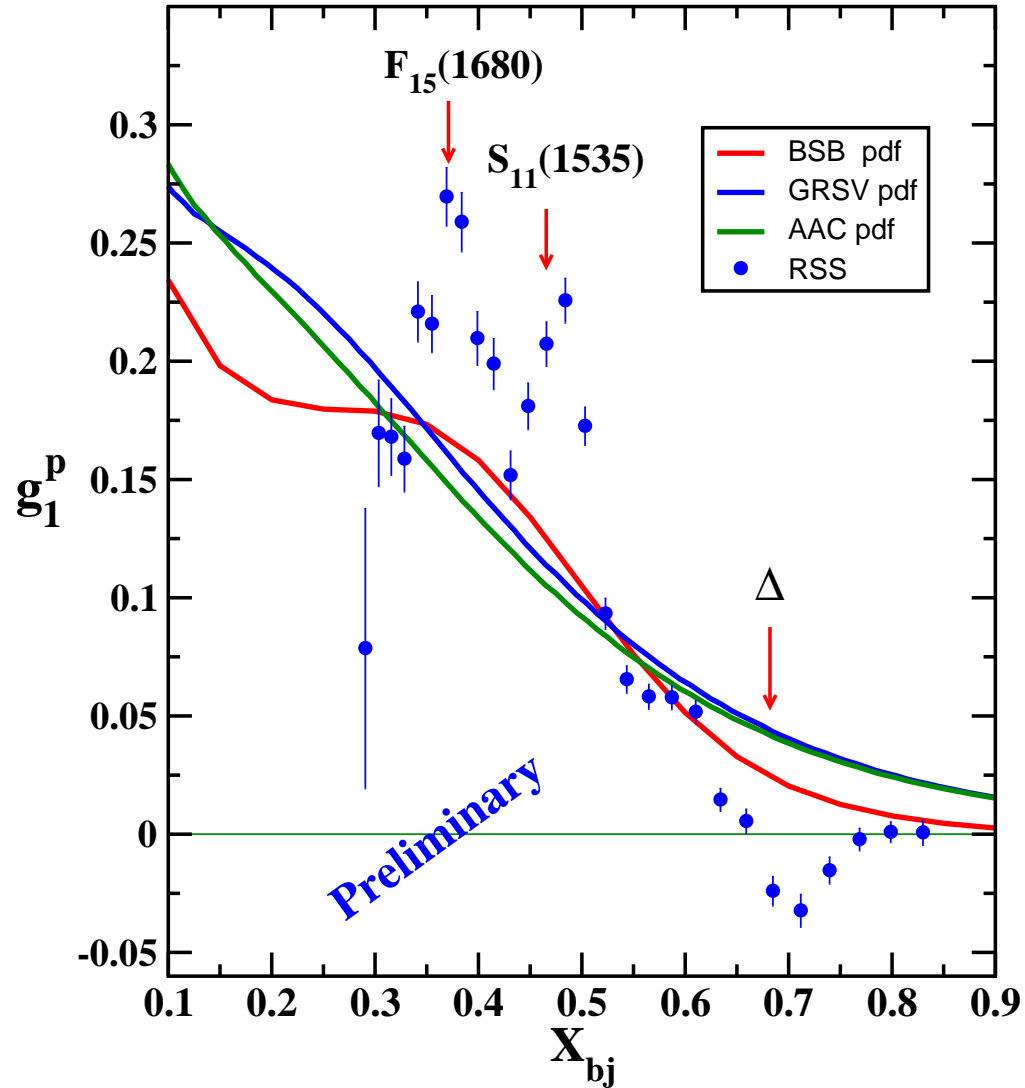
# Proton $g_1$



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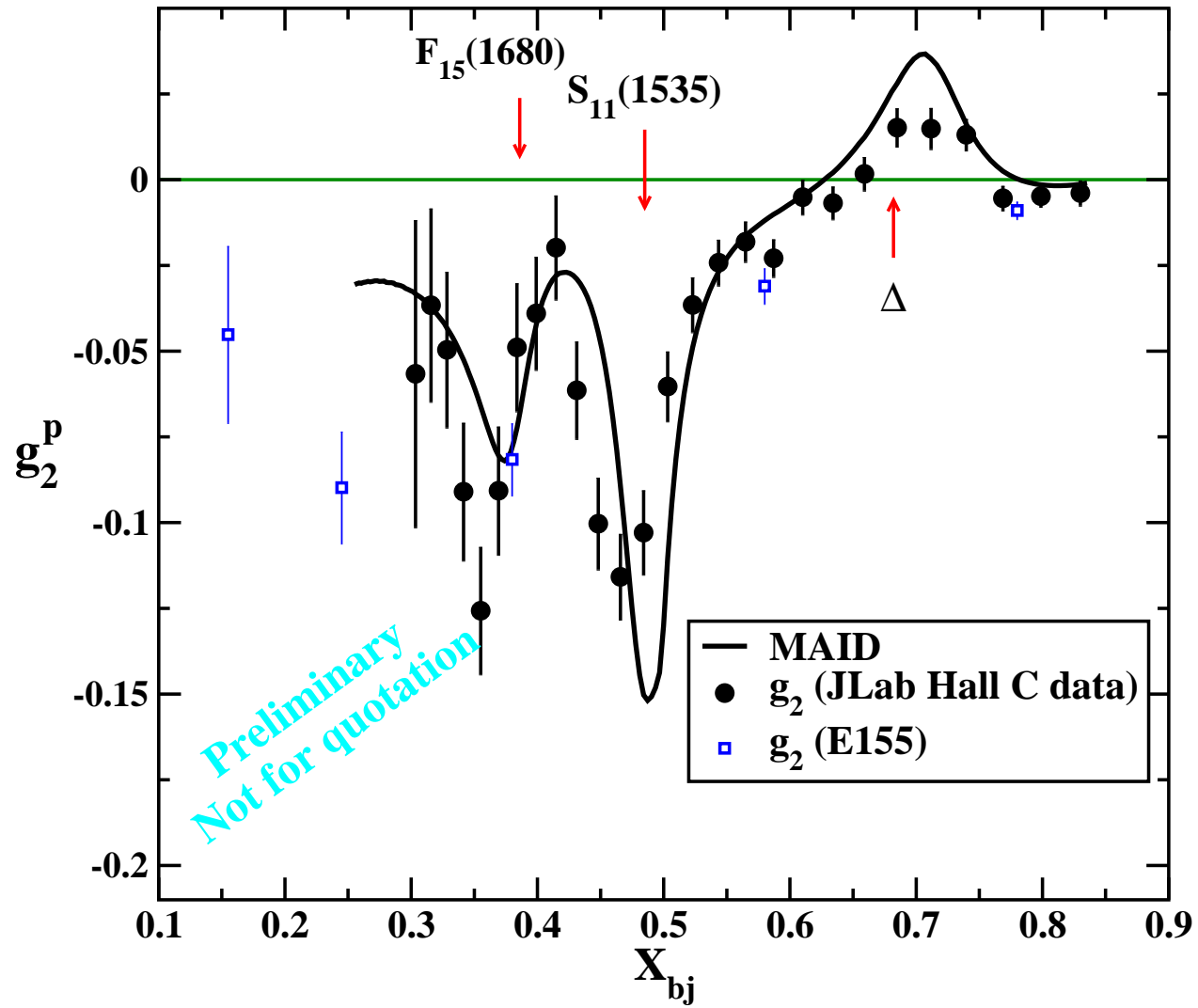
# Proton $g_1$



All pdfs evolved to  $Q^2 = 1.3$

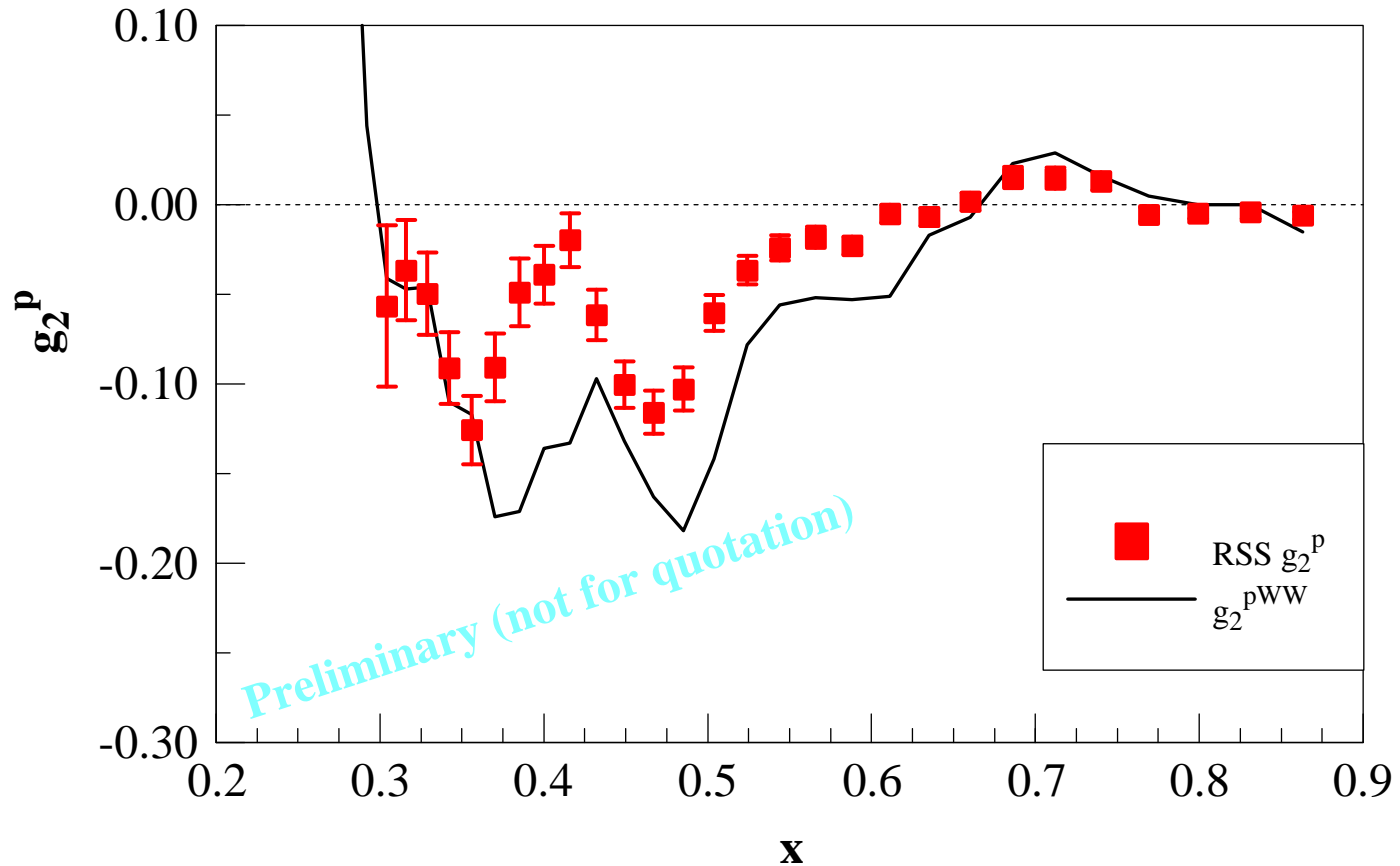
GRSV, AAC have target mass correction.

# Proton $g_2$





# Higher twist in $g_2$



$$g_2 = g_2^{WW} + \bar{g}_2$$

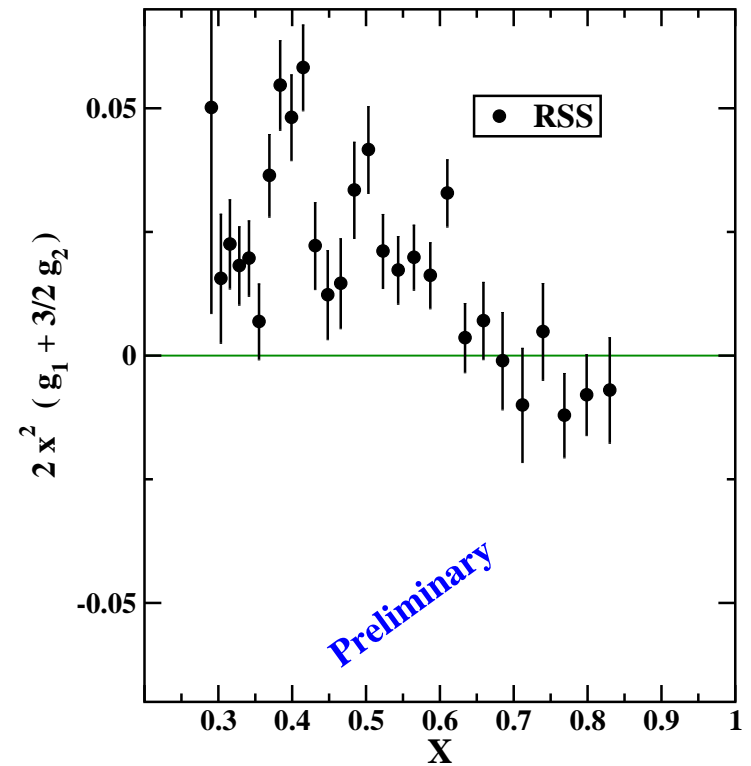
Twist-2 : 
$$g_2^{WW} = -g_1 + \int_x^1 \frac{g_1}{y} dy$$

# Twist-3 : $d_2$

$$d_2 = 3 \int_0^1 x^2 (g_2 - g_2^{\text{WW}}) dx$$

# Twist-3 : $d_2$

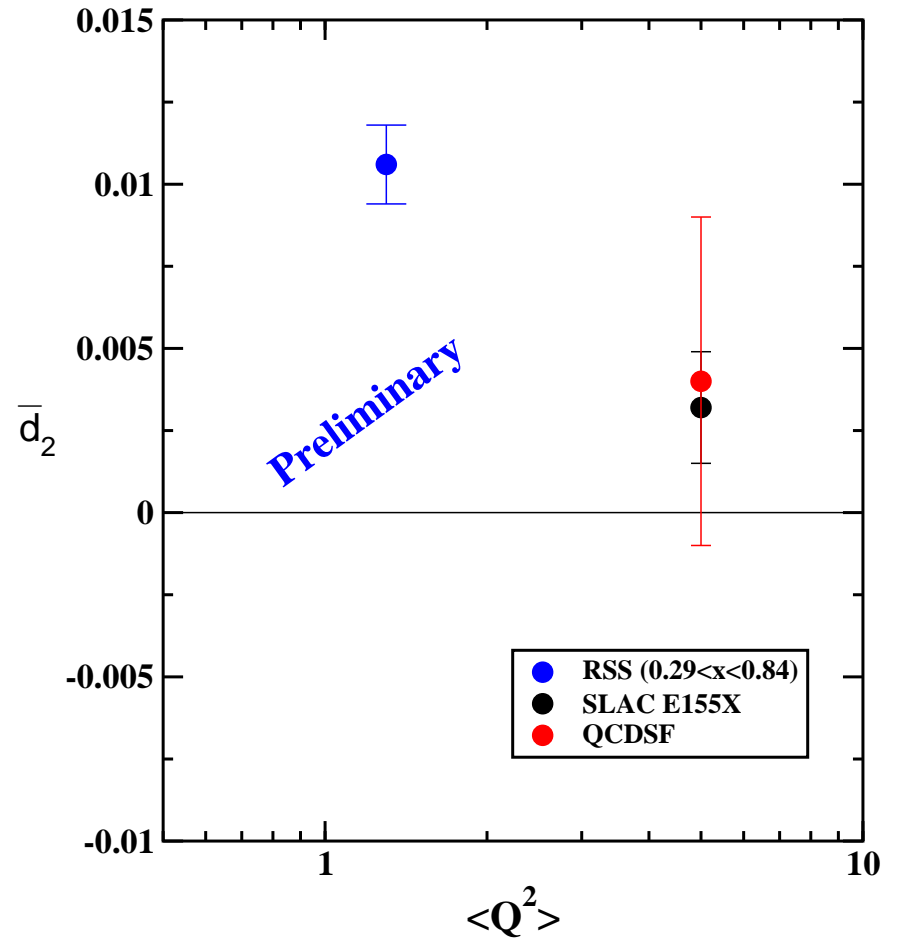
$$\begin{aligned} d_2 &= 3 \int_0^1 x^2 (g_2 - g_2^{\text{WW}}) dx \\ &= 2 \int_0^1 x^2 (g_1 + \frac{3}{2} g_2) dx \end{aligned}$$



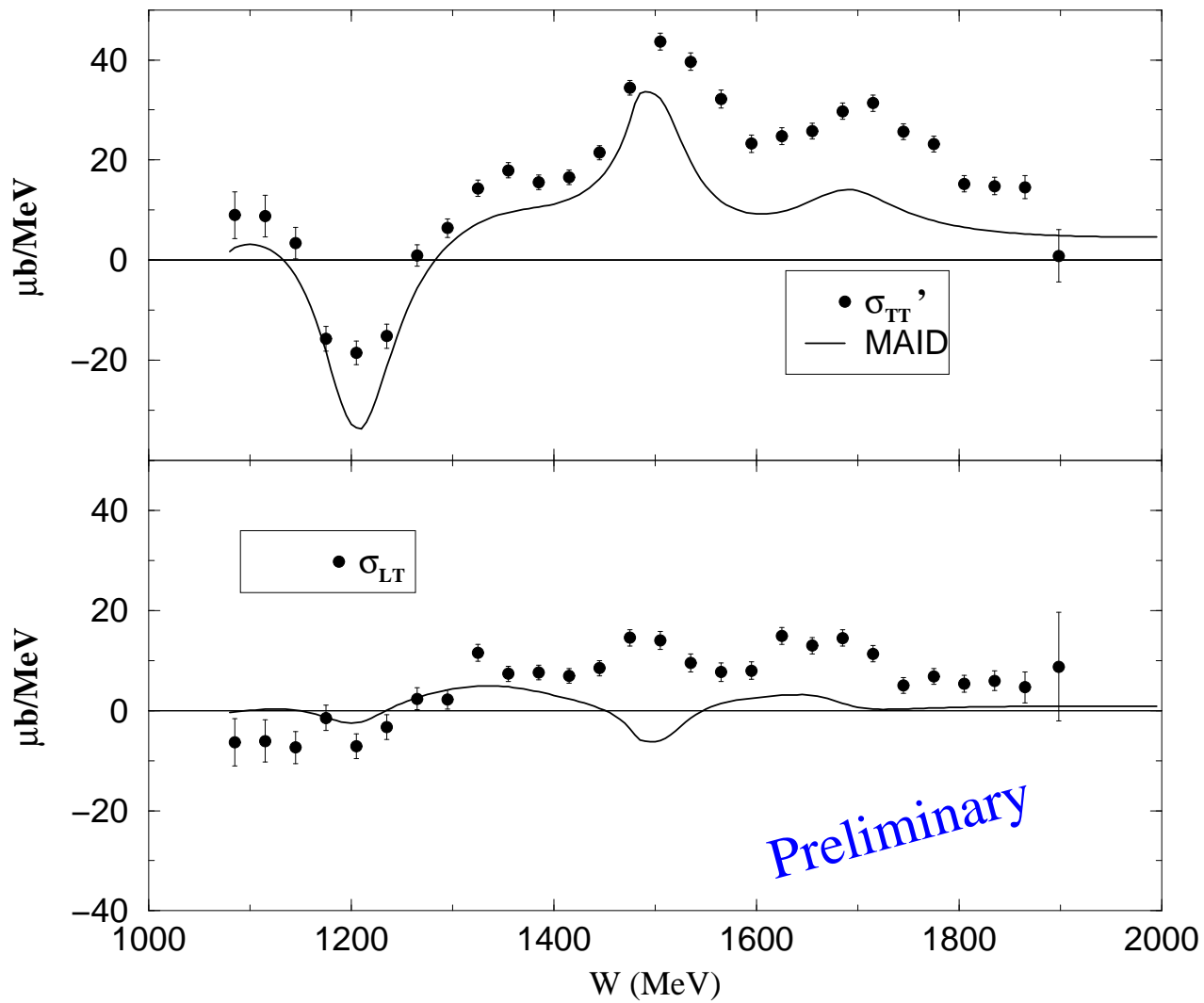
# Twist-3 : $\overline{d_2}$

$$\overline{d_2} = 0.0106 \pm 0.0012$$
$$(0.29 < x_{bj} < 0.84)$$

- Lattice QCD at  $Q^2 = 5$   
 $d_2 = 0.0085 \pm 0.0035$   
QCDSF group , hep-lat/0011091
- SLAC E155 at  $\langle Q^2 \rangle = 5$   
 $\overline{d_2} = 0.0032 \pm 0.0017$



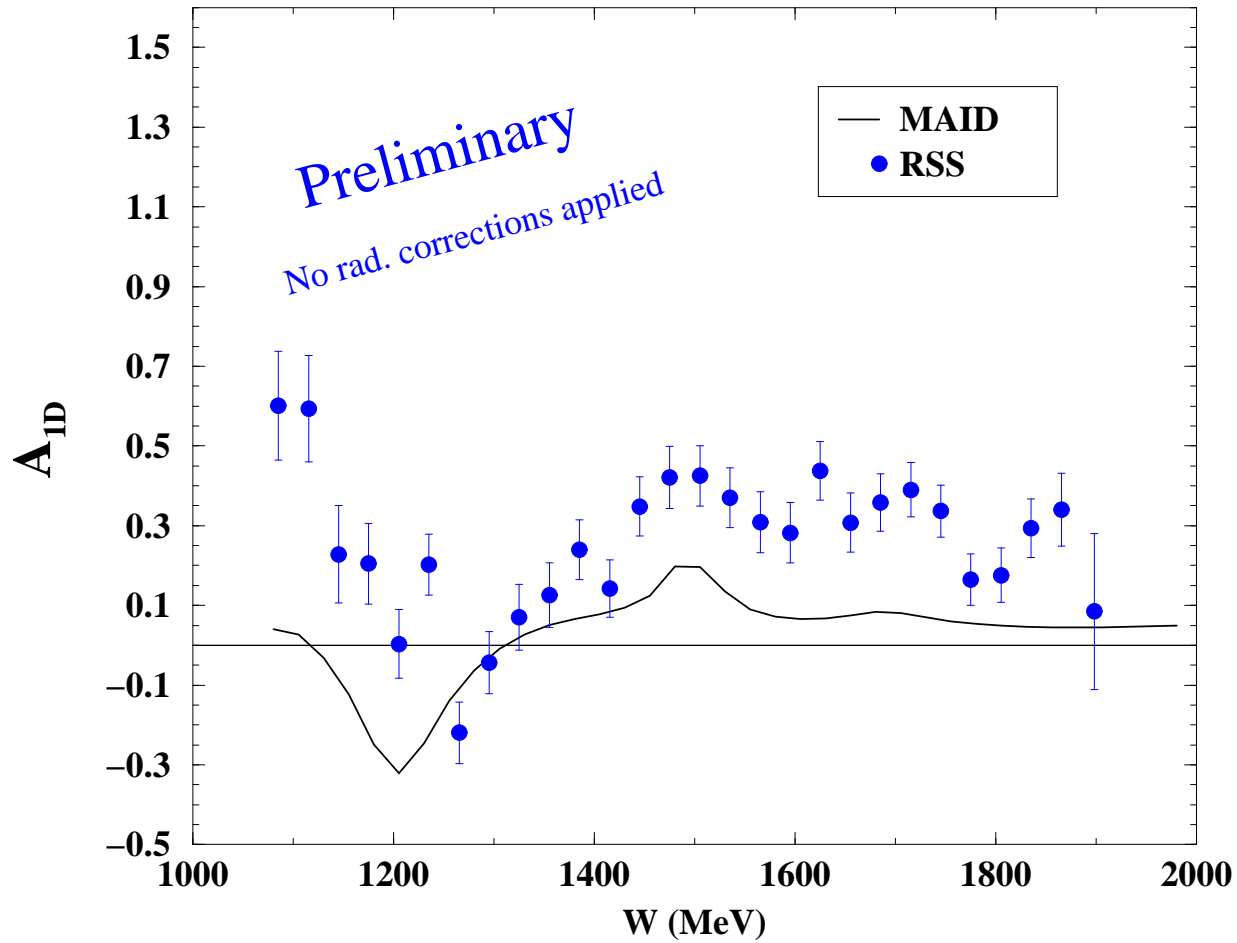
# $\sigma'_{TT}$ and $\sigma'_{LT}$ (Proton)



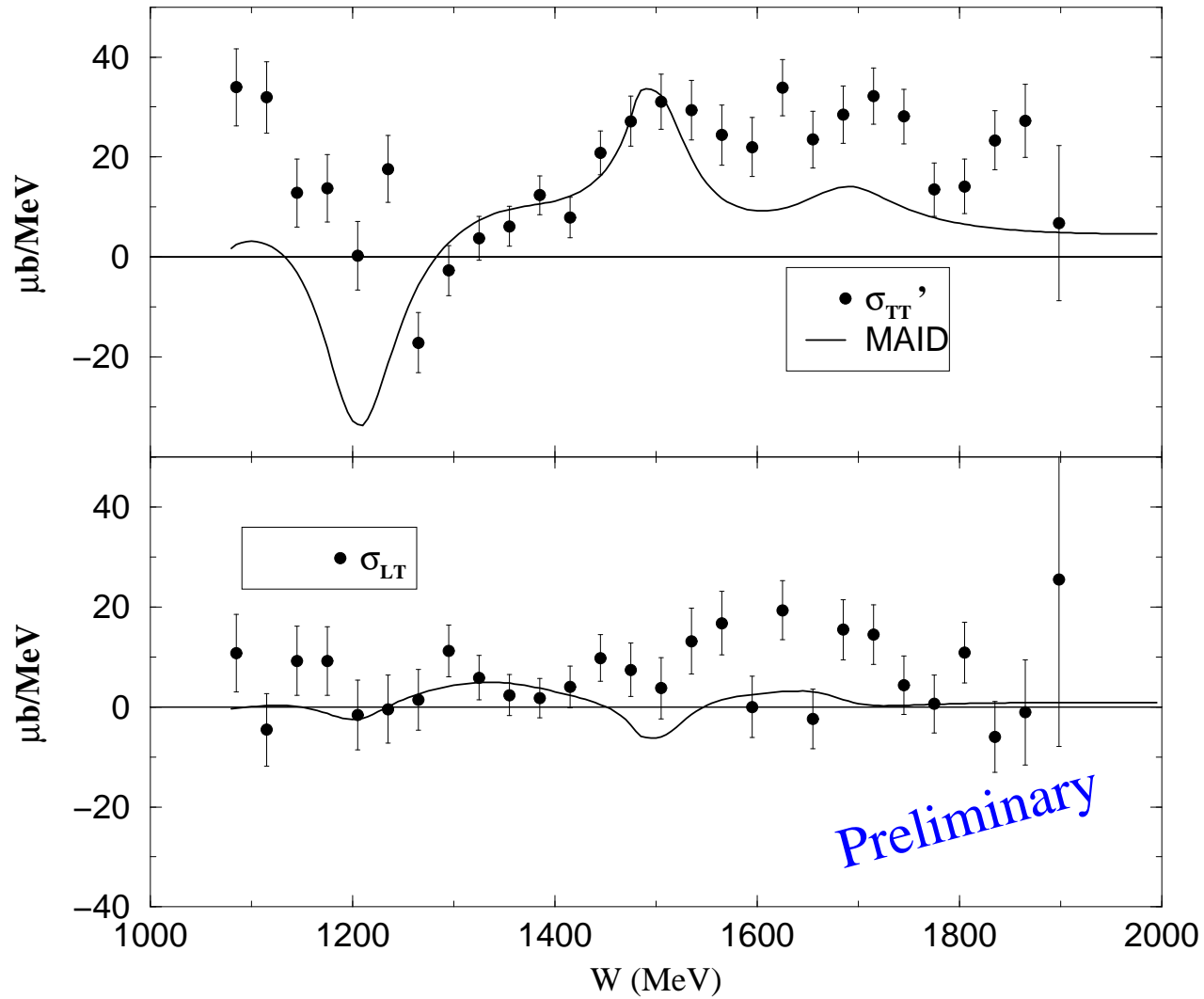
# Very Preliminary Deuteron Results

No Radiative Corrections have been applied.

# Deuteron $A_1$



# $\sigma'_{TT}$ and $\sigma'_{LT}$ (Deuteron)





# RSS Summary

Measured proton/deuteron  $A_{\parallel}$  and  $A_{\perp}$ .

( $Q^2 \approx 1.3$  and  $0.8 < W < 2.0$ )

Proton analysis complete. Extracted  $A_1, A_2, g_1, g_2, d_2$ .

Compared to MAID model.

Compared to DIS data.

Made a qualitative comparison of  $g_1$  to PDFs.

Positive  $d_2$  measured with 10% error !

To Do:

Deuteron radiative corrections (in progress).

Quantitative duality analysis.

Structure function moments.

# Spin Asymmetries on the Nucleon Experiment

E03-109

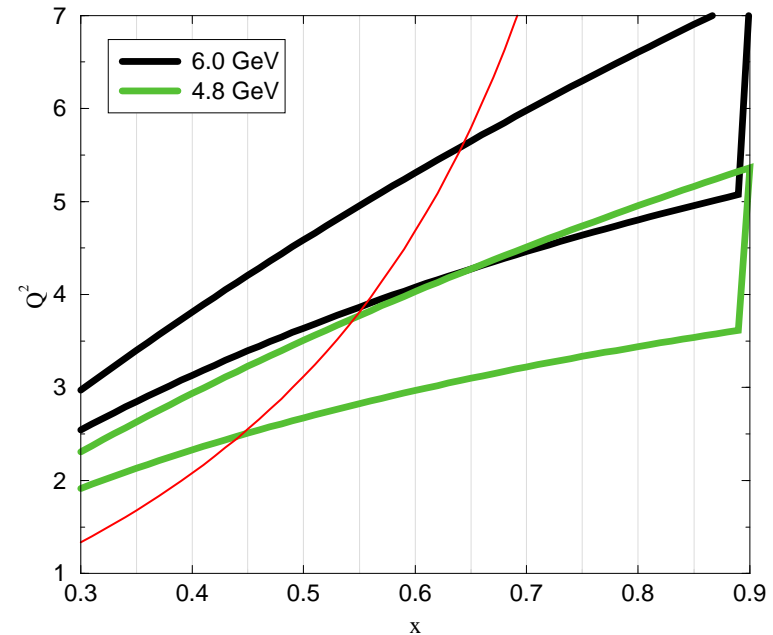
Basel, F.I.U. , Hampton, IHEP Protvino, Kent  
State, Norfolk, N.C A&T, Rensselaer  
Polytechnic, St. Norbert, Temple, TJNAF,  
UVA, William & Mary, Yerevan

Spokesmen

Oscar A. Rondon (UVA)

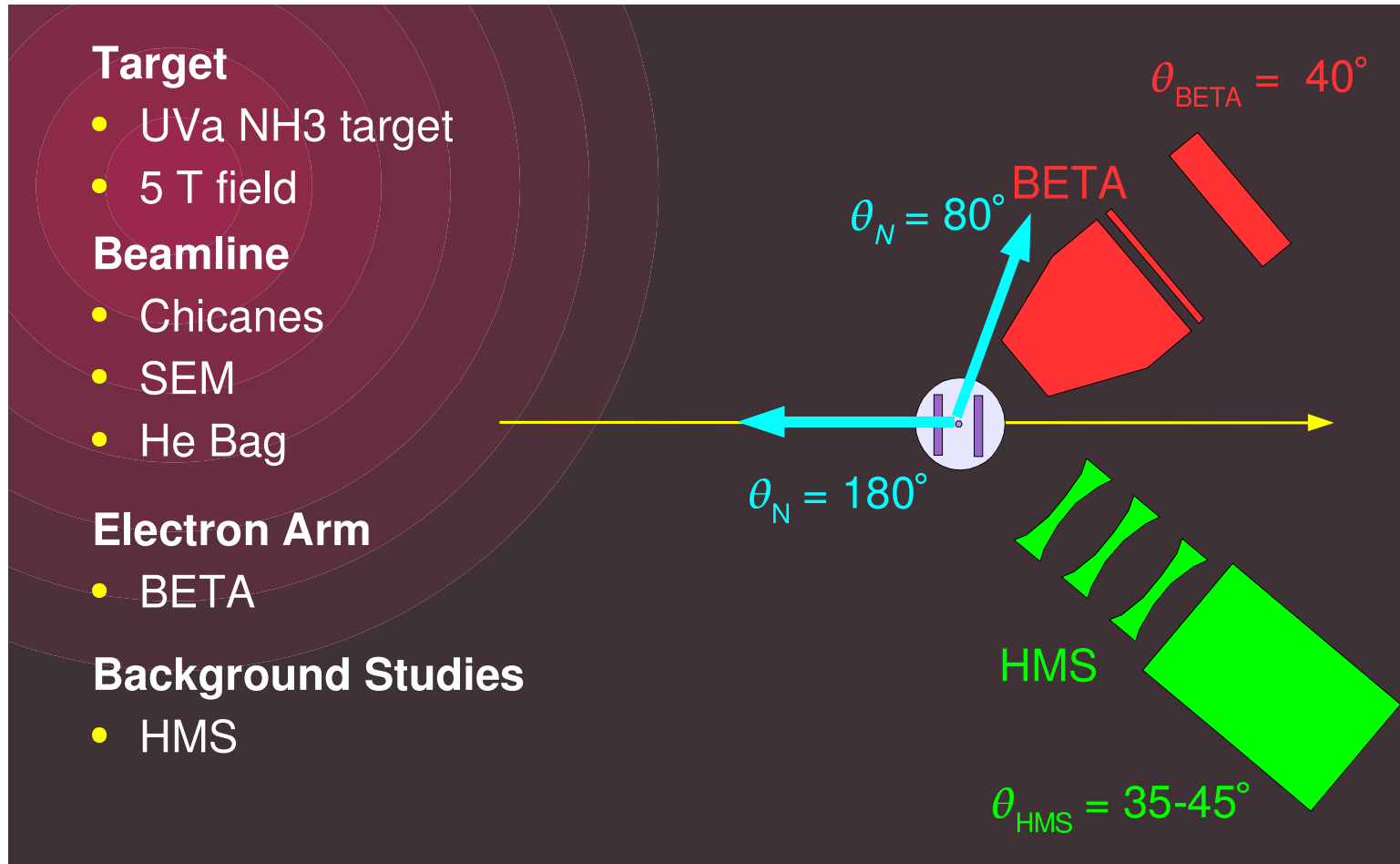
Zein-Eddine Meziani (Temple)

Seonho Choi (Seoul)



- Proton spin structure function  $g_2(x, Q^2)$  and spin Asymmetry  $A_1(x, Q^2)$   
 $2.5 < Q^2 < 6.5 \text{ GeV}^2$  and  $0.3 < x < 0.8$ .
- Study  $x$  and  $Q^2$  dependence, twist-3 effects, moments of  $g_2$  and  $g_1$ , comparison with Lattice QCD predictions, test polarized local duality for  $W > 1.4 \text{ GeV}$ .

# Experimental Setup



# Big Electron Telescope Array (BETA)

3 subsystems

Lead glass calorimeter

Gas Cherenkov

Lucite hodoscope

Target field sweeps low E BG

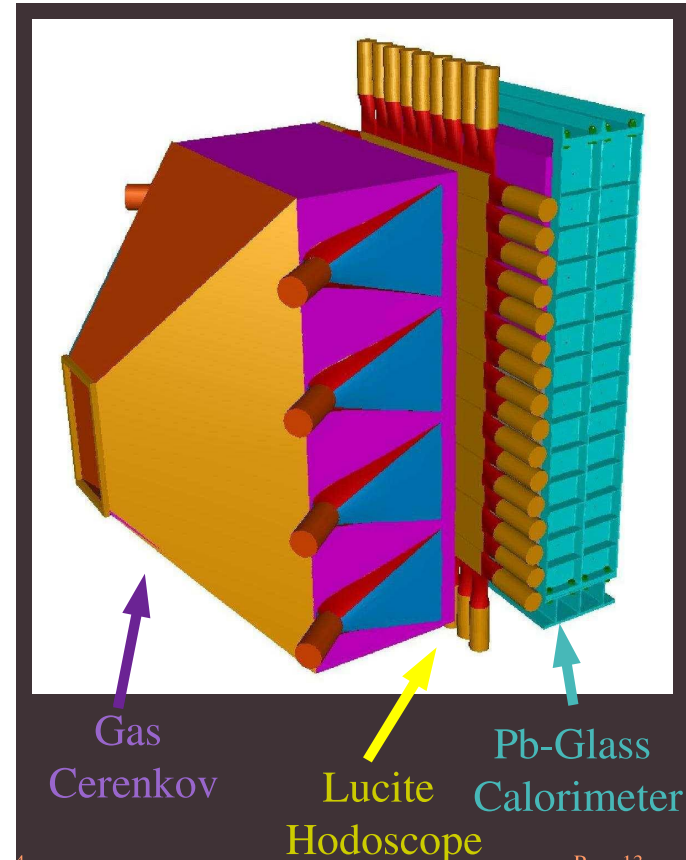
Characteristics

$$\Delta\Omega \approx 194 \text{ msr}$$

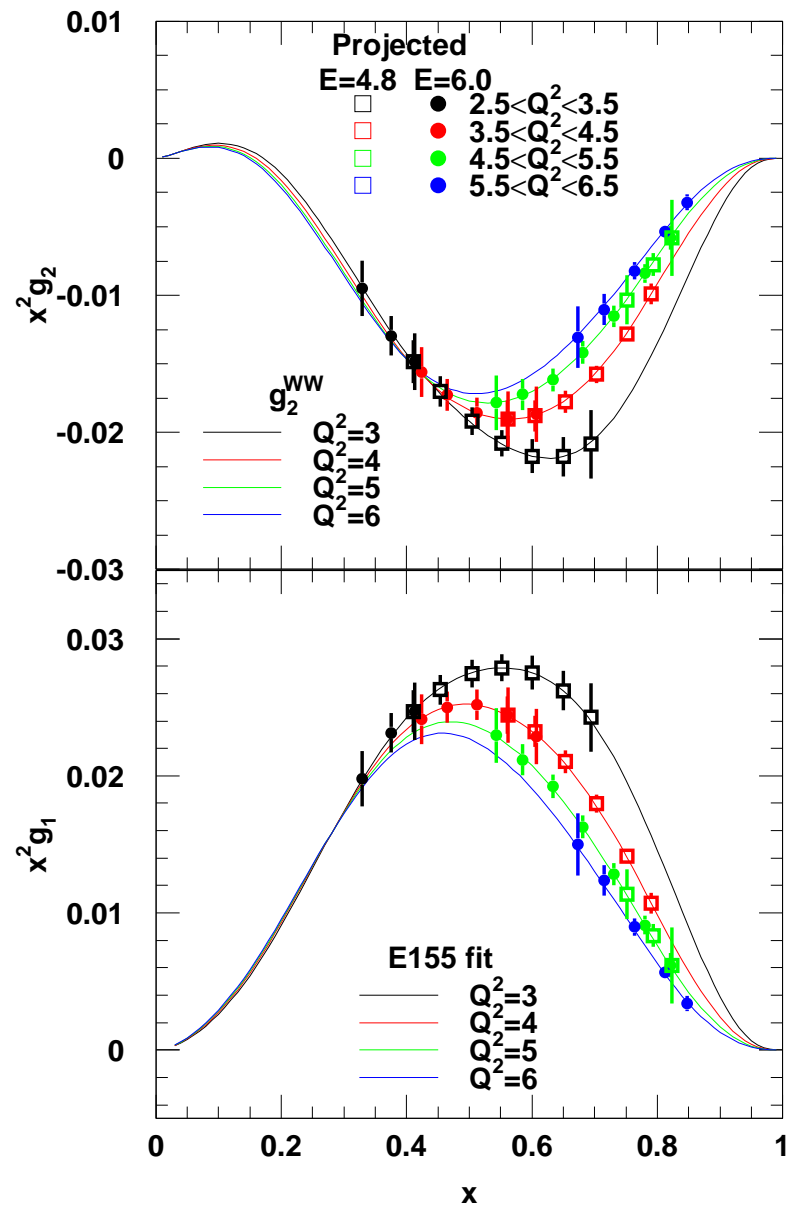
$$\Delta E \approx 5\%/\sqrt{E}$$

$$\Delta\theta \approx 2^\circ$$

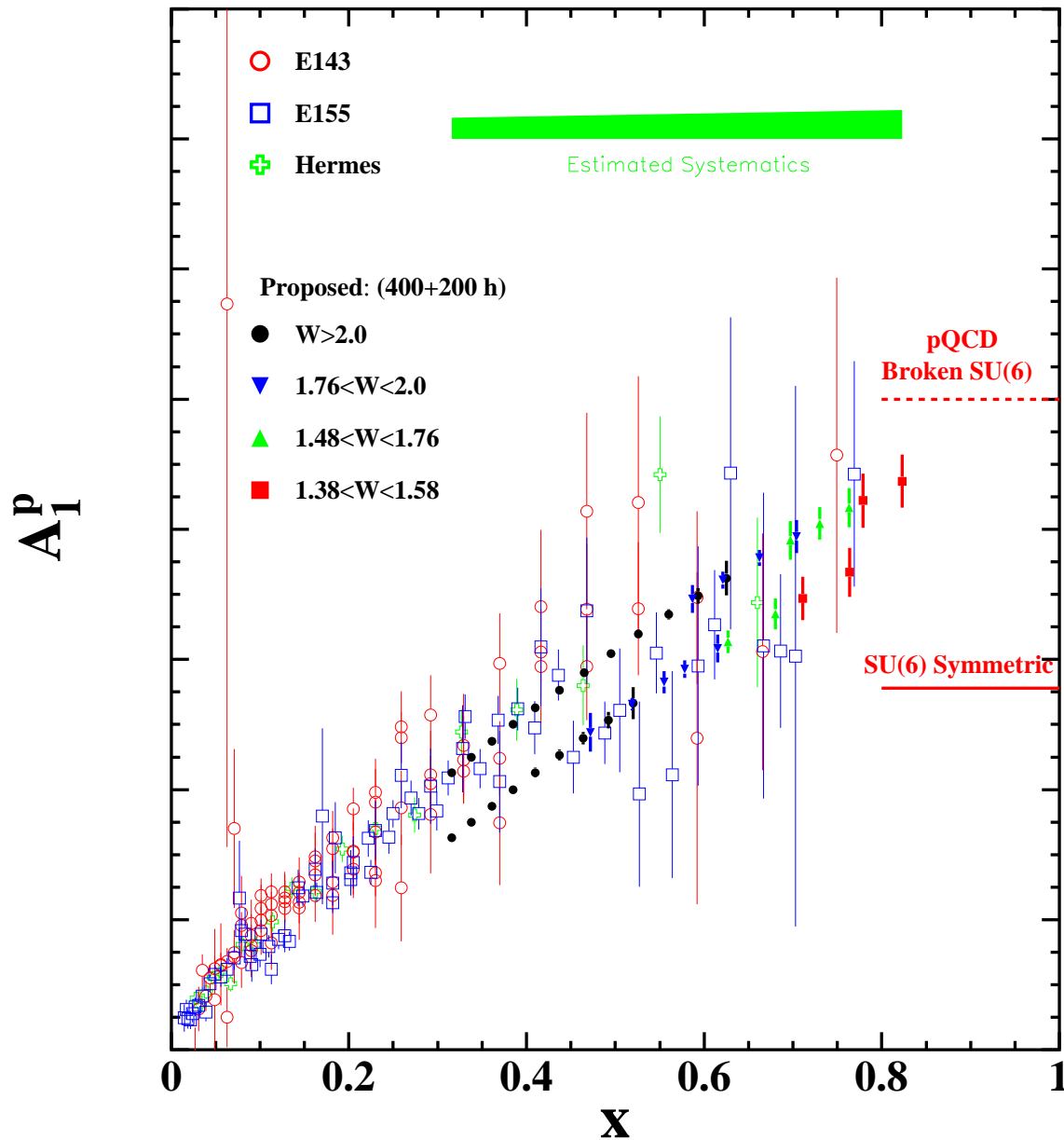
1000:1 pion rejection



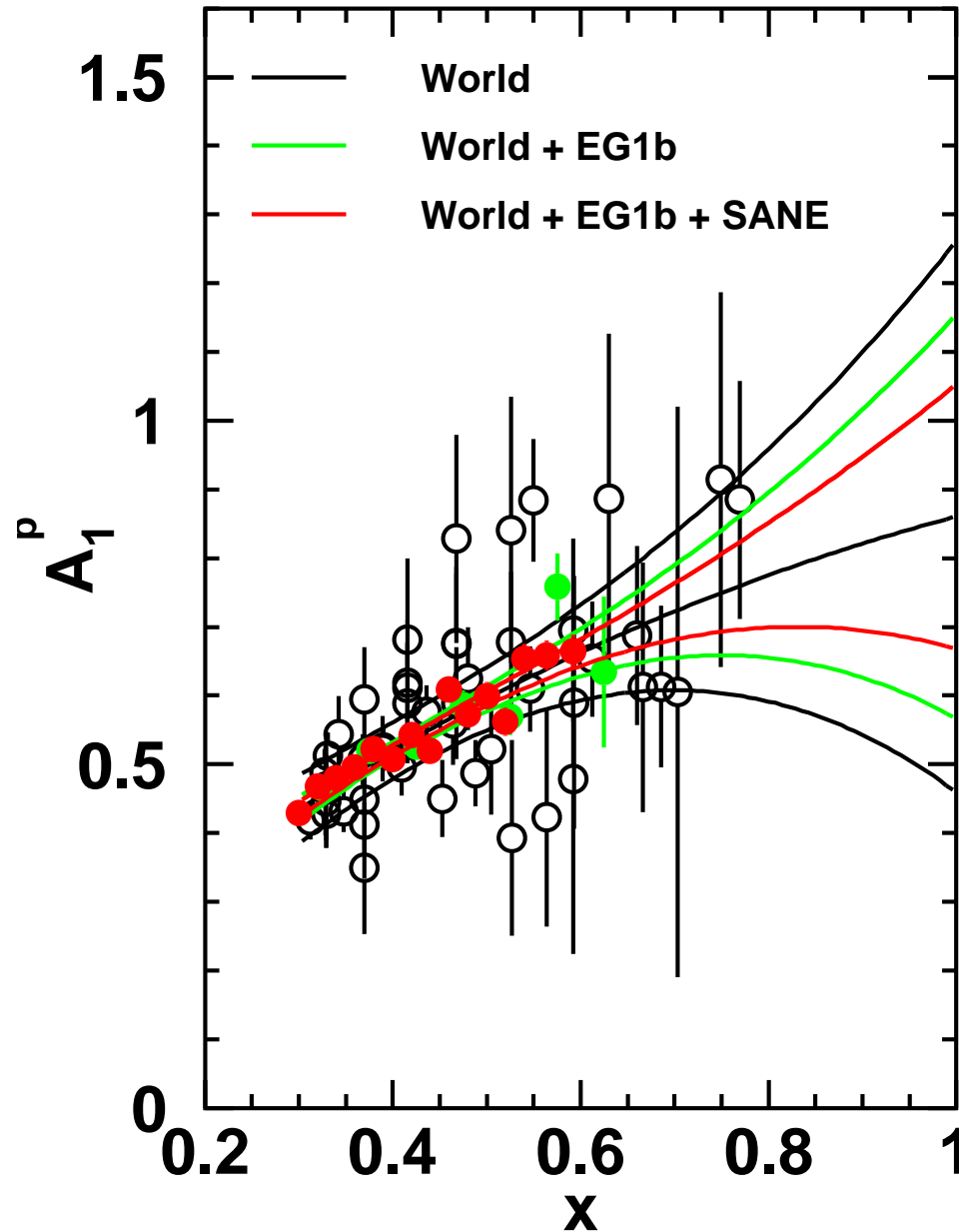
# Expected Results. $x$ and $Q^2$ dependence



# Expected Results for proton $A_1^P$



# Impact at High $x$



# Semi-Inclusive Spin Asymmetries on the Nucleon Experiment

Argonne, Duke, Florida International, Hampton, Kentucky  
Maryland, Massachusetts, Rensselaer Polytechnic, Norfolk, ODU  
Regina, Rutgers, Temple, TJNAF, UVA, William & Mary, Yerevan Physics I.

P. Bosted

(JLab)

D. Day

(UVA)

X. Jiang

(Rutgers)

M. Jones

(JLab)

## Proton and deuteron semi-inclusive longitudinal spin asymmetries

- Polarized DIS reactions  $p(e, e' h)$  and  $d(e, e' h)$  for  $h = \pi^\pm, K^\pm$
- $1.2 < Q^2 < 3.1 \text{ GeV}^2$
- $0.12 < x < 0.43$ ,

## Spin flavor decomposition

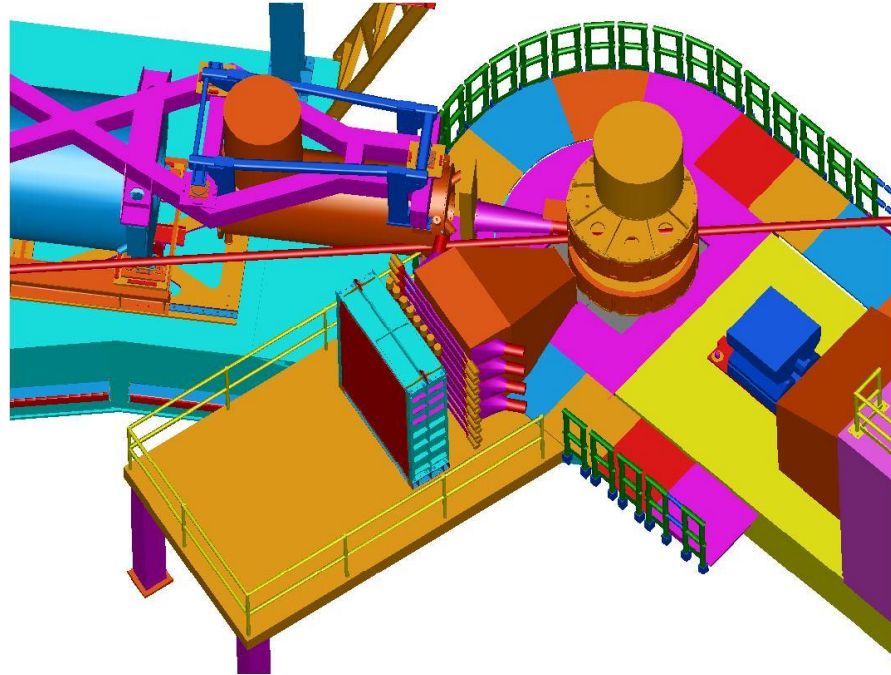
- emphasis on NLO spin flavor decomposition to extract  $\Delta u_v$ ,  $\Delta d_v$  and  $\Delta \bar{u} - \Delta \bar{d}$
- based on measurement of combined asymmetry,  $A_{1N}^{\pi^+ - \pi^-}$ .

## Examine deviation from factorization

- by comparing combined asymmetry,  $A_{1N}^{\pi^+ + \pi^-}$  with the inclusive asymmetry,  $A_{1N}$ .

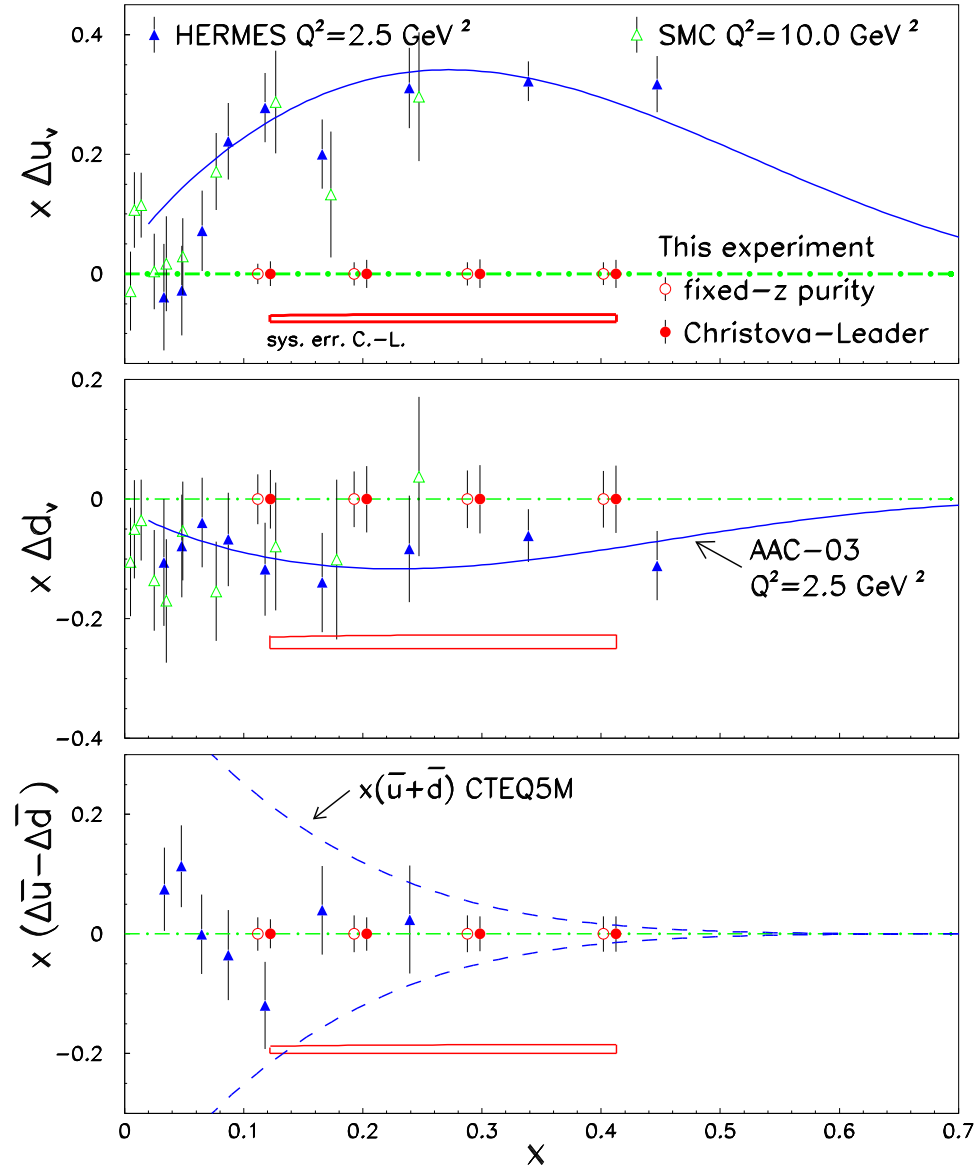


# Experiment Set-up



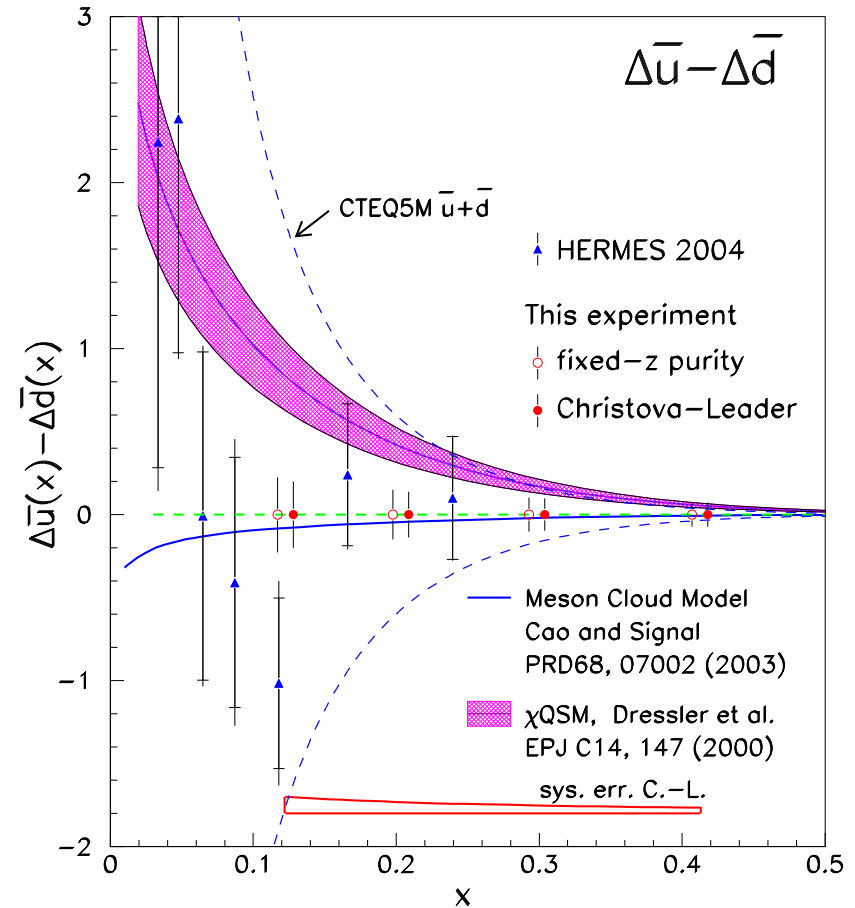
- Electrons detected in BETA at  $30^\circ$
- Hadrons detected in HMS at  $10.8^\circ$  and  $p_{cent} = 2.7 \text{ GeV}/c$

# Expected Results on $\Delta q$



# Is the Polarized Sea Asymmetric?

- Much improved statistical accuracy.
- Could be the first clear observation.
- Test a wide range of model predictions for  $\int (\Delta\bar{u} - \Delta\bar{d}) dx$ 
  - Meson cloud( $\pi$ ): 0
  - Chiral-quark soliton: 0.31
  - Pauli-blocking: 0.2 ~ 0.3
  - Instanton: 0.2
  - Statistical: 0.12
- $\int (\bar{u} - \bar{d}) dx = 0.118 \pm 0.012$  (E866)
- Expect  $\Delta\bar{u} - \Delta\bar{d} > \bar{u} - \bar{d}$



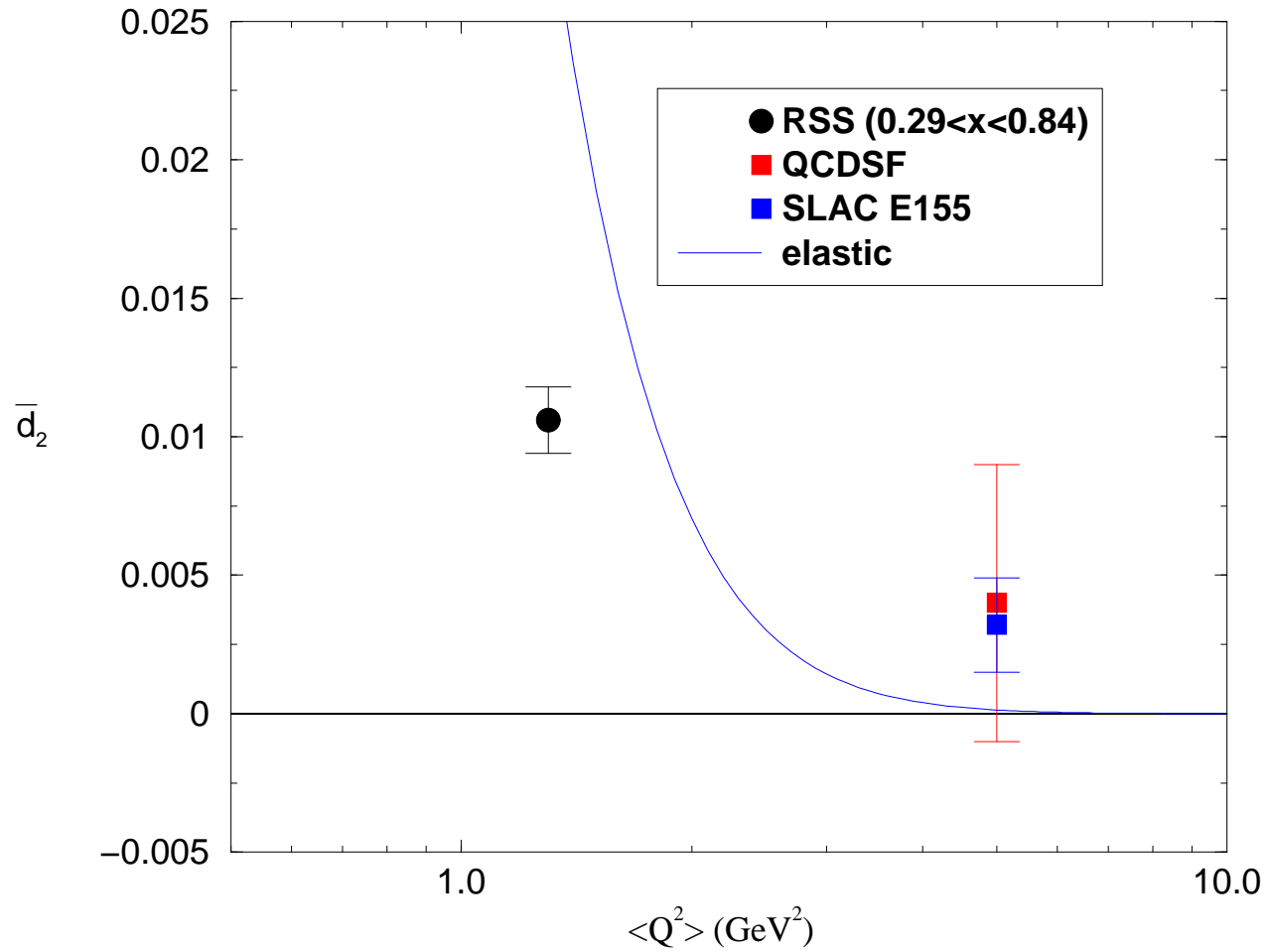
# Semi-Sane Summary

- Experiment E04-113 will start a new generation of spin experiments at JLab
- First data on  $A_{1N}^{\pi^+ - \pi^-}$
- Could be first experiment to observe  $\Delta\bar{u} - \Delta\bar{d} \neq 0$
- Provide strong constraints on polarized PDFs in  $0.12 < x < 0.41$ .
- Complimentary to other high-energy spin physics experiments.
- Lead to new physics with the planned 12 GeV upgrade at JLab.

# Summary of Hall C spin program

- **RSS** :  $A_{\parallel}$  and  $A_{\perp}$  in inclusive electron scattering on protons and deuterons.  
SF and Spin Asymmetries at  $Q^2 = 1.3 \text{ GeV}^2$  and  $0.8 < W < 2.0$
- **SANE**:  $A_{\parallel}$  and  $A_{\perp}$  in inclusive electron scattering on proton with large acceptance detector (BETA)  
Extract  $g_1$  and  $g_2$  in range  
 $2.5 < Q^2 < 6.5$  and  $0.3 < x < 0.8$
- **Semi-SANE**: SIDIS reactions  $p(e, e'h)$  and  $d(e, e'h)$  for  $h = \pi^{\pm}, K^{\pm}$ .  
 $1.2 < Q^2 < 3.1 \text{ GeV}^2$ ,  $0.12 < x < 0.43$ ,  $0.5 < z < 0.7$   
Spin flavor decomposition  
“Test” of validity of factorization by checking if  $A_{1N}^{\pi^+ + \pi^-}$  equals the inclusive asymmetry,  $A_{1N}$ .

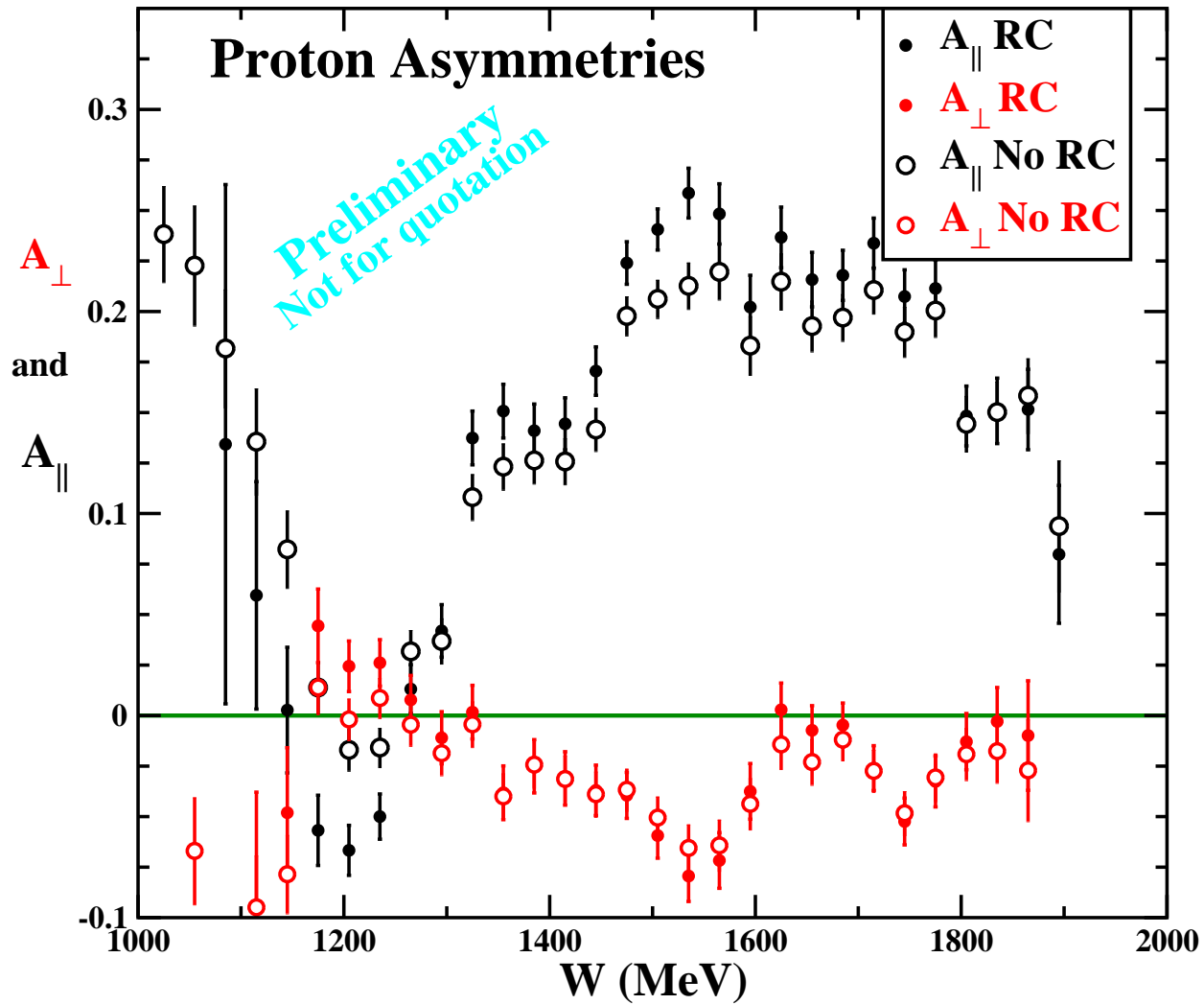
# Elastic contribution to $d_2$



# Sources of Systematic Error

	$^{15}\text{NH}_3$	$^{15}\text{ND}_3$
Nitrogen polarization	<1%	1%
Radiative corrections	2%	3%
Beam Polarization	1.5%	1.5%
Target polarization	2.5%	4%
Dilution factor	3%	3%
Pions, deadtime	1%	1%
Errors from R and F2	3%	3%
<hr/>		
Total error	5.5%	6.8%

# Compare proton $A_{\parallel}$ and $A_{\perp}$ w/o RC





$$A_1 = \frac{C}{D}(A_{\parallel} - dA_{\perp})$$

$$A_2 = \frac{C}{D}(c'A_{\parallel} - d'A_{\perp})$$

- **Kinematic variables**

$C, c', d, d'(E, E', \theta), D(E, E', \theta, R)(R = \sigma_L/\sigma_T)$

- $d' \approx 1, c' \approx d \leq 1$  ( at RSS kinematics)

- $g_1, g_2$  can be extracted directly from  $A_{\parallel}, A_{\perp}$  or  $A_1, A_2$

$$g_1 = \frac{F_1}{1 + \gamma^2} (A_1 + \gamma A_2)$$

$$g_2 = \frac{F_1}{1 + \gamma^2} \left( \frac{A_2}{\gamma} - A_1 \right); \quad \gamma^2 = \frac{Q^2}{\nu^2}$$

- Need  $F_1 = F_2(1 + \gamma^2)/2x/(1 + R)$  in the resonance region.  
Measurement of  $F_2$  and  $R$  in resonance region