

Overview of recent and future A_1^n measurements

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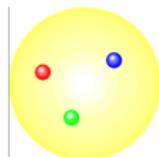
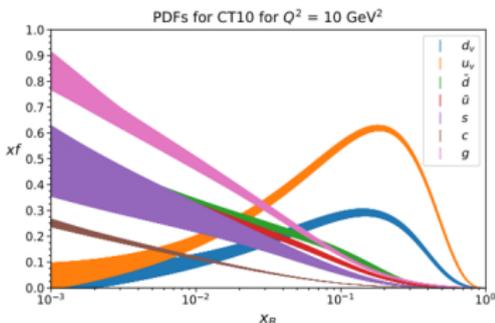
For the E12-06-011 Collaboration



- Introduction: Nucleon spin structure and A_1^n
- Jefferson Lab 12 GeV Hall C A_1^n experiment (E12-06-110) context
- Preliminary A_1^{3He} Results
- Radiative correction methodology and improved ^3He model
- Physics motivation for a 22 GeV A_1^n measurement
- Conclusions and Outlook

Nucleon Spin Structure and A_1^n

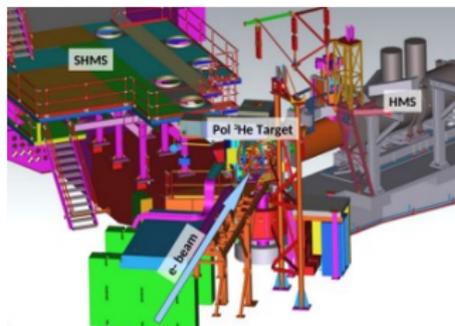
- The virtual-photon asymmetry $A_1(x, Q^2) = (\sigma_{1/2} - \sigma_{3/2}) / (\sigma_{1/2} + \sigma_{3/2})$ probes quark spin distributions in the nucleon.
- **At large Bjorken- x** , valence quarks dominate; A_1 measurements provide a clean test of nucleon spin structure models.
- Theoretical models (naive SU(6) quark model, relativistic quark models, pQCD) make distinct predictions for $A_1^n(x \rightarrow 1)$.
- **Previous JLab results (6 GeV era)**: A_1^n becomes positive near $x \sim 0.5$, but the down-quark polarization $\Delta d/d$ remained negative up to $x \approx 0.61$, in tension with simple pQCD expectations.



X

12 GeV Hall C A_1^n Experiment (E12-06-110)

- **Goal:** Measure neutron A_1^n up to $x \approx 0.75$ (DIS), extending the spin-structure data into the deep valence region.
- **Setup:** 10.4 GeV polarized electron beam on a high-pressure polarized ^3He gas target (effective neutron target).
 - **Beam polarization:** $\sim 85\%$
 - **Beam current:** $30 \mu\text{A}$
- **Spectrometers:** Hall C HMS and Super-HMS (SHMS) detected scattered electrons over a broad x , Q^2 range.
- **Asymmetries:** Measured longitudinal (A_{\parallel}) and transverse (A_{\perp}) double-spin asymmetries on ^3He , then computed $A_1^{^3\text{He}}$ and $A_2^{^3\text{He}}$.

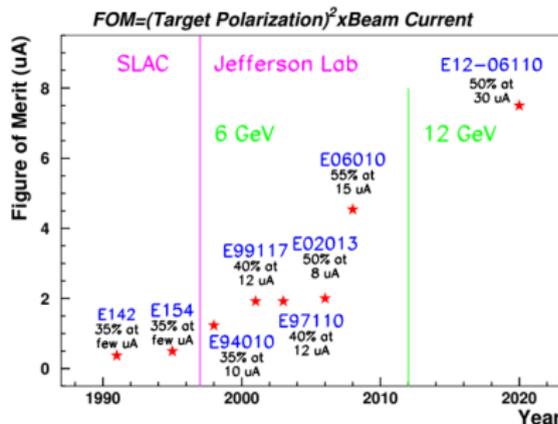
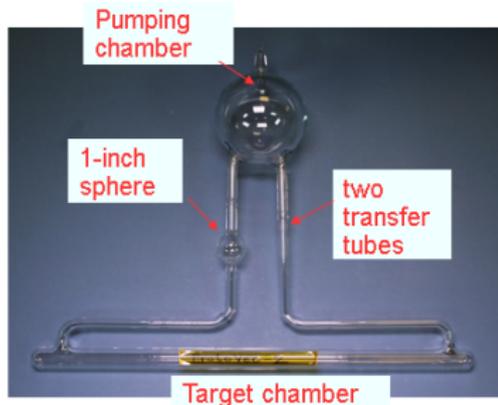


Kine	Spec	E_b GeV	E_p GeV	θ ($^\circ$)	beam time (hours)
$\Delta(1232)$	SHMS	2.17	-1.79736	8.5	4.0
Elastic	SHMS	2.17	-2.12860	8.5	8.0

Kine	Spec	E_b GeV	E_p GeV	θ ($^\circ$)	e^- production (hours)	e^+ prod. (hours)	Tot. Time (hours)
DIS							
3	HMS	10.38	2.90	30.0	88.0	0.0	88.0
4	HMS	10.38	3.50	30.0	511.0	0.0	511.0
B	SHMS	10.38	3.40	30.0	511.0	4.0	515.0
C	SHMS	10.38	2.60	30.0	88.0	4.0	92.0

Polarized ^3He as an Effective Neutron Target

- Polarized ^3He is widely used as an effective polarized neutron target.
- Effective nucleon polarizations in ^3He (from nuclear wavefunctions):
 $P_n \approx 0.86$ for the neutron, $P_p \approx -0.03$ for a proton.
- Nuclear corrections (e.g., FSI, Δ -isobar admixtures) are relatively small for inclusive spin structure but are quantified in extraction formulas.
- The upgraded Hall C polarized ^3He target achieved **over 50% in-beam polarization** with a $30 \mu\text{A}$ current in the 12 GeV run, enabling high statistical precision.



Measured $A_1^{3\text{He}}$ Asymmetries

- We collected A_{\parallel} and A_{\perp} on ^3He across bins in x (with $W > 2 \text{ GeV}$ to ensure DIS).
- The ratio $g_1^{3\text{He}}/F_1^{3\text{He}}$ is formed directly from measured asymmetries:

$$\frac{g_1^{3\text{He}}(x, Q^2)}{F_1^{3\text{He}}(x, Q^2)} = \frac{1}{D(1 + \gamma^2)} [A_{\parallel}^{3\text{He}}(x, Q^2) + \tan(\frac{\theta}{2}) A_{\perp}^{3\text{He}}(x, Q^2)]$$

$$\gamma = \frac{2Mx}{\sqrt{Q^2}}, \quad D = \frac{1 - (1 - y)\epsilon}{1 + \epsilon R} \approx y, \quad \epsilon = \left(1 + 2(1 + \gamma^2) \tan^2 \frac{\theta}{2}\right)^{-1}$$

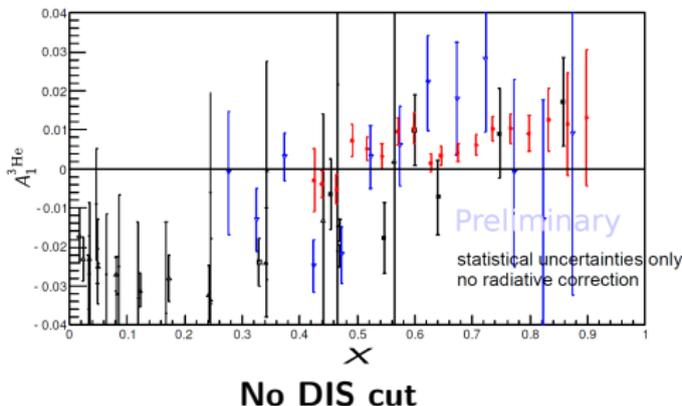
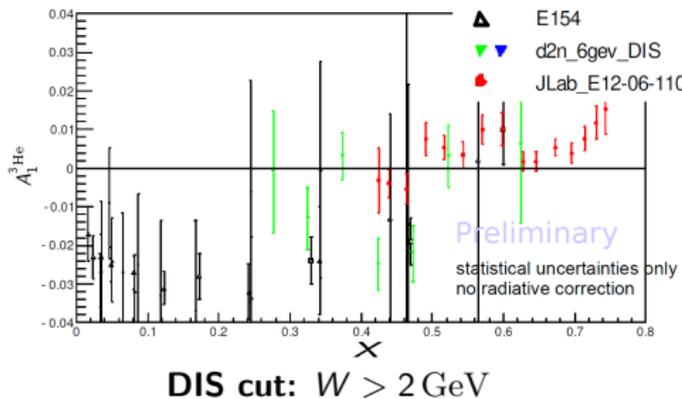
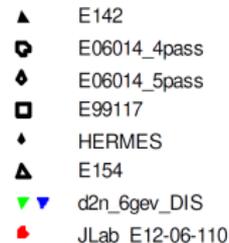
- M is the nucleon mass, θ the scattering angle, E' the scattered energy.
- $R = \sigma_L/\sigma_T$ is the longitudinal-to-transverse cross-section ratio.
- D is the depolarization factor converting virtual-photon to electron asymmetries.
- These ^3He asymmetries serve as input for extracting A_1^n by **accounting for proton contributions and nuclear spin structure.**

Preliminary $A_1^{3\text{He}}$ Results

- The neutron asymmetry A_1^n is extracted from $A_1^{3\text{He}}$ using effective polarization factors.

$$A_1^n = \frac{1}{P_n} \frac{F_2^{3\text{He}}}{F_2^n} \left(A_1^{3\text{He}} - 2 P_p \frac{F_2^p}{F_2^{3\text{He}}} A_1^p \right)$$

- This method uses measured (or fitted) A_1^p for the proton and known P_n, P_p to solve for the neutron contribution.

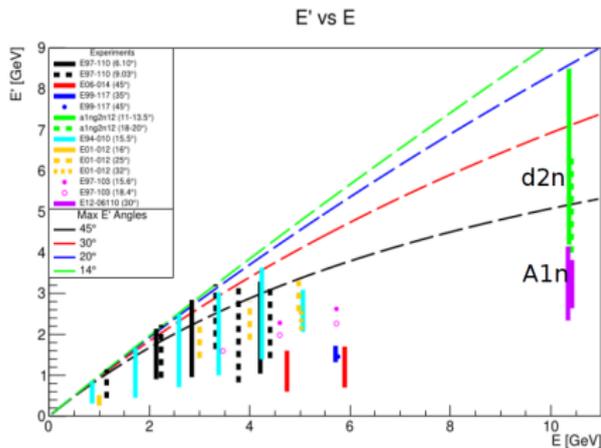


Radiative Corrections: Overview

- Measured spin asymmetries must be corrected for QED radiative effects (internal bremsstrahlung, vertex/self-energy, and external bremsstrahlung) to obtain true Born asymmetries.
- Radiative processes affect both polarized (numerator) and unpolarized (denominator) cross-sections, so the correction mixes g_1, g_2 with F_1, F_2 .
- Typically, one computes a radiative correction factor $(1 + \delta)$ such that $A_1^{\text{Born}} = A_1^{\text{meas}} / (1 + \delta)$, where δ is obtained by convolving radiator functions with structure functions.
- **Accurate radiative correction is crucial at high x** , where small shifts in asymmetry (few percent) can have large impact on physics conclusions.

Structure of Radiative Correction Calculation

- The radiative correction is calculated by integrating over the energy-loss spectrum: essentially a convolution of QED radiator functions with the target structure functions (unpolarized $F_{1,2}^{3\text{He}}$ and polarized $g_{1,2}^{3\text{He}}$).
- This requires a model of the ^3He structure functions for **all relevant x and Q^2** ; including contributions outside the measured kinematics due to radiation.
- **Output:** Correction factors applied to each kinematic bin's asymmetry. We typically iterate until the Born and measured asymmetries converge under the correction.



(Figure by Carter Hedinger)

Radiative Correction Challenges for ^3He

- Mixed nuclear content: Radiative tails involve both neutron and proton scattering within ^3He . **The relative proton/neutron contributions must be accurately modeled.**
- Uncertainties in $g_2^{^3\text{He}}$: Often g_2 is not directly measured; models (Wandzura-Wilczek) or data-driven fits are used, contributing systematic uncertainty.
- External radiation: The ^3He glass cell windows and walls cause energy loss.
- At large x , **even a few-percent uncertainty in the RC can shift the small asymmetry noticeably**, so precision in RC modeling is essential.

Custom ^3He Structure Function Fit

- We parameterize $g_1^{^3\text{He}}/F_1^{^3\text{He}}$ with flexible functional forms, constrained by existing polarized data on ^3He and theoretical expectations.
- Inputs for the fit include [world data on polarized \$^3\text{He}\$](#) (from SLAC, HERMES, JLab 6 GeV and 12 GeV)
- The fit reproduces measured $A_1^{^3\text{He}}$ (through g_1/F_1) in the kinematic range of interest and extrapolates smoothly to higher x and Q^2 .
- Our fit provides $g_1^{^3\text{He}}$ and, via Wandzura-Wilczek, $g_2^{^3\text{He}}$ as continuous functions for **all required kinematics** in the radiative correction.

- From [Xiaochao Zheng's thesis](#) (table F.1) for the neutron:

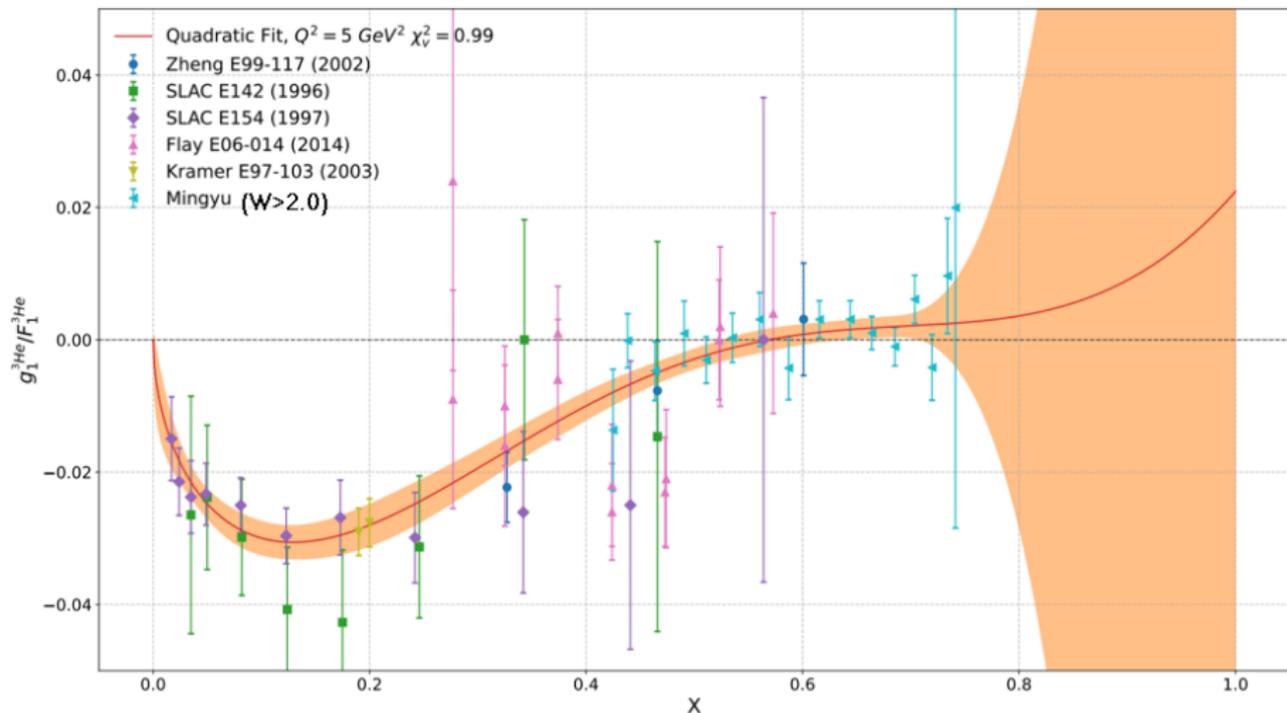
$$f_{XZ}(x, Q^2) = x^\alpha \cdot (a + bx + cx^2) \cdot \left(1 + \frac{\beta}{Q^2}\right)$$

- New fit using modified functional form:

$$f_{mXZ}(x, Q^2) = x^\alpha \cdot \left(a + bx + cx^2 + d e^{\left(\frac{x-x_0}{2\sigma}\right)^2}\right) \cdot \left(1 + \frac{\beta}{Q^2}\right)$$

x_0 = center of the low x dip in the data, σ = width of the the low x dip.

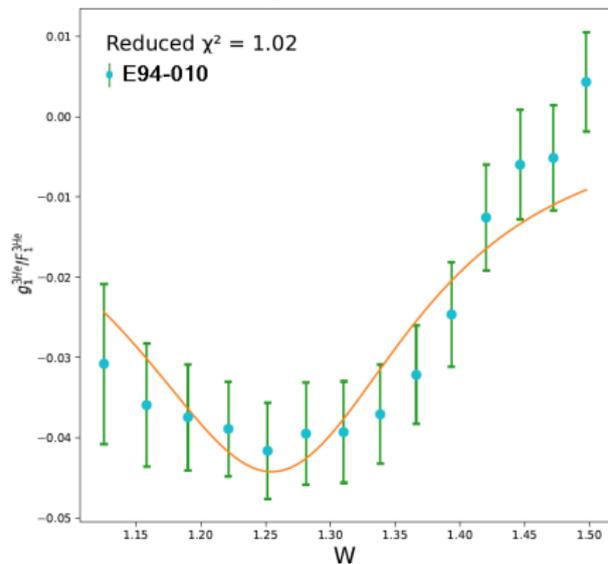
DIS Fit



Resonance Fitting

- Fit g_1/F_1 $\Delta(1232)$ resonance peaks with Breit–Wigner distribution
- Change Breit–Wigner so k' represents the actual peak height and refit $\Delta(1232)$

$$Q^2 = 0.740$$



$$f(E) = \frac{k'}{(E^2 - M^2) + M^2 \Gamma^2}$$

$$k' = k \cdot M^2 \cdot \Gamma^2$$

$$M = M_{\Delta(1232)}$$

Resonance Parameter Q^2 Dependence

$$\Gamma(Q^2) = U_{\text{nucl}} \cdot \left[\frac{a}{(1 + Q^2/b)^c} \right],$$

$$M(Q^2) = U_{\text{nucl}} \cdot [1.232 - a \cdot e^{-Q^2/b}],$$

$$U_{\text{nucl}} = \frac{0.7}{1.0 + \exp(\frac{Q^2 - 1.7}{0.3})}.$$

- Parameterized using differential evolution best1bin method

$$L(x) = f + e x,$$

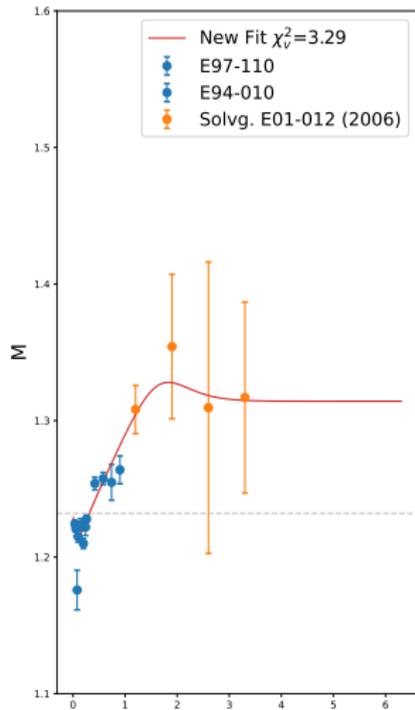
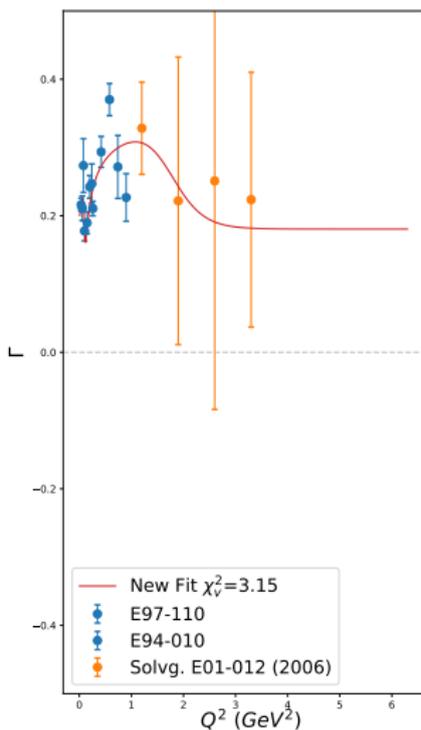
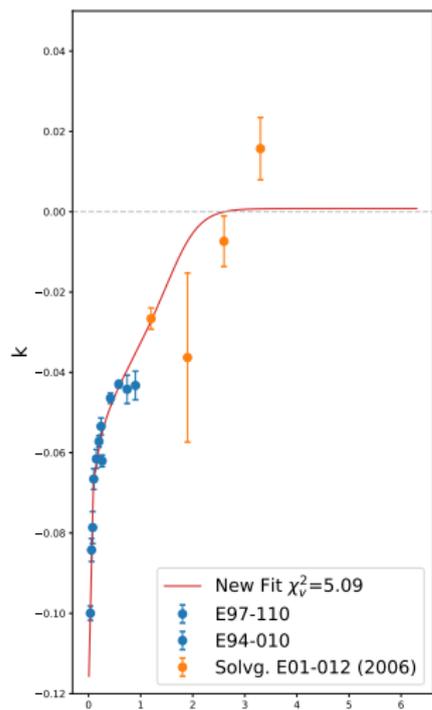
$$N(x) = -a \exp(-x/b) + \frac{c}{x},$$

$$s(x) = \frac{1}{1 + \exp[-k(x - x_0)]},$$

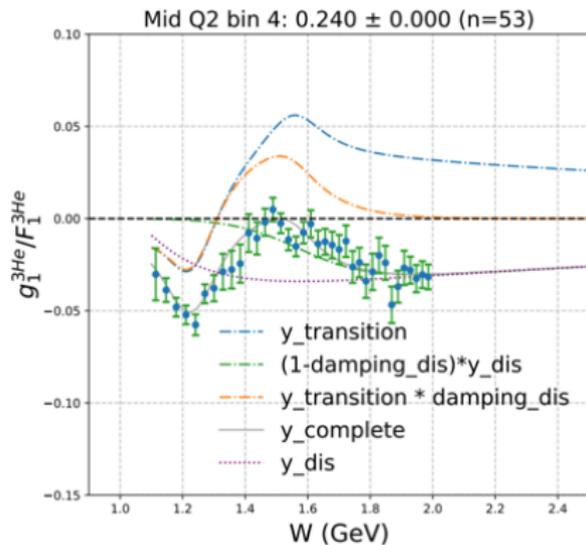
$$k(x) = U_{\text{nucl}} [1 - s(x)] L(x) + s(x) N(x).$$

- $Q^2 \leq 0.1$: strictly linear ($L(x)$)
- Transition with Sigmoid-based smooth step function ($s(x)$) to exponential ($N(x)$)
- As Q^2 increases, bounds constrained fit to approach zero
- Multiple fits for k were tested with little change to end RC results

Fit 0506



Transition region: Resonance to DIS

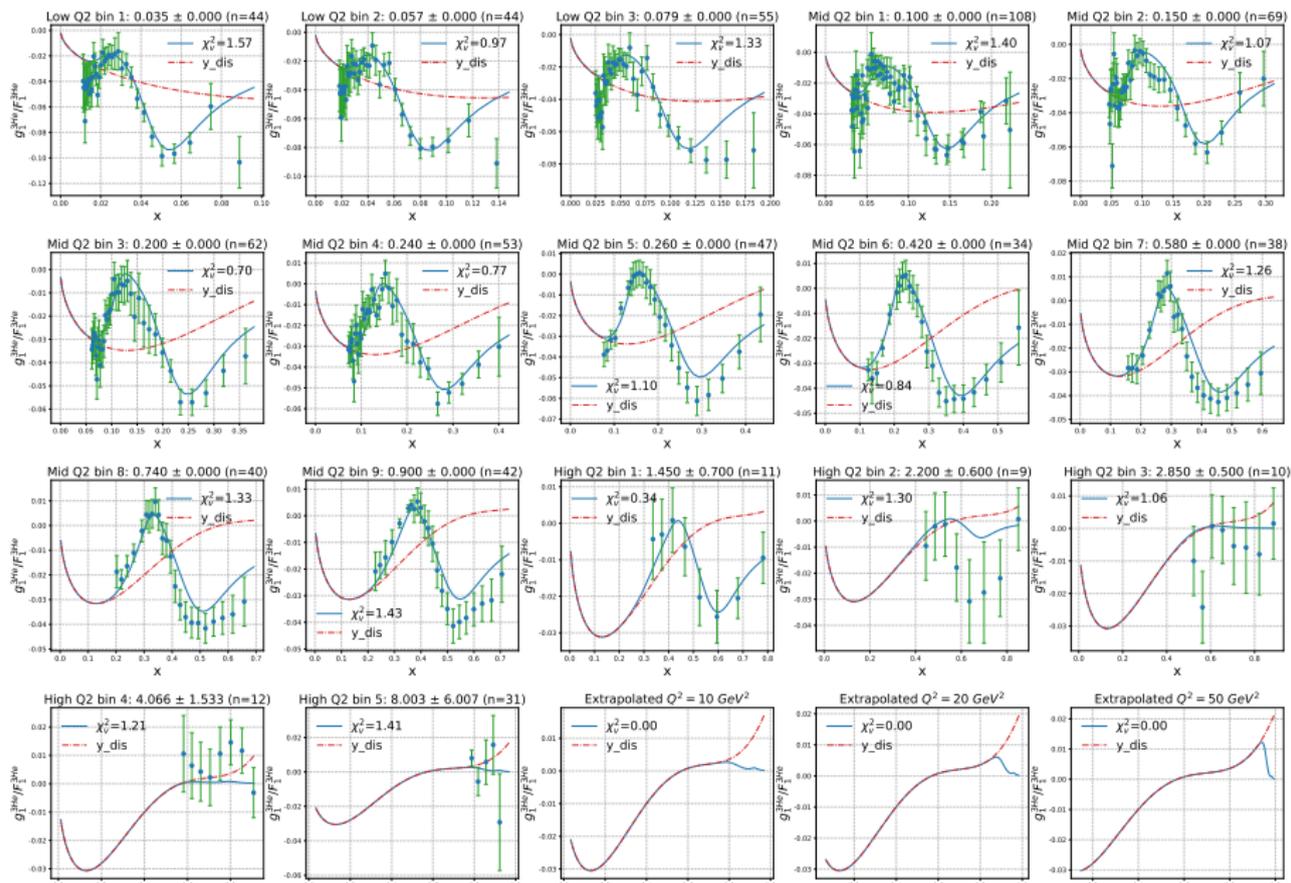


$$y_{\text{transition}} = y_{\text{BW, bump}} + (y_{\text{BW, res}} - y_{\text{DIS}}),$$

$$y_{\text{complete}} = y_{\text{transition}} D_{\text{transition}} + y_{\text{DIS}},$$

$$D_{\text{transition}} = \frac{1.0}{1.0 + \exp\left(\frac{W - W_{\text{transition}}}{\text{width}}\right)}$$

g_1/F_1 vs x_{bj}



- **New QE model:** Updated quasi-elastic cross-section model for inclusive scattering; improved prediction of the QE peak and tail shapes.

- **Elastic nucleon contributions:**

$$\tau = \frac{Q^2}{4M^2}$$

$$F_1^{N(\text{el})}(Q^2) = \left[\frac{1}{2} G_{MN}^2(Q^2) \right] \delta(1-x),$$

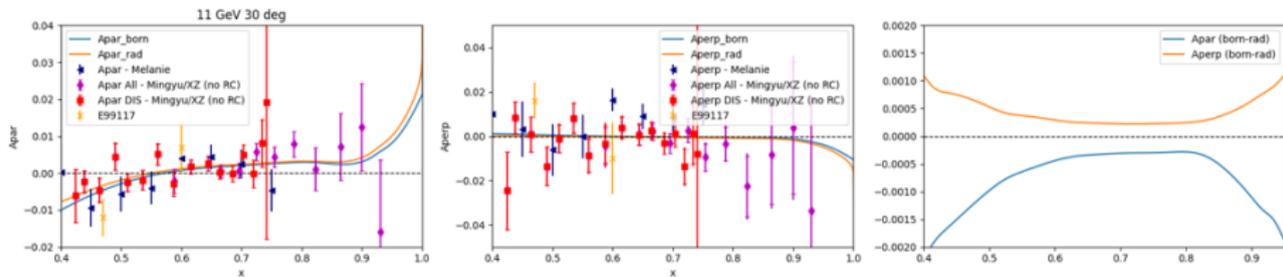
$$F_2^{N(\text{el})}(Q^2) = \left[\frac{G_{EN}^2(Q^2) + \tau G_{MN}^2(Q^2)}{1 + \tau} \right] \delta(1-x).$$

$$g_1^{(\text{el})}(x, Q^2) = \frac{1}{2(1 + \tau)} G_M(Q^2) [G_E(Q^2) + \tau G_M(Q^2)] \delta(x-1),$$

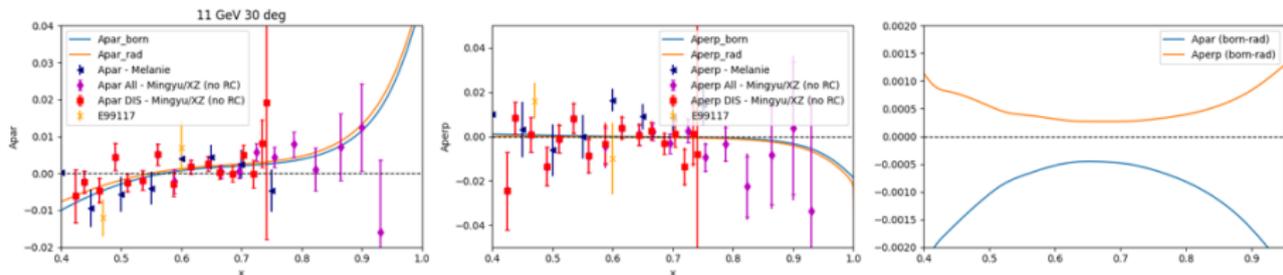
$$g_2^{(\text{el})}(x, Q^2) = \frac{\tau}{2(1 + \tau)} G_M(Q^2) [G_E(Q^2) - G_M(Q^2)] \delta(x-1).$$

- **F1F221:** Specialized fit of ^3He structure functions (F_1 , F_2) used as input in radiative corrections at moderate Q^2 .
- Global fit of g_1/F_1 for ^3He (combined inelastic + elastic contributions).

Radiative Corrections



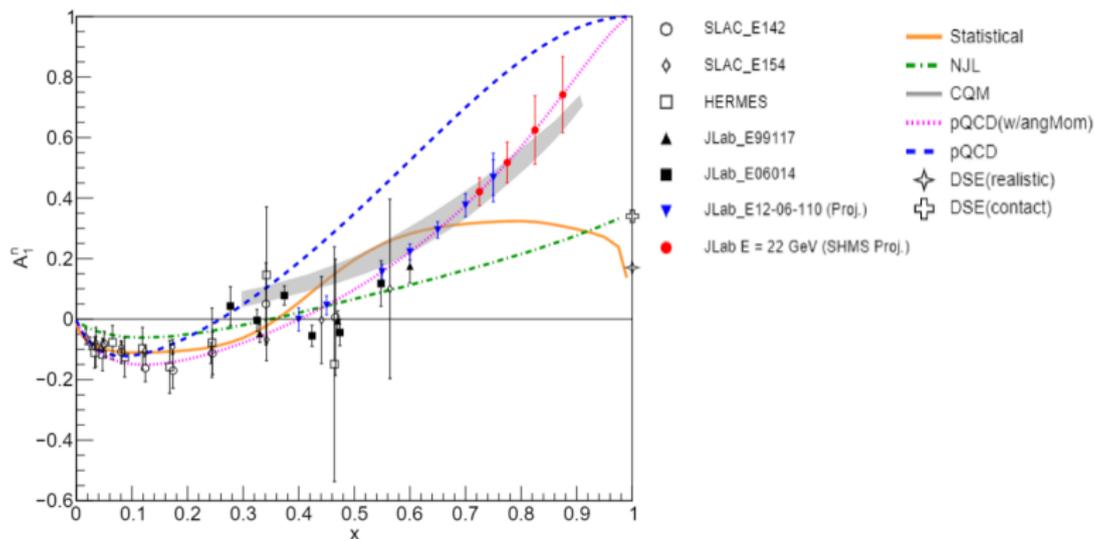
SF1+G1F1 complete 0506 fit



SF1+G1F1 DIS 0506 fit

- A 22 GeV CEBAF upgrade would extend the A_1^n measurement into the region $x > 0.75$ (up to ≈ 0.90).
- This kinematic reach tests fundamental QCD predictions: for example, pQCD (hadron helicity conservation) suggests $A_1^n \rightarrow 1$ as $x \rightarrow 1$, whereas models with orbital motion delay this rise.
- High- x data determine whether $\Delta d/d$ becomes positive at extreme x , resolving puzzles from 6/12 GeV data.
- It also solidifies the polarized valence PDF knowledge: combining precise A_1^n and A_1^p up to $x \sim 0.9$ tightly constrains $\Delta u(x)$, $\Delta d(x)$ near 1.

- Inclusive DIS measurement of A_1^n at 22 GeV in Hall C using the polarized ^3He target and HMS+SHMS spectrometers.
- **Kinematics:** With 22 GeV beam, scattering at moderate angles (few degrees) can reach $x \approx 0.9$ at $Q^2 \sim 6 - 10 \text{ GeV}^2$.



(Studies by Cameron Cotton)

Conclusion and Outlook

- Radiative corrections are critical for reliable extraction of A_1^n from polarized ^3He measurements.
- We developed a **custom ^3He structure function fit** approach to improve the accuracy of these corrections.
- The Hall C 12 GeV A_1^n experiment (E12-06-110) will extend our knowledge of neutron spin structure to $x \approx 0.75$ (gaining insight on $\Delta d/d$).
- **A_1^n finishing analysis, results coming soon!**
- A future 22 GeV A_1^n measurement would push into the **extreme valence region** ($x > 0.75$), providing a crucial test of QCD spin predictions.
- These efforts place our work within the broader Jefferson Lab spin structure program, advancing both experimental techniques and our understanding of nucleon spin.

Acknowledgments

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- [Hall C 12 GeV A1n/d2n Collaboration](#)
- **PhD Theses:** M. Chen, M. L. Cardona
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Extra

Extracting the d_2^n Moment

- Once A_1^n (or g_1^n) is determined, one can compute higher moments like the twist-3 d_2^n defined by $d_2^n = \int_0^1 x^2 [2g_1^n(x) + 3g_2^n(x)] dx$.
- The d_2^n moment probes quark-gluon correlations inside the neutron (“color Lorentz forces”) and provides an important test of non-perturbative QCD models.

Summary of Radiative Correction Advances

- We implemented a tailored ^3He structure function model into the radiative correction for A_1^n analysis.
- This addresses nuclear effects systematically, reducing reliance on separate smearing of nucleon fits.
- Preliminary studies show that the custom RC produces stable correction factors and shifts the final A_1^n by only a few percent relative to standard methods.
- Such refined radiative corrections are essential for achieving the final precision goals of the 12 GeV A_1^n results and for interpreting them correctly.

Context in Jefferson Lab Spin Program

- The 12 GeV Hall C A_1^n data complement other measurements: A_1^p (CLAS12), A_1^n in Hall A/SoLID, g_2^n , SIDIS (TMDs) and more.
- Together they build a comprehensive picture of the nucleon spin decomposition, especially in the valence region where JLab has unique reach.
- Our work on radiative corrections and ^3He fits supports this broader effort by ensuring the neutron data are as accurate as possible.
- Looking ahead, the proposed 22 GeV A_1^n (with Hall C/SoLID) will extend this program to unprecedented kinematics, testing fundamental QCD.

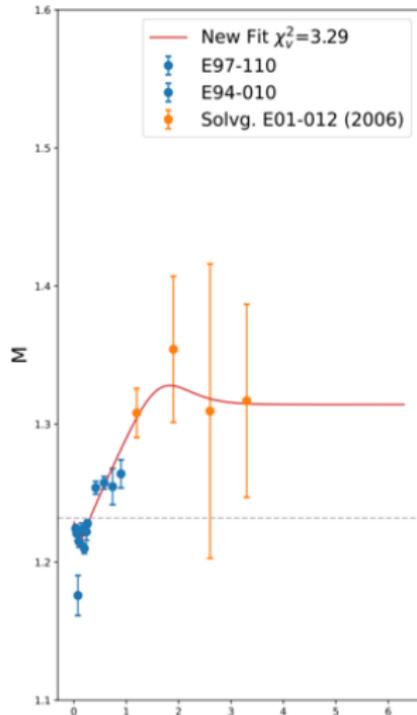
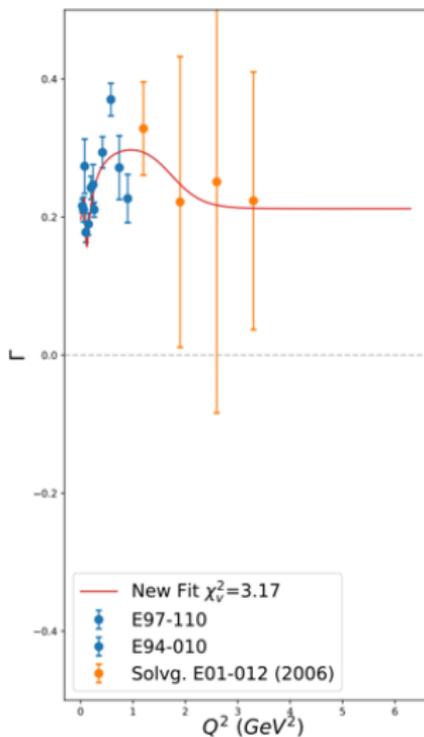
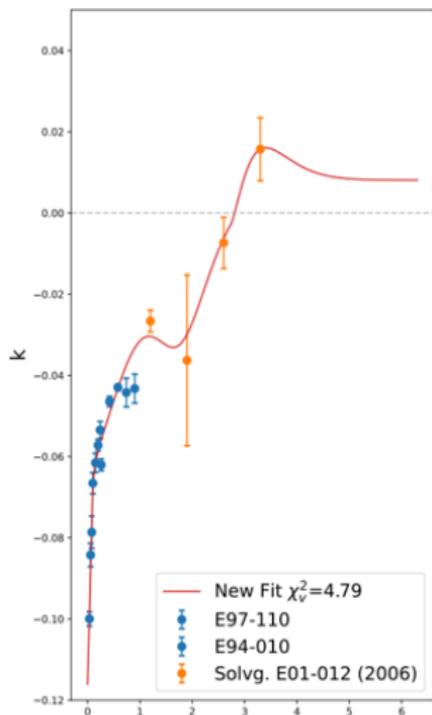
$$w_s(x) = \min\left(\max\left(\frac{x - 2.75}{5.0 - 2.75}, 0\right), 1\right),$$

$$\theta(x) = \begin{cases} 0, & x \leq 2.75, \\ \frac{\pi/2}{5.0 - 2.75} (x - 2.75), & 2.75 < x \leq 5.0, \\ \frac{\pi - (\pi/2)}{9.0 - 5.0} (x - 5.0) + \frac{\pi}{2}, & 5.0 < x \leq 9.0, \\ \pi, & x > 9.0, \end{cases}$$

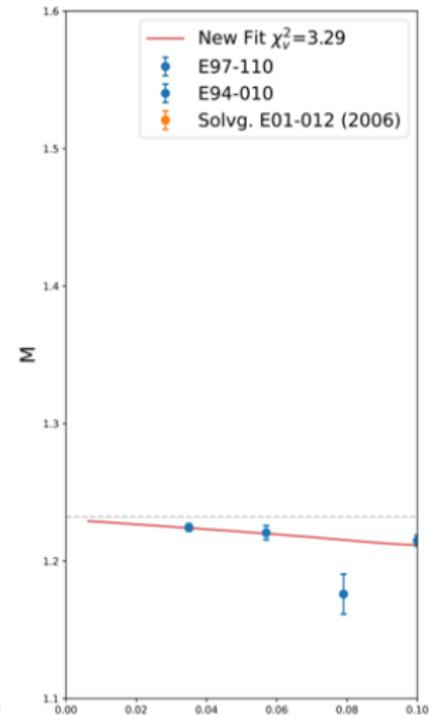
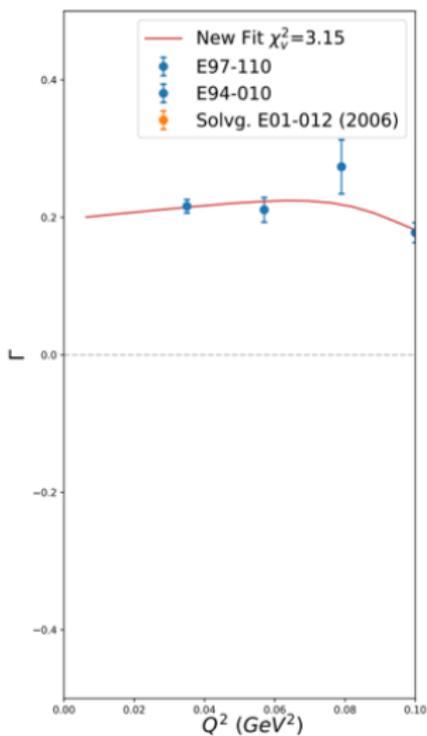
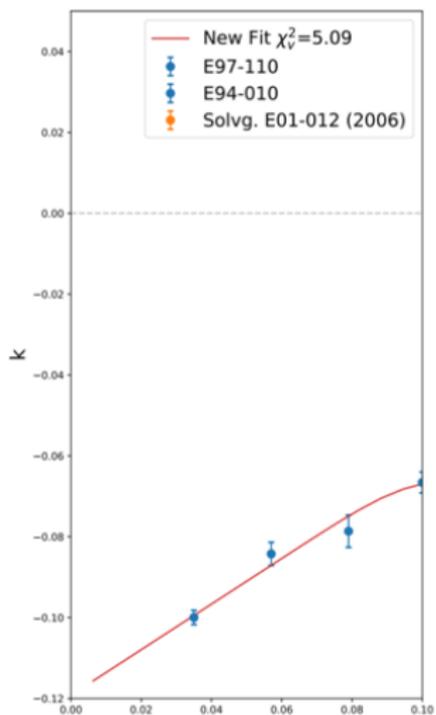
$$k(x) = U_{\text{nucl}} \times \begin{cases} f + e x, & x \leq 0.1, \\ (1 - w(x)) (f + e x) + w(x) \left(a + \frac{c}{x}\right) \exp(-x/d), & 0.1 < x \leq 2.75, \\ \left(a + \frac{c}{x}\right) \exp(-x/d) + w_s(x) [b \sin(\theta(x))], & x > 2.75, \end{cases}$$

$$w(x) = \frac{x - 0.1}{2.75 - 0.1}.$$

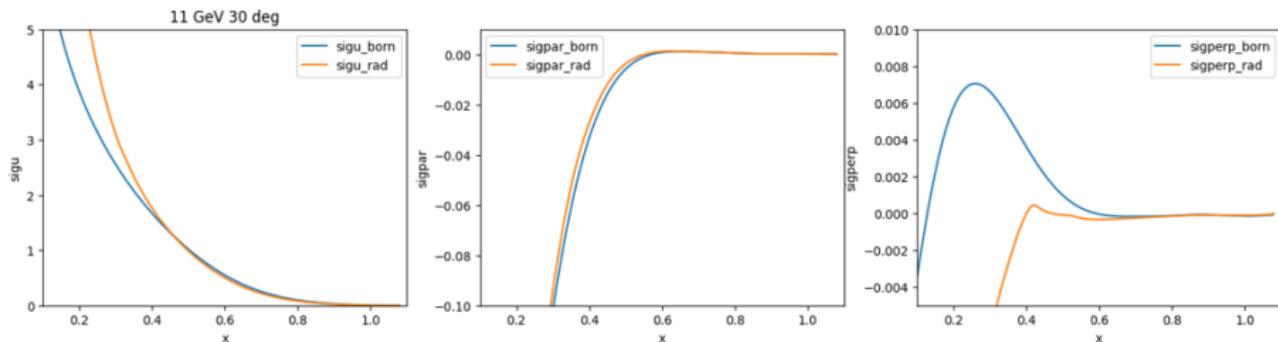
Resonance Fit 0506-ktune for k



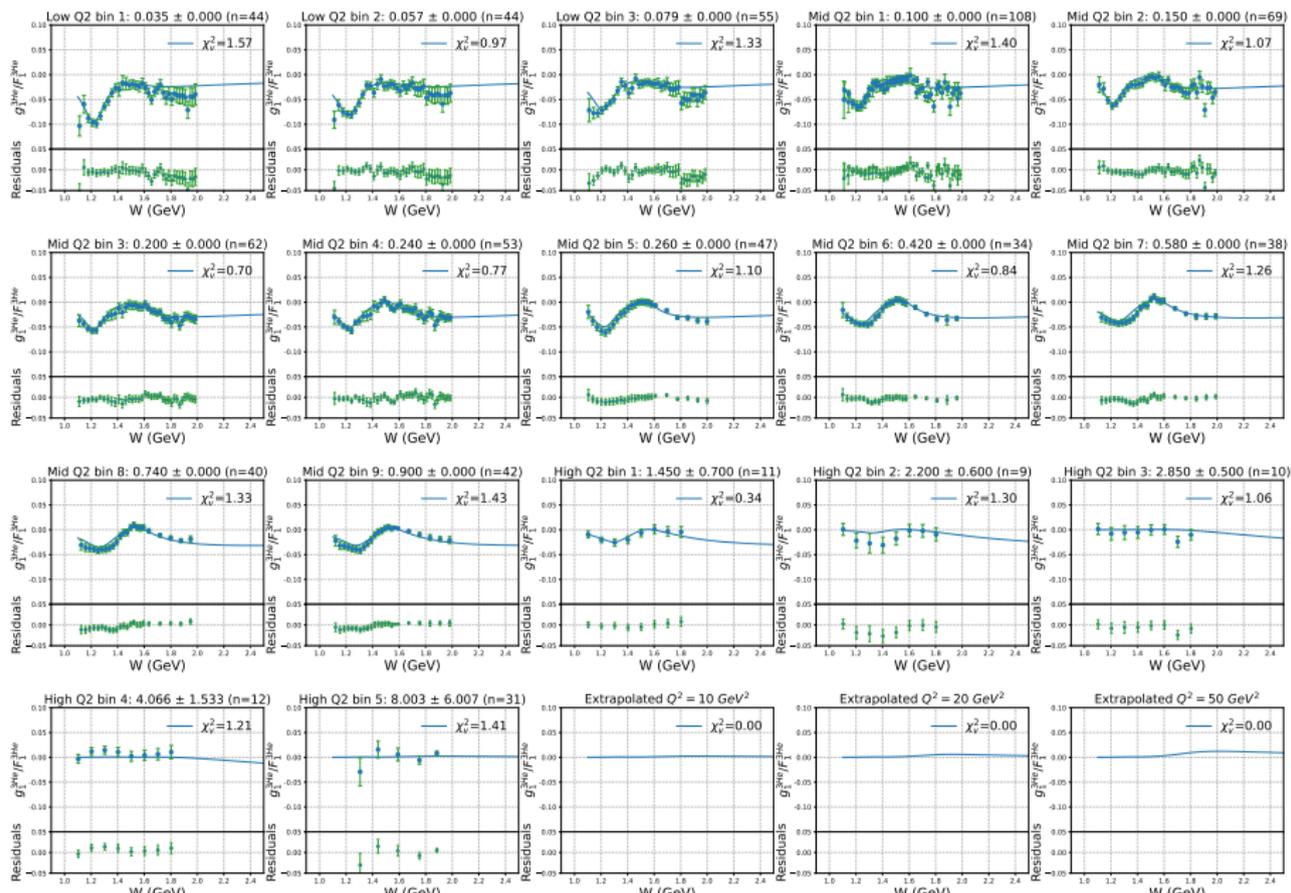
Fit 0506 Small Q^2



- **Fit 0506:** Primary new global fit using the latest QE model and RC updates as default configuration.



g_1/F_1 vs W



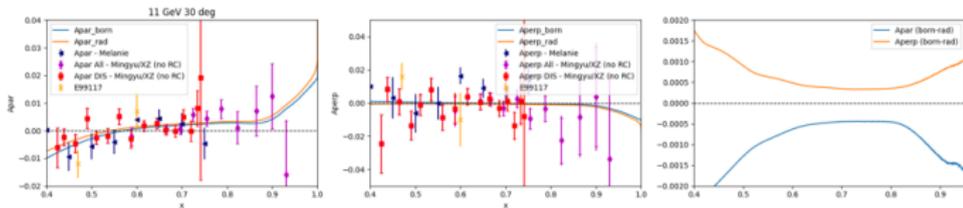
Radiative Correction Methods

- **Standard inclusive RC** (Mo–Tsai formalism) applied with the updated cross-section models (QE, resonance, DIS channels).
- QE-specific updates: use comparison with data for fine tuning.
- Improvements in binning, target material treatment, and inclusion of resonance/DIS tails in subsequent updates.
- Iterative procedure: apply RC to data, update input g_1/F_1 , and repeat until convergence.

Radiative Correction Comparisons (QE Variations)

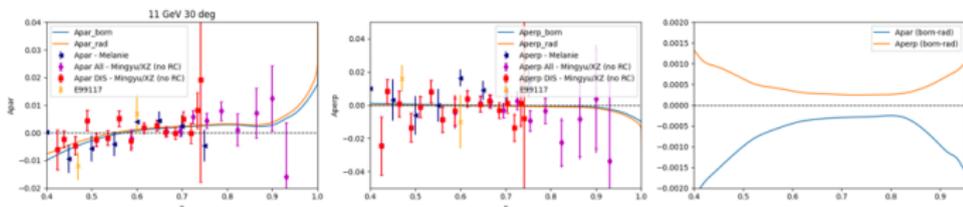
SF1

G1F1cmplt
0506
bound2
noQEg2WW
15Eb QEBA
(131)



SF1

G1F1cmplt
0506
bound2
noQEg2WW
15Eb QE95
(141)



SF1

G1F1cmplt
0506
bound2
noQEg2WW
15Eb QE86
(151)

