A Precision Measurement of d_2^n: Probing Color Forces

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for the E06-014 Collaboration

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Outline

1. Physics Motivation
2. Experimental Setup
3. Analysis
4. Results
5. Summary and Current Status

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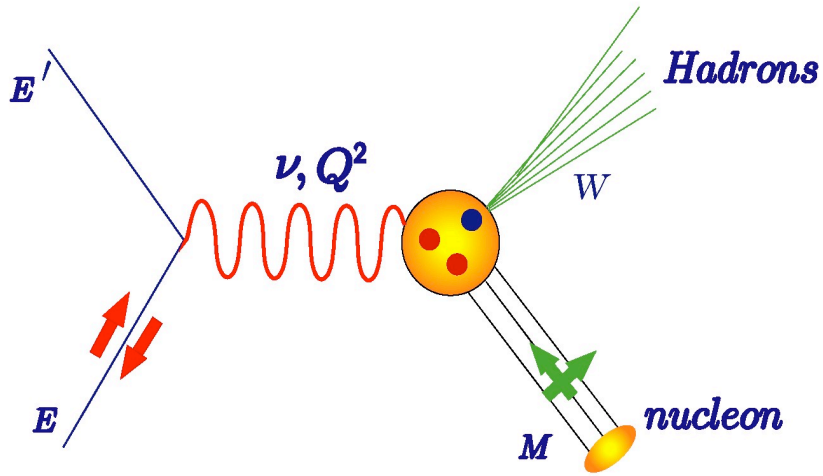
Polarized DIS

- Longitudinally polarized electrons
- Longitudinally/Transversely polarized nucleon
- Probes the spin content of the nucleon
- We measure scattering electron's cross-sections and asymmetries



Double Spin Asymmetries

$$A_{\parallel} = \frac{N^{\downarrow,\Uparrow} - N^{\uparrow,\Uparrow}}{N^{\downarrow,\Uparrow} + N^{\uparrow,\Uparrow}} \quad A_{\perp} = \frac{N^{\downarrow,\Rightarrow} - N^{\uparrow,\Rightarrow}}{N^{\downarrow,\Rightarrow} + N^{\uparrow,\Rightarrow}}$$

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Spin Structure Functions

- $A_\parallel$, $A_\perp$, and σ_0 used to evaluate g_1 and g_2
- With $y = \nu/E$

Spin Structure Functions

$$g_1 = \frac{MQ^2}{4\alpha^2}\frac{2y}{(1-y)(2-y)}\sigma_0\left[A_\parallel + \tan(\theta/2)\,A_\perp\right]$$

$$g_2 = \frac{MQ^2}{4\alpha^2}\frac{y^2}{(1-y)(2-y)}\sigma_0\left[-A_\parallel + \frac{1+(1-y)\cos\theta}{(1-y)\sin\theta}A_\perp\right]$$

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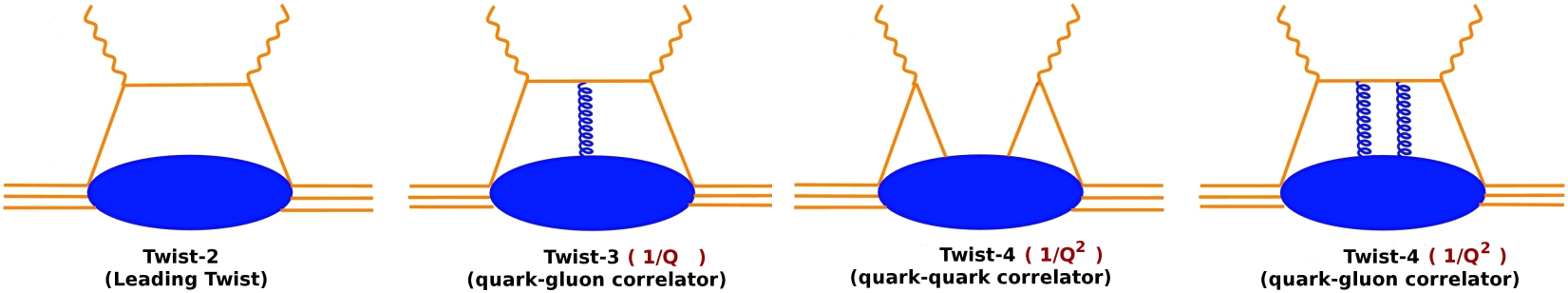
Twist

- Twist = operator dimension - spin

$$d_2 \propto \langle qGq \rangle = \text{twist-3}$$
$$f_2 \propto \langle qGGq \rangle \text{ or } \langle qqqq \rangle = \text{twist-4}$$

	q	G
Dimension	3/2	2
Spin	1/2	1
Twist	1	1



g_1 Spin Structure Function

- Leading twist is twist-2

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- Described in parton model interpretation as being probability of striking a polarized quark

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- Described in parton model interpretation as being probability of striking a polarized quark
- Operator product expansion used to reveal higher (suppressed) twist contributions

g_1 Twist Expansion

$$\Gamma_1 \equiv \int_0^1 g_1 dx = \mu_2 + \frac{\mu_4}{Q^2} + \frac{\mu_6}{Q^4} + ...$$

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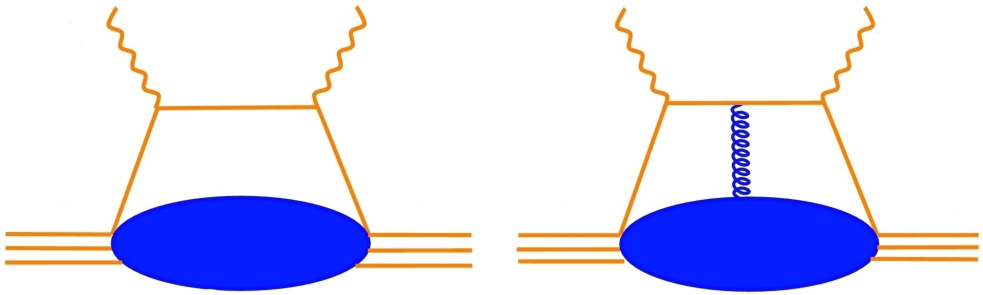
g_2 Spin Structure Function

- Has no simple parton model interpretation
- Contains higher twist contribution at leading order (no suppression!)
- Allows for *clean* probe of quark-gluon correlations



(quark-gluon correlator)

[1] S. Wandzura and F. Wilczeck Phys. Lett. B 72,1977.

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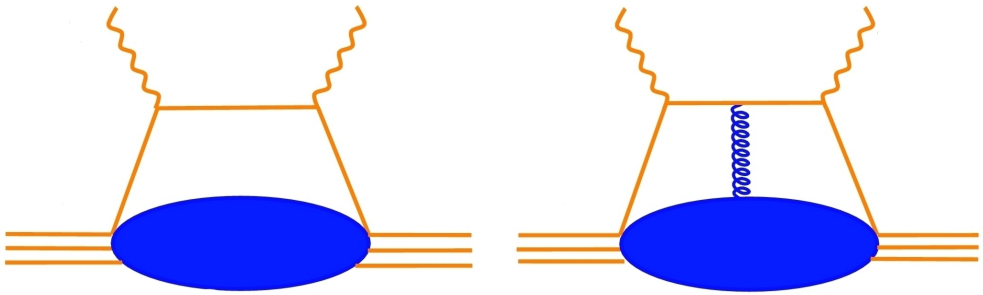

(quark-gluon correlator)

- At leading order g_2 can be separated into g_1 like and quark-gluon contributions
- $g_2\left(x,Q^2\right) = g_2^{WW}\left(x,Q^2\right) + \bar{g_2}\left(x,Q^2\right)$

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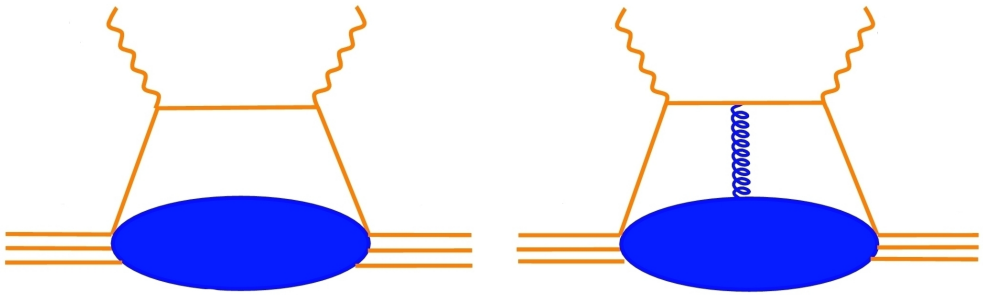

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- $g_2^{WW}\left(x,Q^2\right) = -g_1\left(x,Q^2\right) + \int_x^1 \frac{dy}{y} g_1\left(y,Q^2\right)$ (Wandzura-Wilczeck relation[1])
- $\bar{g_2}\left(x,Q^2\right) = -\int_x^1 \frac{dy}{y}\frac{d}{dy}\left[\frac{m}{M}h_T\left(y,Q^2\right) + \xi\left(y,Q^2\right)\right]$

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d_2

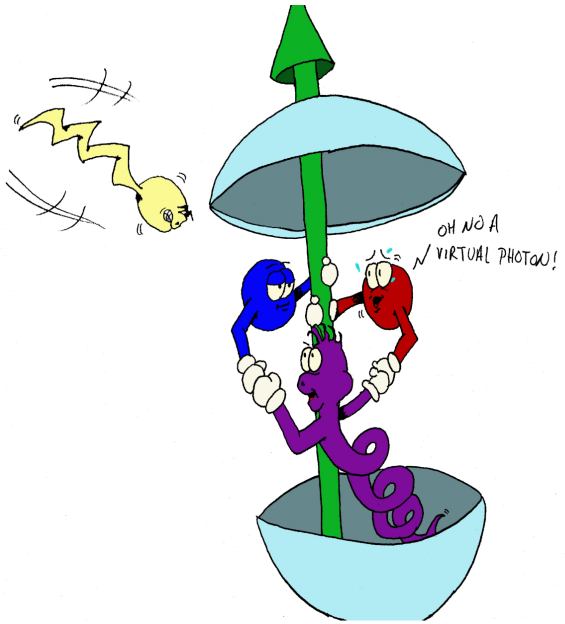
Accessing Quark-Gluon Correlations

- Quark-gluon correlations can be accessed through the quantity d_2
- d_2 can be evaluated through g_1 and g_2

d_2

$$d_2(Q^2) = 3\int_0^1 x^2 \bar{g}_2(x,Q^2)\,dx = \int_0^1 x^2\left[3g_2(x,Q^2) + 2g_1(x,Q^2)\right]dx$$

d_2
A Simplistic Approach



- Consider a polarized nucleon (only two quarks in the cartoon) and a virtual photon

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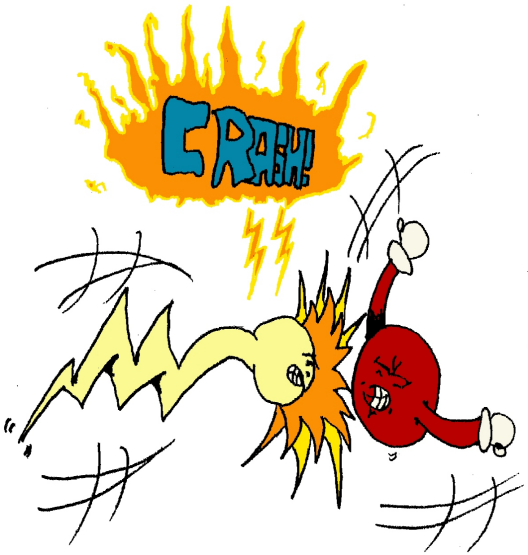
A Simplistic Approach



- virtual photon probes the nucleon and strikes a quark

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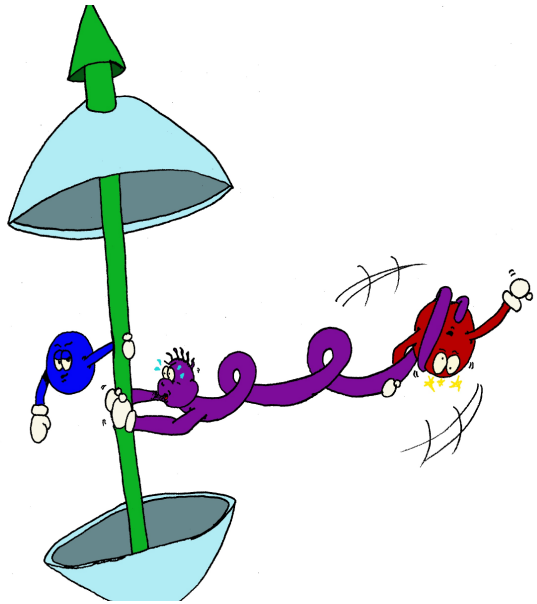

- d_2 is the average transverse force acting on the struck quark immediately after being struck by a virtual photon[2]

[2] M. Burkardt. Phys. Rev. D 88, 114502 (2013)

d_2
The Lorentz Color Force

- Consider charge e moving near speed of light ($\vec{v} = (0, 0, -1)$) along the $-\hat{z}$ direction

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The Lorentz Color Force

- Consider charge e moving near speed of light ($\vec{v} = (0, 0, -1)$) along the $-\hat{z}$ direction
  - Electro-magnetic Lorentz force:

$$\begin{aligned} F^y &= e\left[\vec{E} + \vec{v} \times \vec{B}\right]^y \\ &= e\left(E^y - B^x\right) = -e\sqrt{2}F^{+y} \end{aligned}$$

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- Color Lorentz force:

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- Where B and E are the color magnetic and electric fields[3]
- Can calculate color forces through d_2 and twist-4 matrix element f_2[4]

$$F_E = -\frac{M^2}{6}(2d_2 + f_2) \qquad F_B = -\frac{M^2}{6}(4d_2 - f_2)$$

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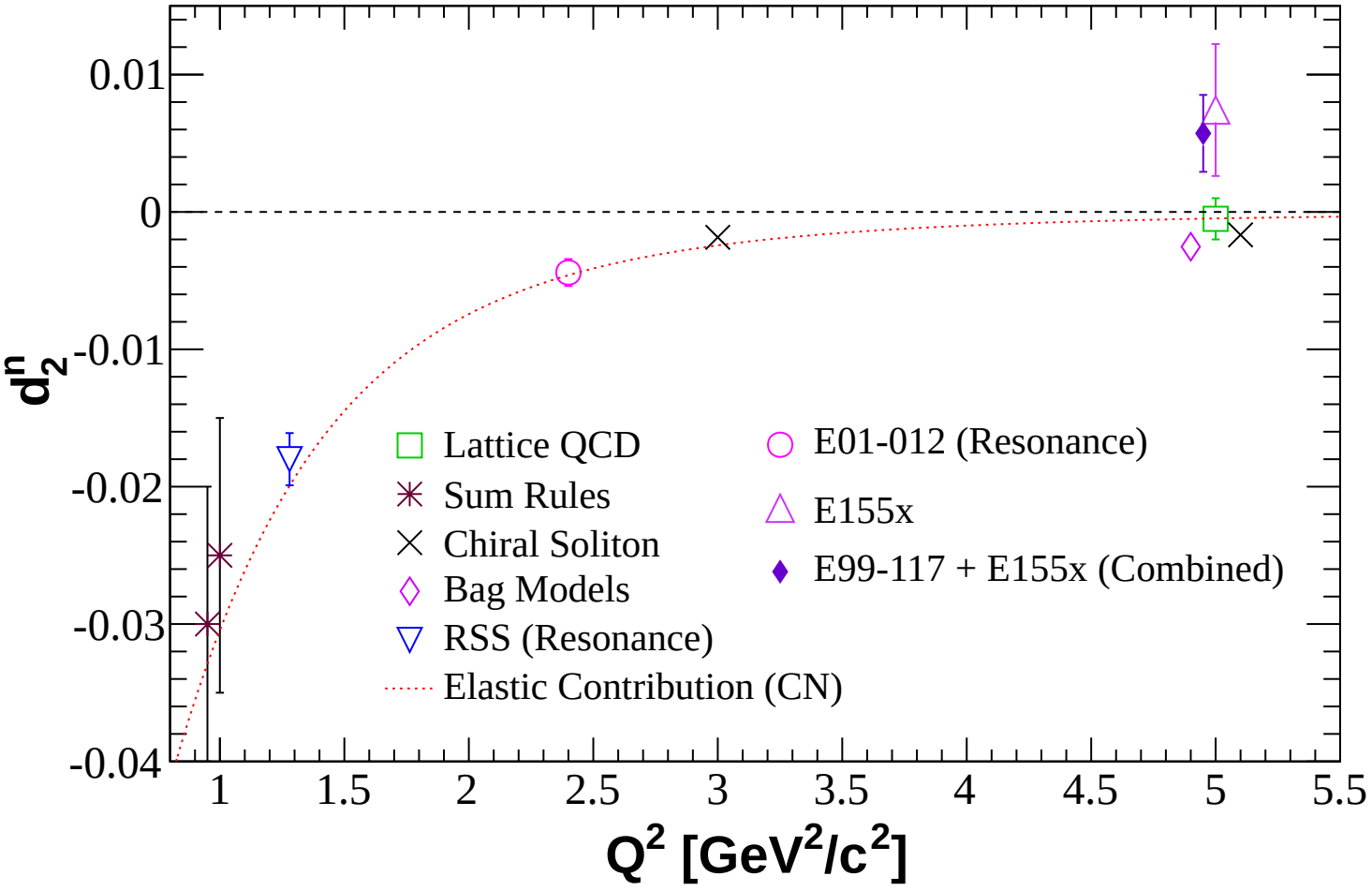
d_2 World Data

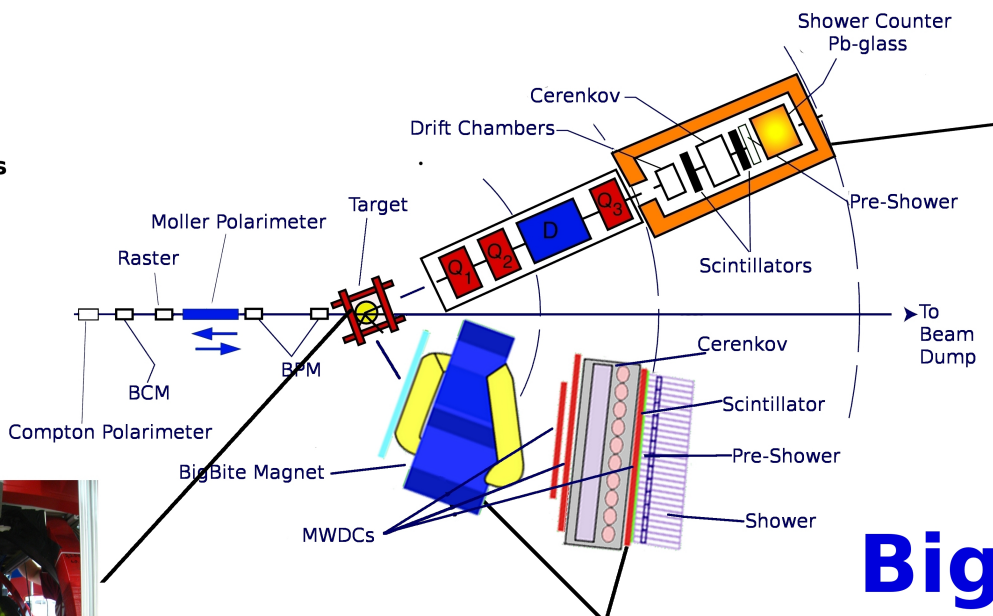


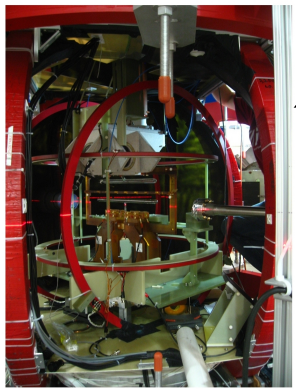
E06-014 Experiment

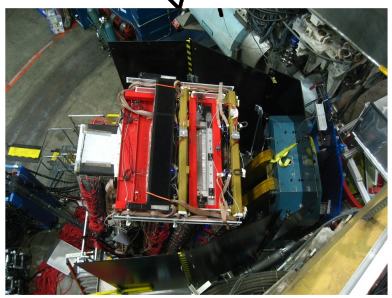
Experimental Setup

LHRS:

- **45^o relative to beam**
- **Measured cross-sections**



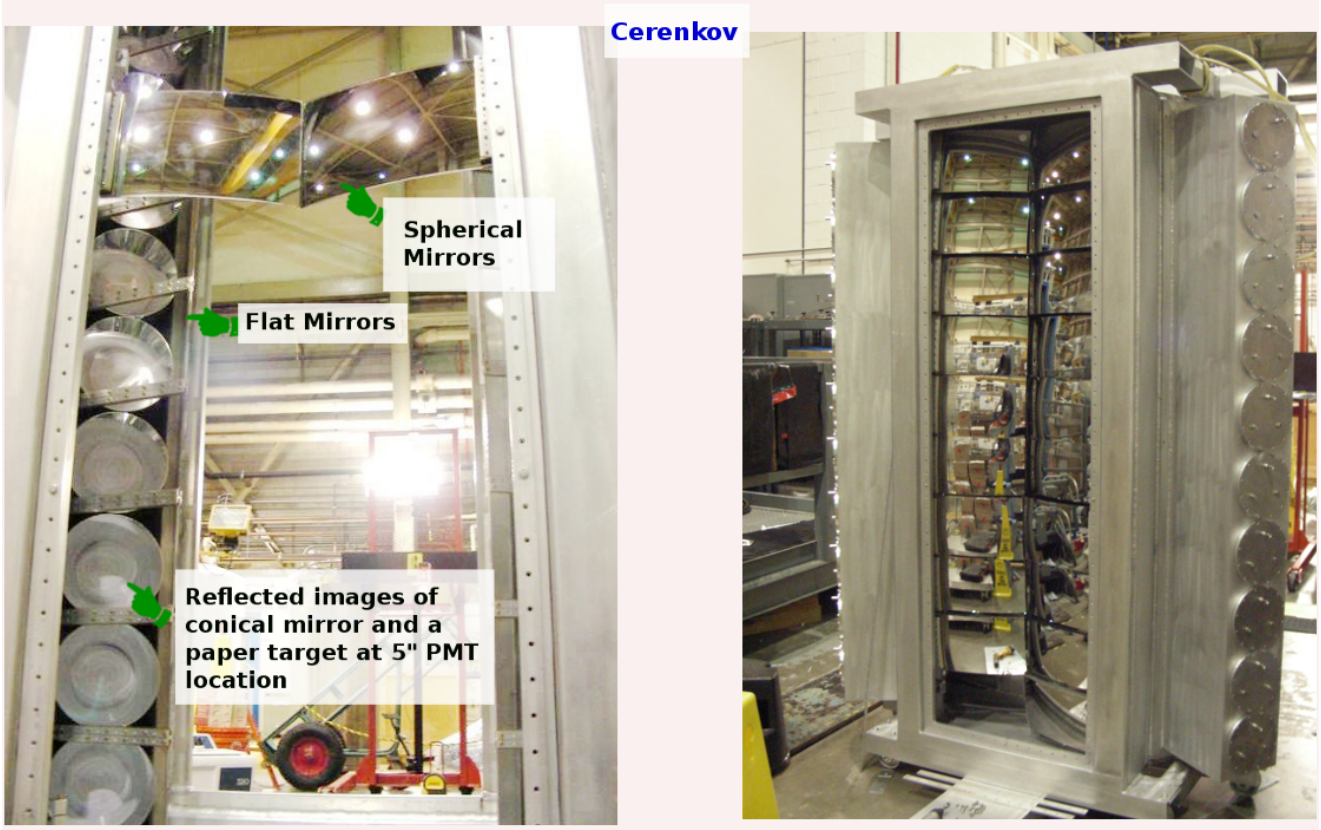




BigBite:

- **45^o relative to beam**
- **Measured asymmetries**
- **Longitudinal electron polarization**
- **Longitudinal / transverse 3He target**

Čerenkov Detector



- Designed to fit between BB MWDC
- Electron drift distance $\sim$ 40 cm
- C_4F_8O gas

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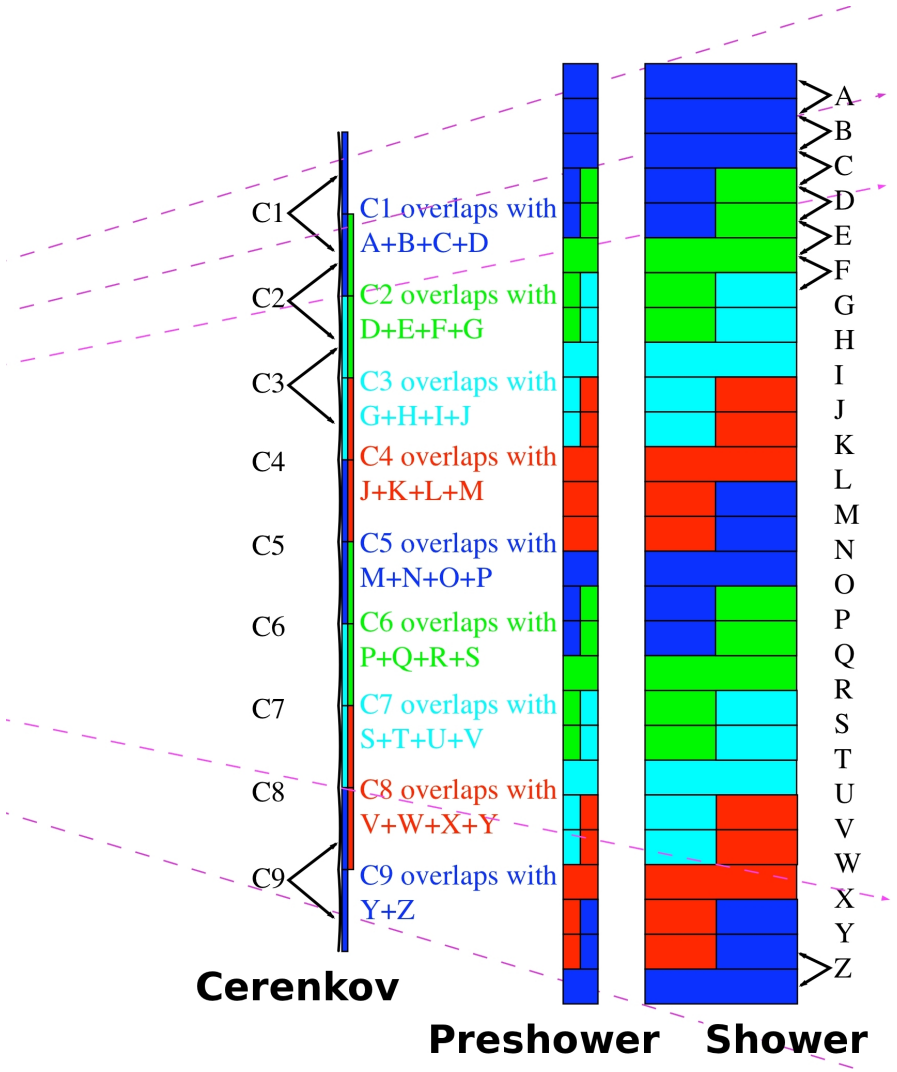
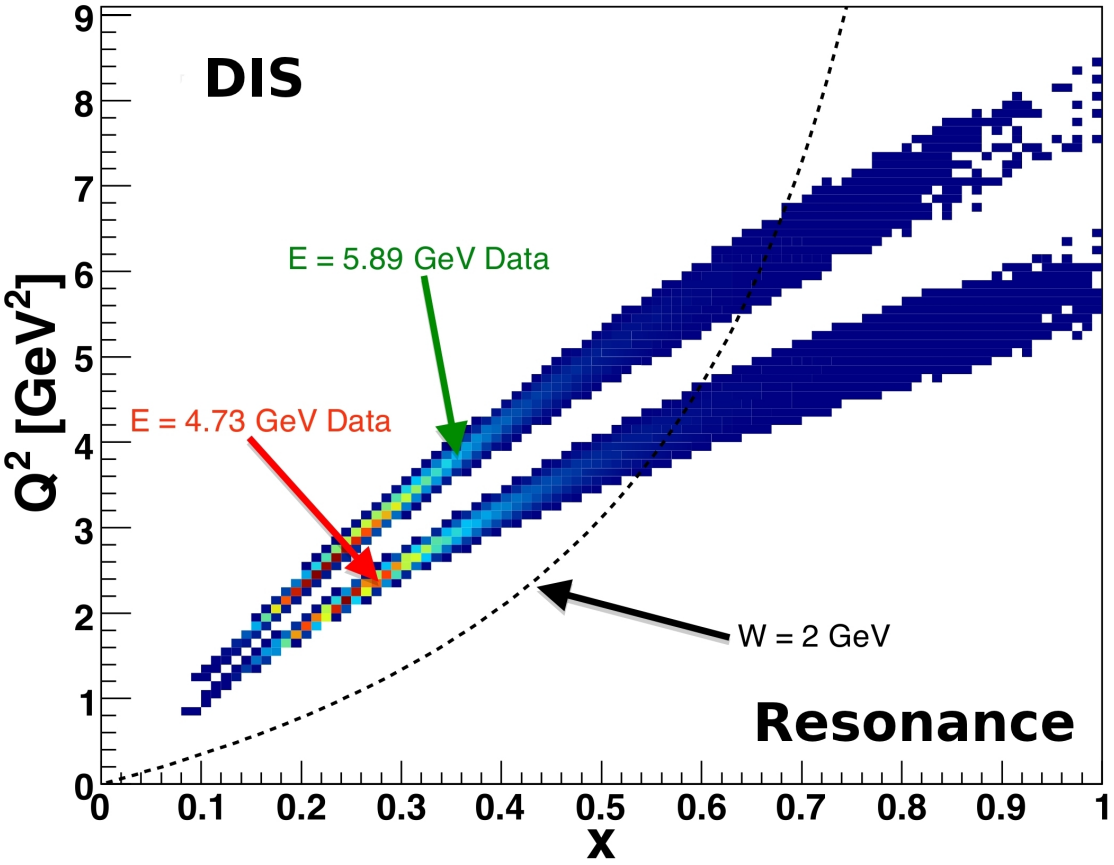
Main Electron Trigger



E06-014 Experiment

Kinematic Coverage



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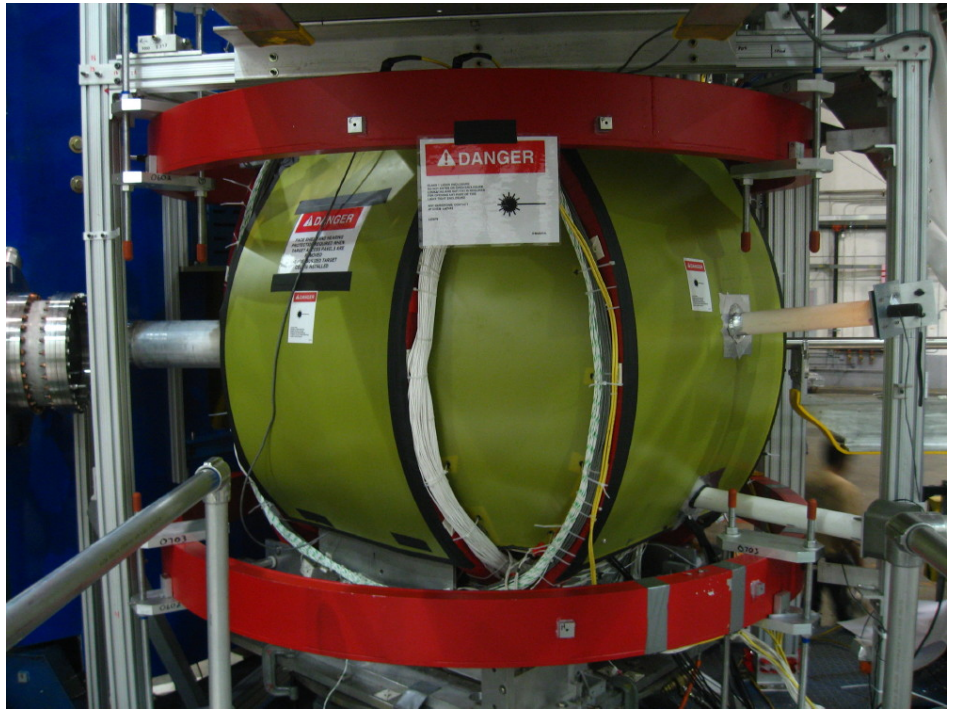
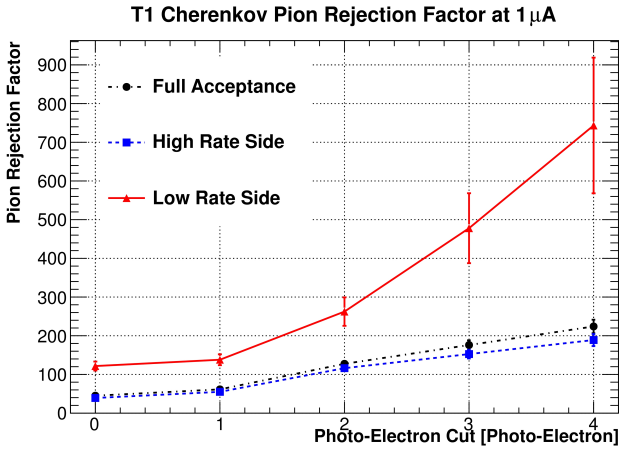
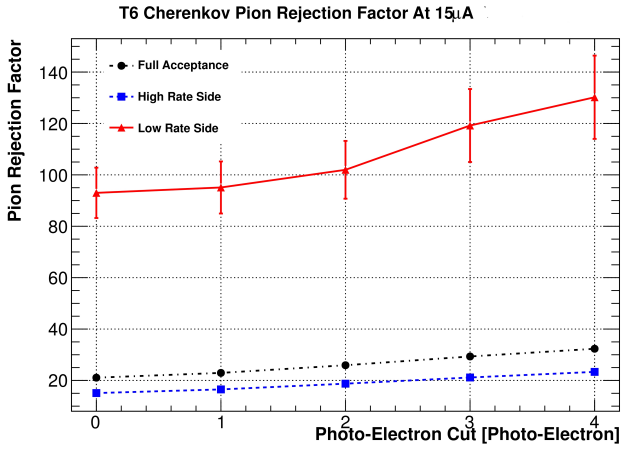
Polarization Achievements

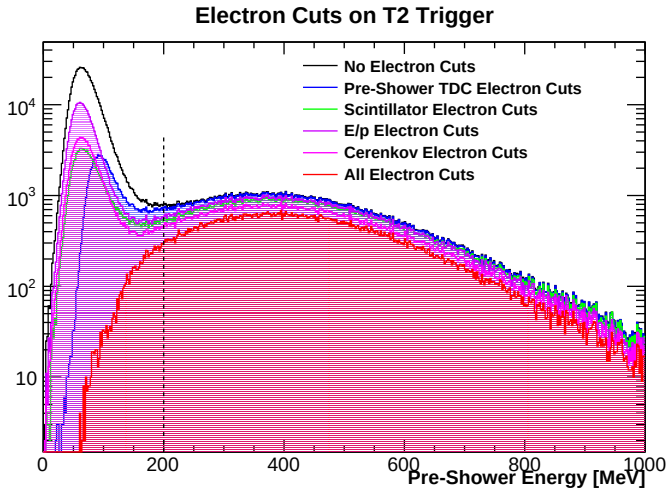
- **Target Polarization**
  - Measured using NMR polarimetry
  - Calibrated using EPR polarimetry
  - Cross checked with know water polarization
  - Average target polarization : 50%
- **Beam Polarization**
  - Measured using Compton and Møller
  - Split into 3 run periods
  - E = 5.9 GeV: 73%, 79%
  - E = 4.7 GeV: 63%



Pion Rejection



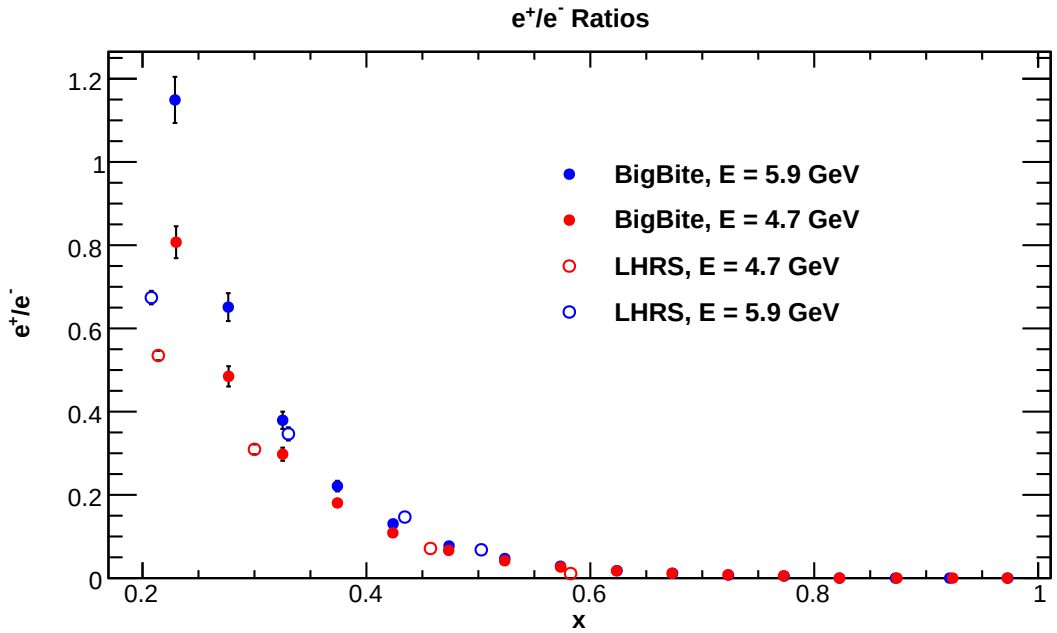




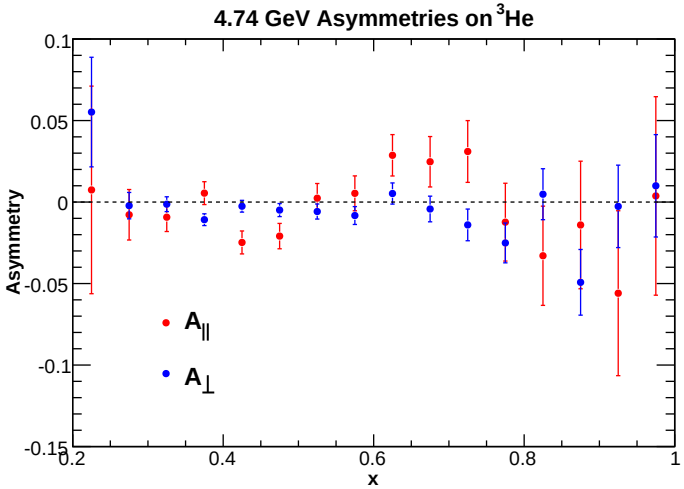
- Total pion rejection $> 10^4$ (both BB/LHRS)
- $\frac{\pi^-}{e^-}$ contamination $\sim$ 3% (lowest x-bin)
- Pions treated as dilution only (both BB/LHRS)

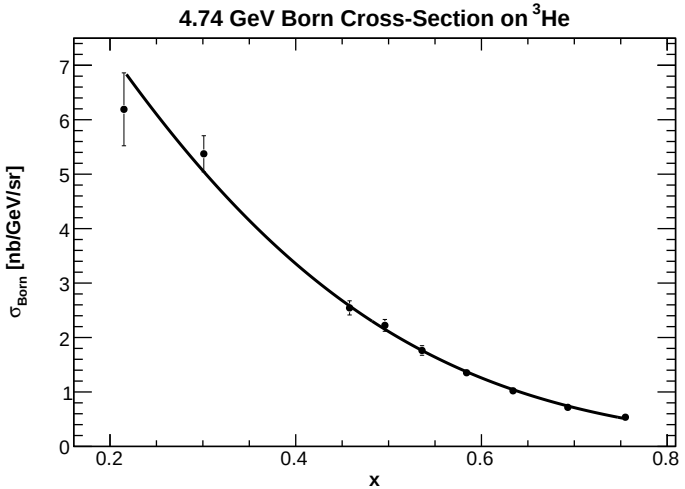
Pair-Production Contamination

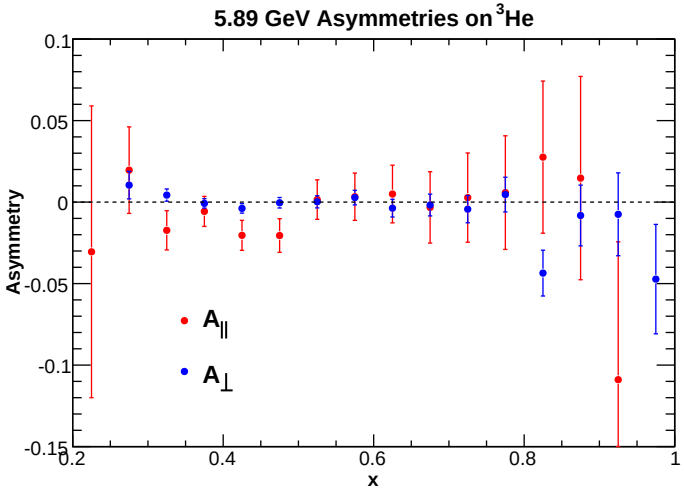
- **Asymmetry**
  - Measured using positrons bending down in BB
  - Asymmetry size $\sim$ 1-2%
- **Dilution**
  - Measured positrons by flipping BB magnet polarity
  - Significant contamination at low x
  - Quickly falls off with increasing x

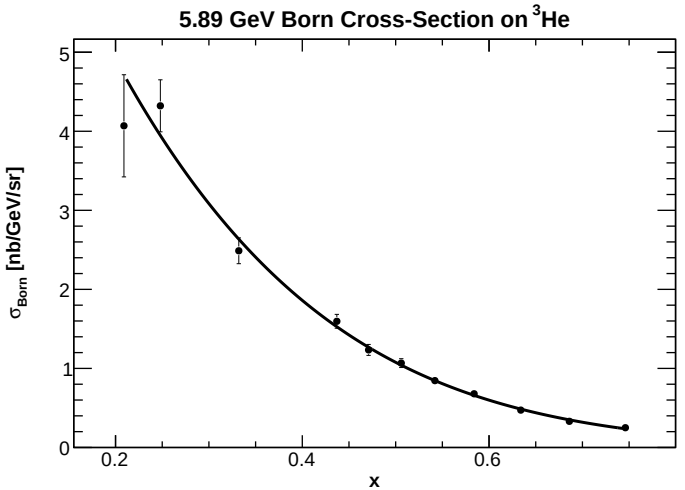


Asymmetries and Cross Sections









Structure Functions

Selected World ^{3}He Data

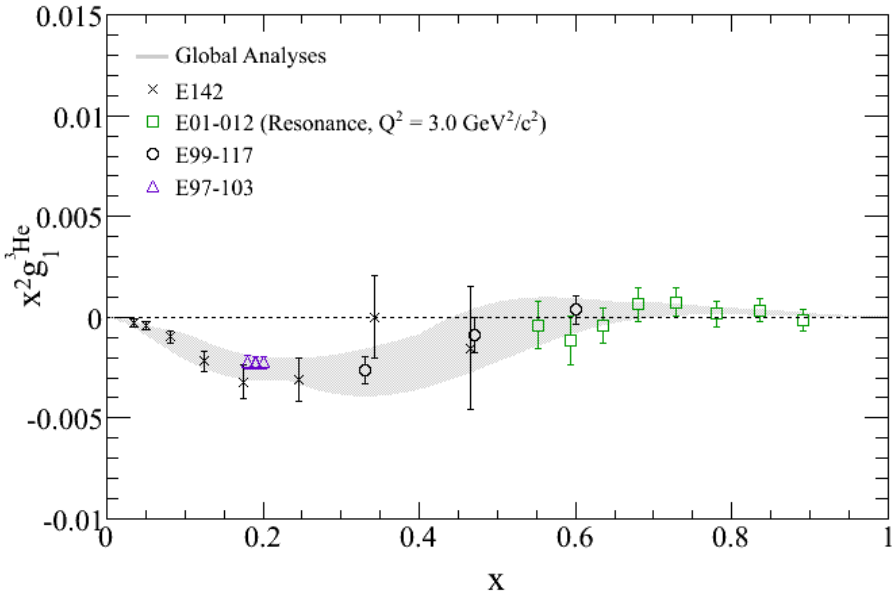


Figure: $g_1^{^3\mathrm{He}}$

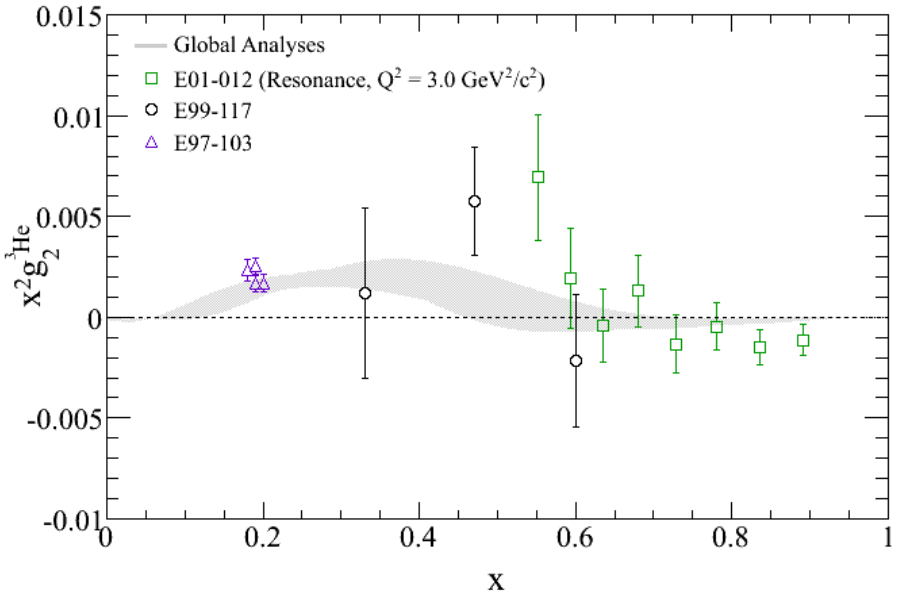
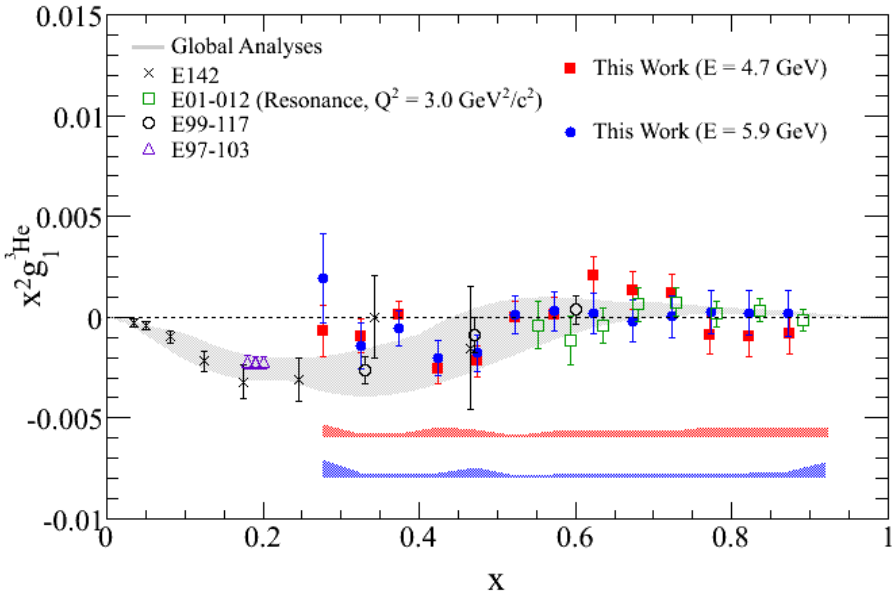


Figure: $g_2^{^3\mathrm{He}}$

Structure Functions

^{3}He Results



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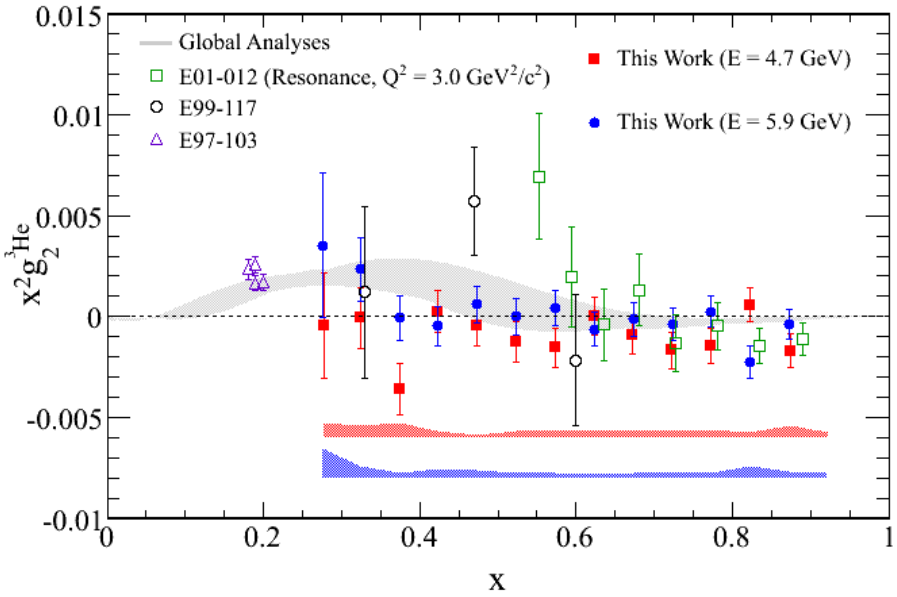

Figure: $g_2^{^3\mathrm{He}}$

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Extracting Neutron Information

- Neutron information extracted using convoluted wave function analysis (F. Bissey et al. Phys. Rev. C, 65:064137, 2002)

$$d_2^{^3He} = \tilde{P}_n d_2^n + 2\tilde{P}_p d_2^p$$

- $\tilde{P}_n \sim$ 86% (neutron polarization)
- $\tilde{P}_p \sim$ -3% (proton polarization)
- d_2^p evaluated from various global analyses

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Completing the Integral

Measured Contribution

- Complete d_2^n is given as:

$$d_2^n = (d_2^n)_{\mathrm{low-x}} + (d_2^n)_{\mathrm{measured}} + (d_2^n)_{\mathrm{elastic}}$$

- Two $\langle Q^2 \rangle$ values of 3.21 and 4.32 GeV^2
- Q^2 ranged from $\sim$ 2 - 7 GeV^2
- $0.25 \leq x \leq 0.90$

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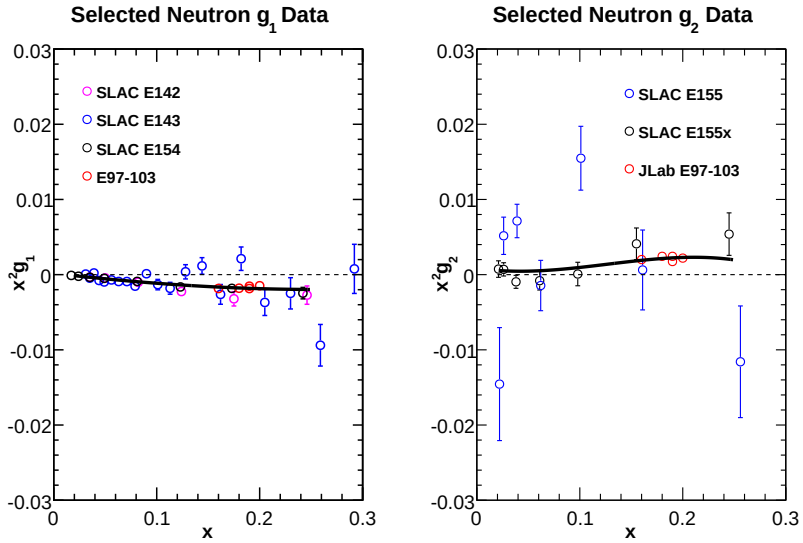
Completing the Integral

Low x Contribution

- Complete d_2^n is given as:

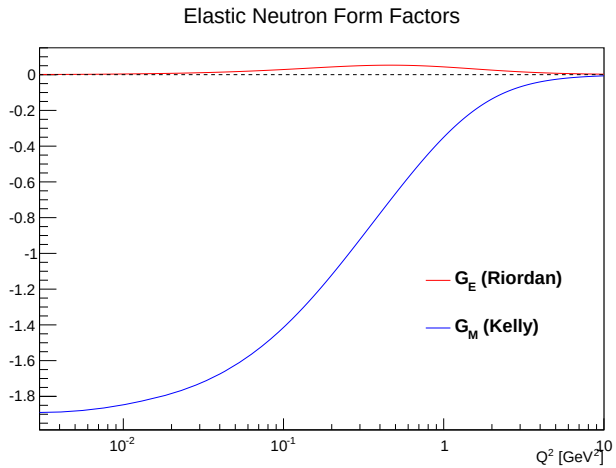
$$d_2^n = (d_2^n)_{\mathrm{low-x}} + (d_2^n)_{\mathrm{measured}} + (d_2^n)_{\mathrm{elastic}}$$

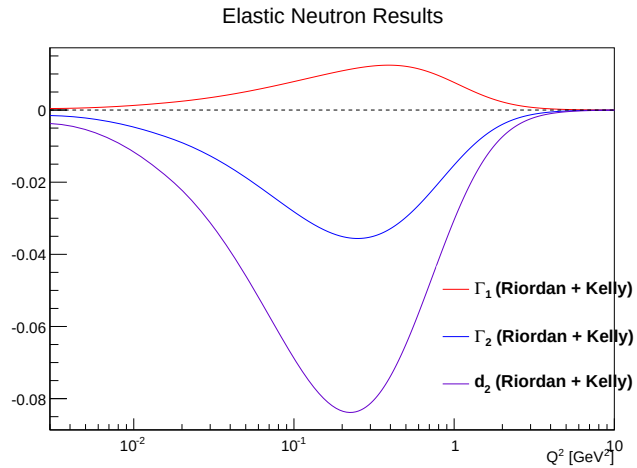
- Low-x contribution suppressed by x^2 weighting
- To estimate the low-x range ($0.02 \leq x \leq 0.25$) fits to world data were used



Completing the Integral

Large x Contribution





- Complete d_2^n is given as:

$$d_2^n = (d_2^n)_{\mathrm{low-x}} + (d_2^n)_{\mathrm{measured}} + (d_2^n)_{\mathrm{elastic}}$$

- The elastic contribution to d_2^n was computed using the G_E^n [a] and G_M^n [b]

[a] S. Riordan et al., Phys. Rev. Lett. 105, 262302 (2010)

[b] J. J. Kelly, Phys. Rev. C 70, 068202 (2004)

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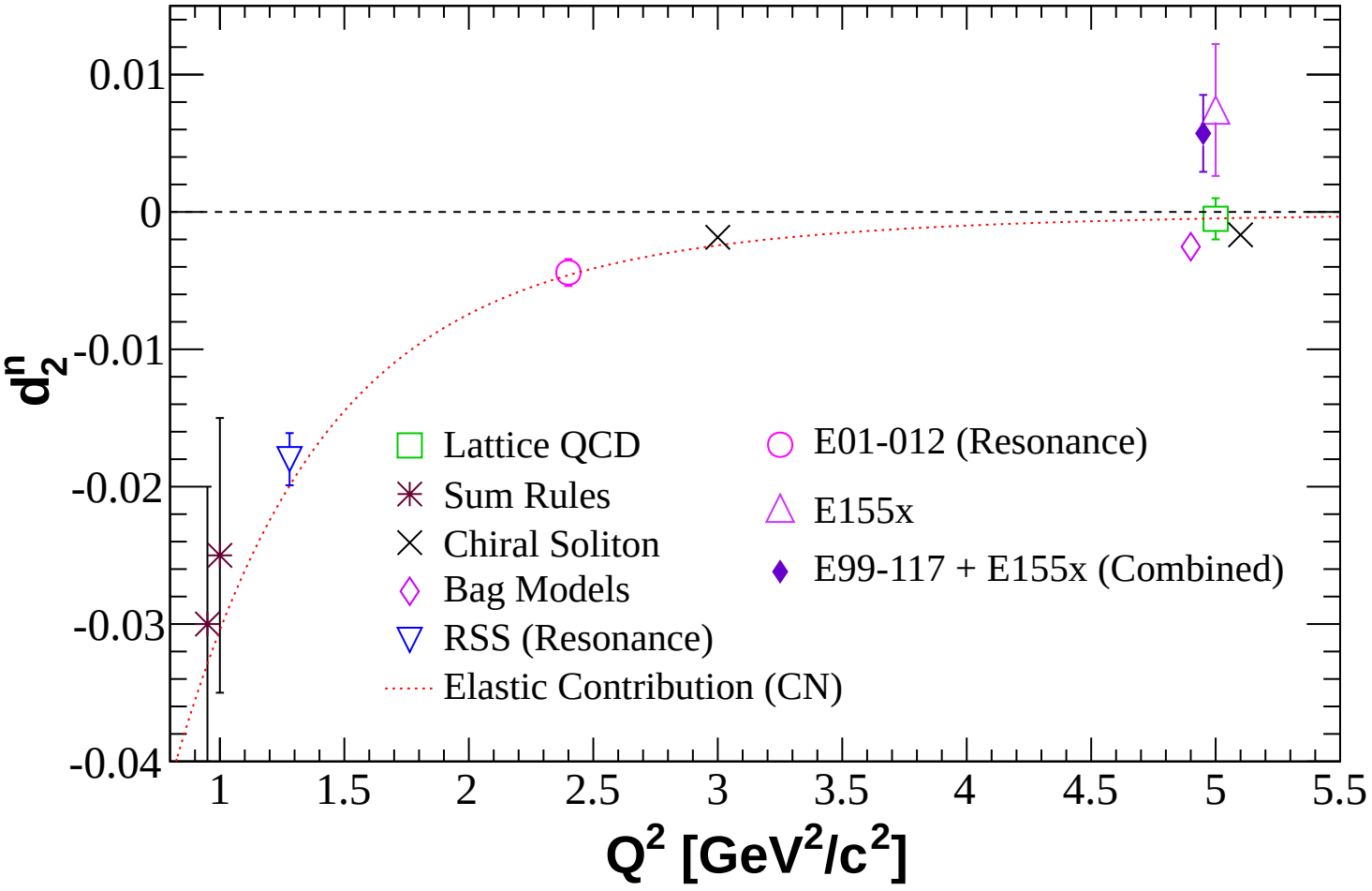
d_2^n World Data



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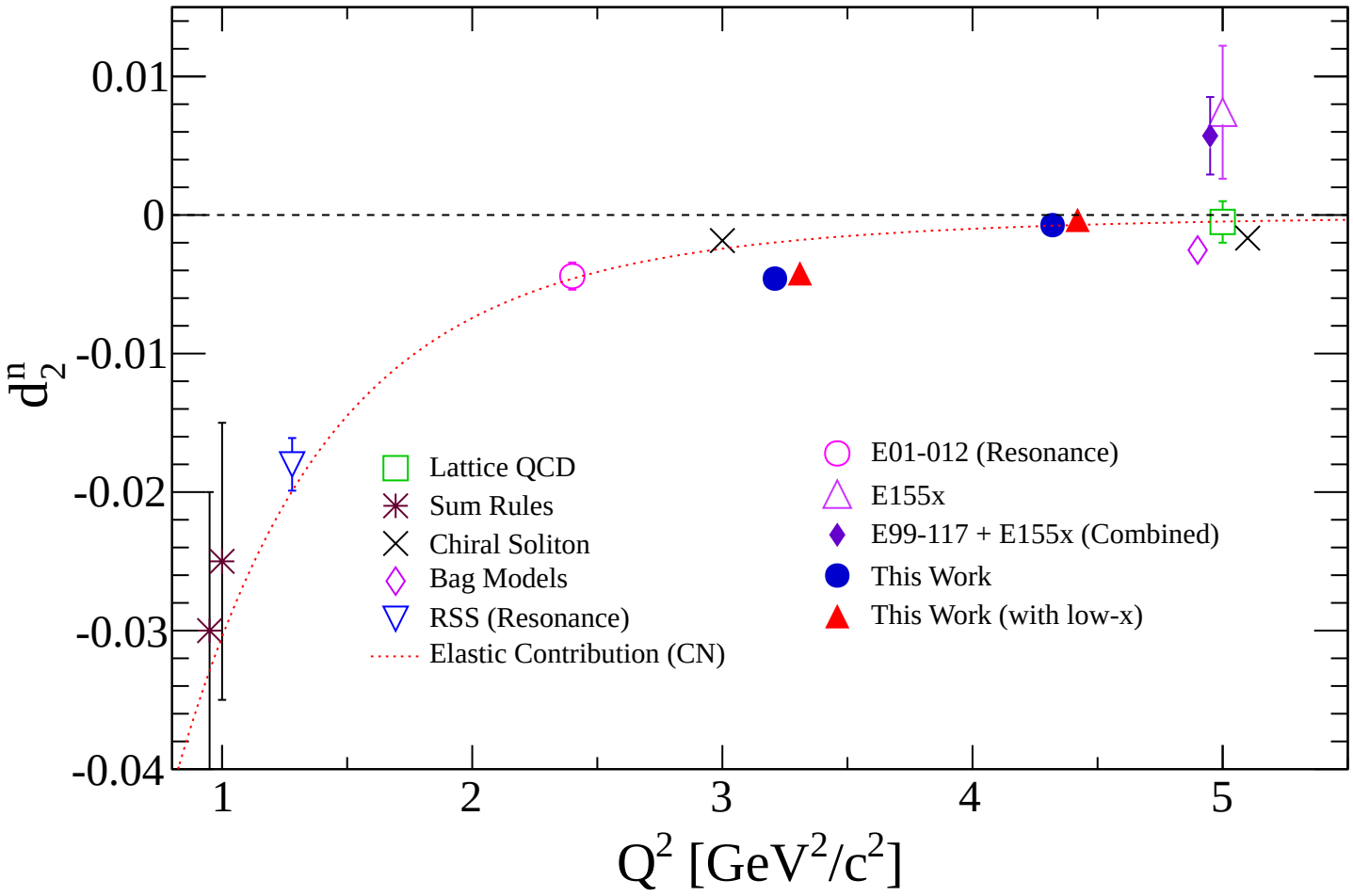
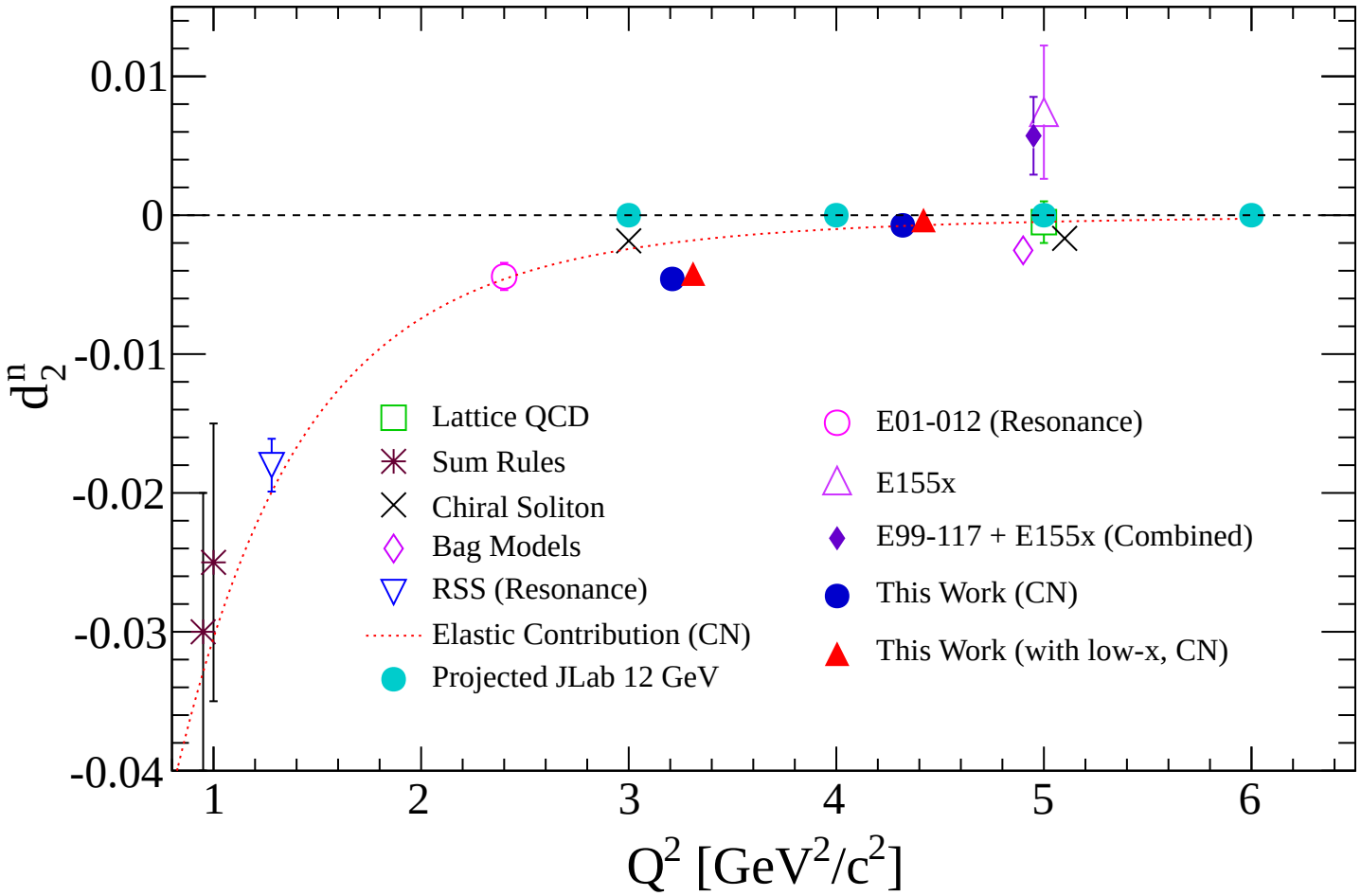
d_2^n Results


0.01
0
-0.01
-0.02
-0.03
-0.04
1
2
3
4
5
d_2^n
Q^2 [GeV^2/c^2]
Lattice QCD
Sum Rules
Chiral Soliton
Bag Models
RSS (Resonance)
Elastic Contribution (CN)
E01-012 (Resonance)
E155x
E99-117 + E155x (Combined)
This Work
This Work (with low-x)

d_2^n at 12 GeV


0.01
0
-0.01
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-0.03
-0.04
1
2
3
4
5
6
d_2^n
Q^2 [GeV^2/c^2]
Lattice QCD
Sum Rules
Chiral Soliton
Bag Models
RSS (Resonance)
Elastic Contribution (CN)
Projected JLab 12 GeV
E01-012 (Resonance)
E155x
E99-117 + E155x (Combined)
This Work (CN)
This Work (with low-x, CN)

f_2^n Extraction

$$\Gamma_1^n \equiv \int_0^1 g_1 dx = \mu_2 + \frac{\mu_4}{Q^2} + \frac{\mu_6}{Q^4} + O\left(\frac{1}{Q^6}\right) + \ldots \qquad \left(a_2^n = \int_0^1 x^2 g_1^n dx\right)$$

f_2^n Extraction

$$\Gamma_1^n \equiv \int_0^1 g_1 dx = \mu_2 + \frac{\mu_4}{Q^2} + \frac{\mu_6}{Q^4} + O\left(\frac{1}{Q^6}\right) + \ldots \qquad \left(a_2^n = \int_0^1 x^2 g_1^n dx\right)$$

$$\mu_4 = \frac{M^2}{9}\left(a_2 + 4d_2 + 4f_2\right)$$

f_2^n Extraction

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$$\mu_4 = \frac{M^2}{9}\left(a_2 + 4d_2 + 4f_2\right)$$

$$\Delta\Gamma_1^n \equiv \Gamma_1^n - \mu_2 = \frac{M^2}{9Q^2}\left(a_2 + 4d_2 + 4f_2\right) + \frac{\mu_6}{Q^4} + O\left(\frac{1}{Q^6}\right) + \ldots$$

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f_2^n Extraction

$$\Gamma_1^n \equiv \int_0^1 g_1 dx = \mu_2 + \frac{\mu_4}{Q^2} + \frac{\mu_6}{Q^4} + O\left(\frac{1}{Q^6}\right) + \ldots \qquad \left(a_2^n = \int_0^1 x^2 g_1^n dx\right)$$

$$\mu_4 = \frac{M^2}{9}\left(a_2 + 4d_2 + 4f_2\right)$$

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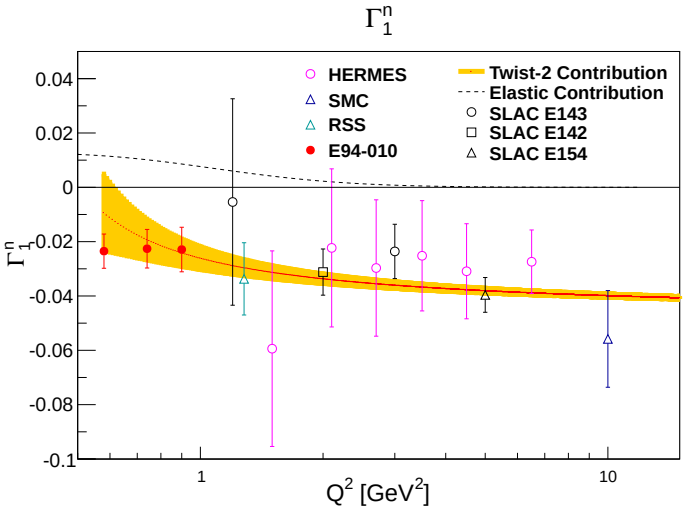
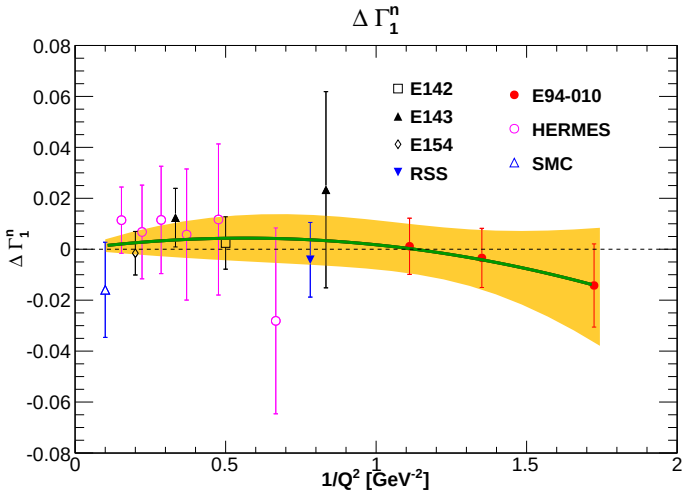
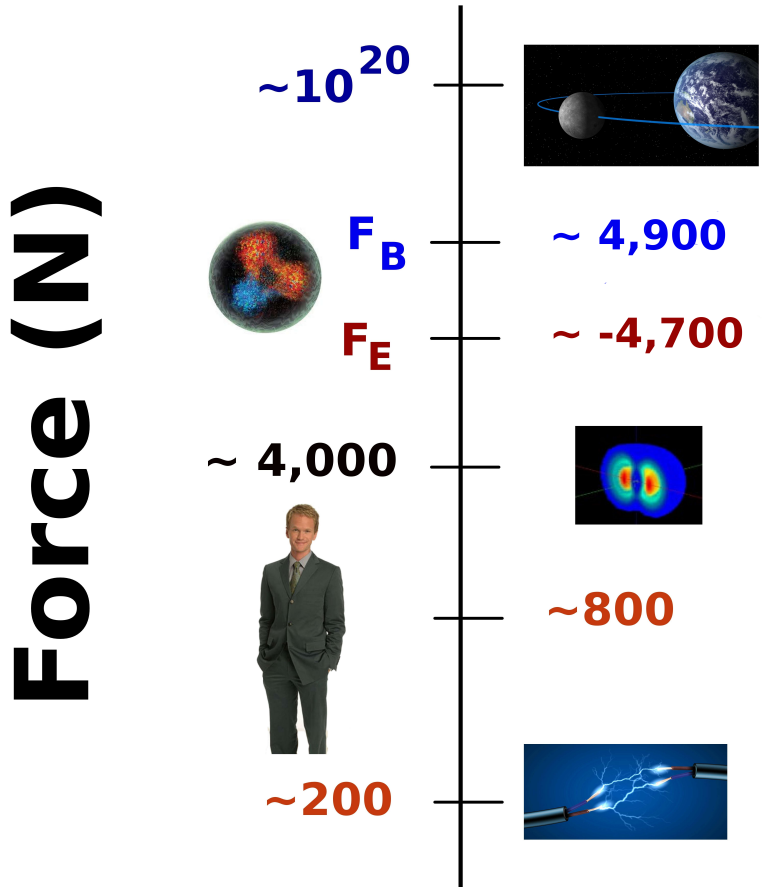




Color Forces



Summary and Status

- **Summary**
  - d_2^n is small
  - d_2^n measurement is consistent with lattice calculations, chiral soliton, and bag models
  - $d_2^n < f_2^n$
  - Color forces nearly equal in magnitude but opposite in sign (at higher Q^2)
- **Status**
  - d_2^n paper has been submitted to PRL for review
  - A_1^n paper in preparation (D. Parno)
  - E06-014 archival paper in preparation (D. Flay)

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Y. Zhang
Y.-W. Zhang
B. Zhao
X. Zheng

Co-spokesperson Ph.D. (complete) Ph.D. (in progress)

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Q^2 Dependence

DSSV Fits

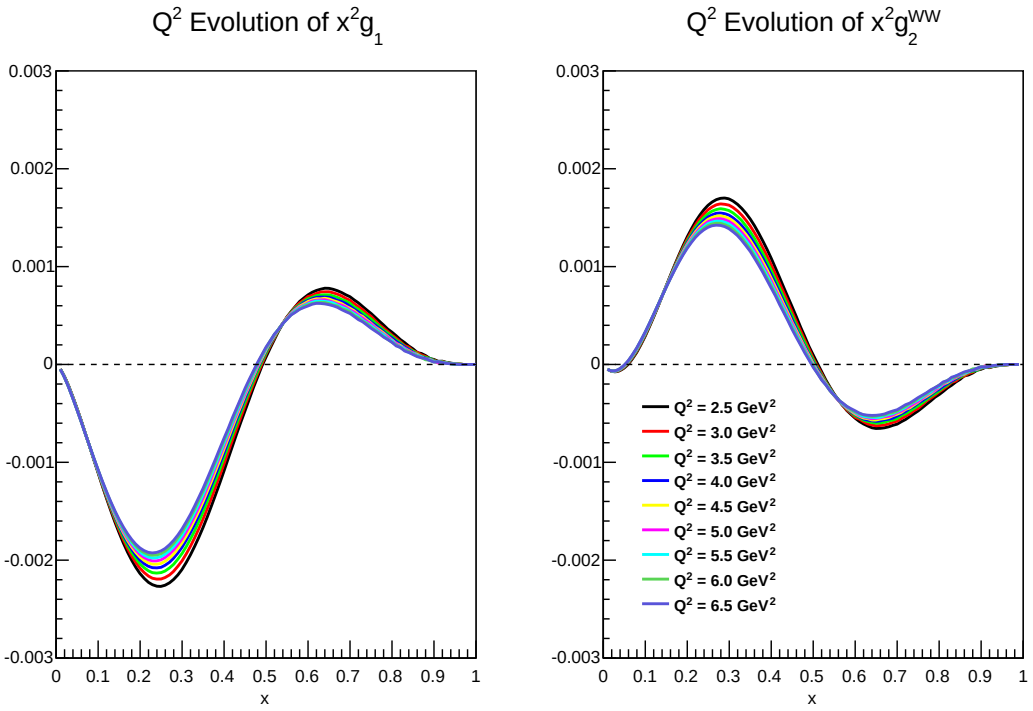
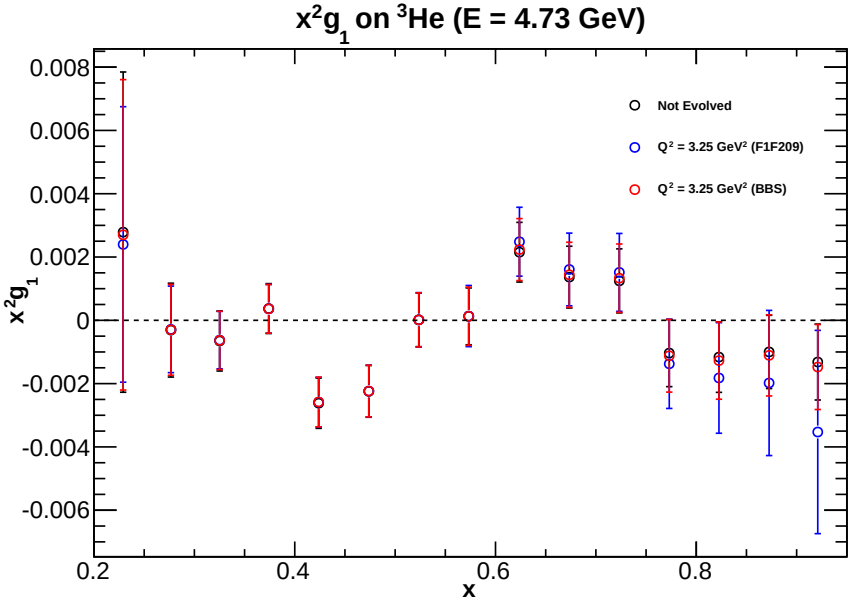
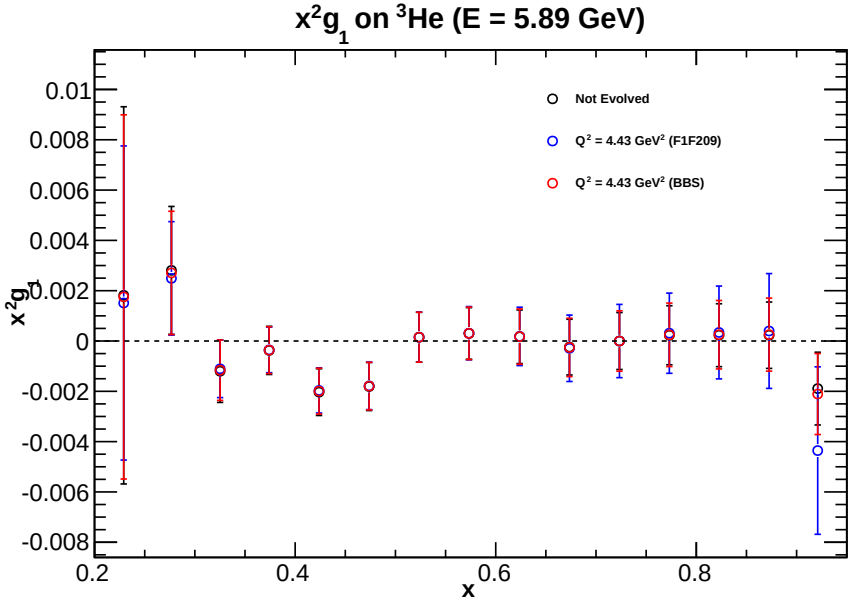


Figure: Polarized structure functions for different constant Q^2 values.

g_1 Q^2 Evolution

Assumes g_1/F_1 is Q^2 independent





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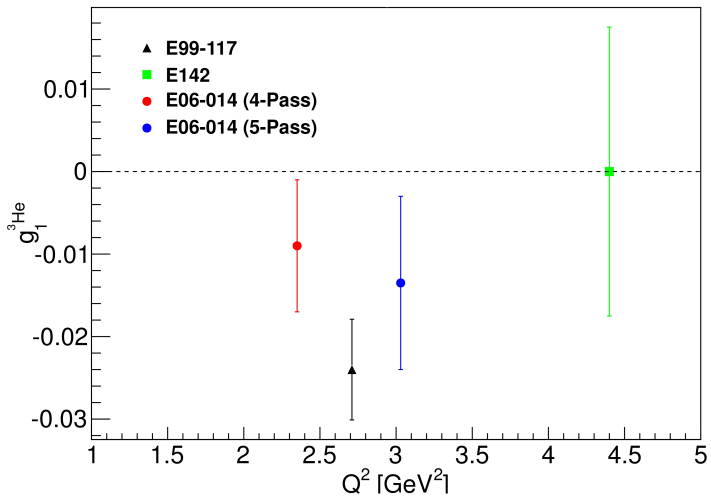
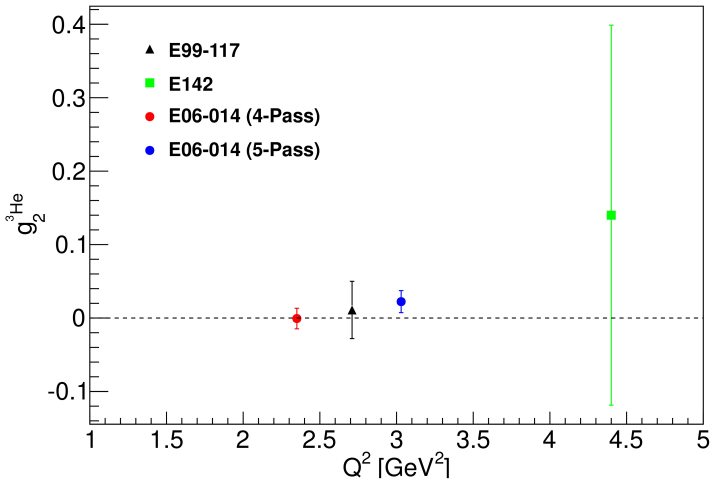
Q^2 Dependence

Experimental Measurements

- Compared several measured experimental values at different Q^2
- $\langle x \rangle$ = 0.33





Electron Asymmetries

$$A^{e^-} = \left(\frac{1}{P_t P_b D_{N_2}}\right) \cdot \left(\frac{A_m^{e^-} - \left(\frac{e^+}{e^-}\right) A_m^{e^+}}{1 - \left(\frac{\pi^-}{e^-}\right) - \left(\frac{e^+}{e^-}\right) + \left(\frac{\pi^+}{e^+}\right)\left(\frac{e^+}{e^-}\right)}\right)$$

where:

- $A_m^{e\pm}$ is the asymmetry measured in BigBite
- P_t is the target polarization
- P_b is the electron beam polarization
- D_{N_2} is the asymmetry dilution due to $\sim$ 1% N_2 gas being present in target cell (determined using N_2 target)

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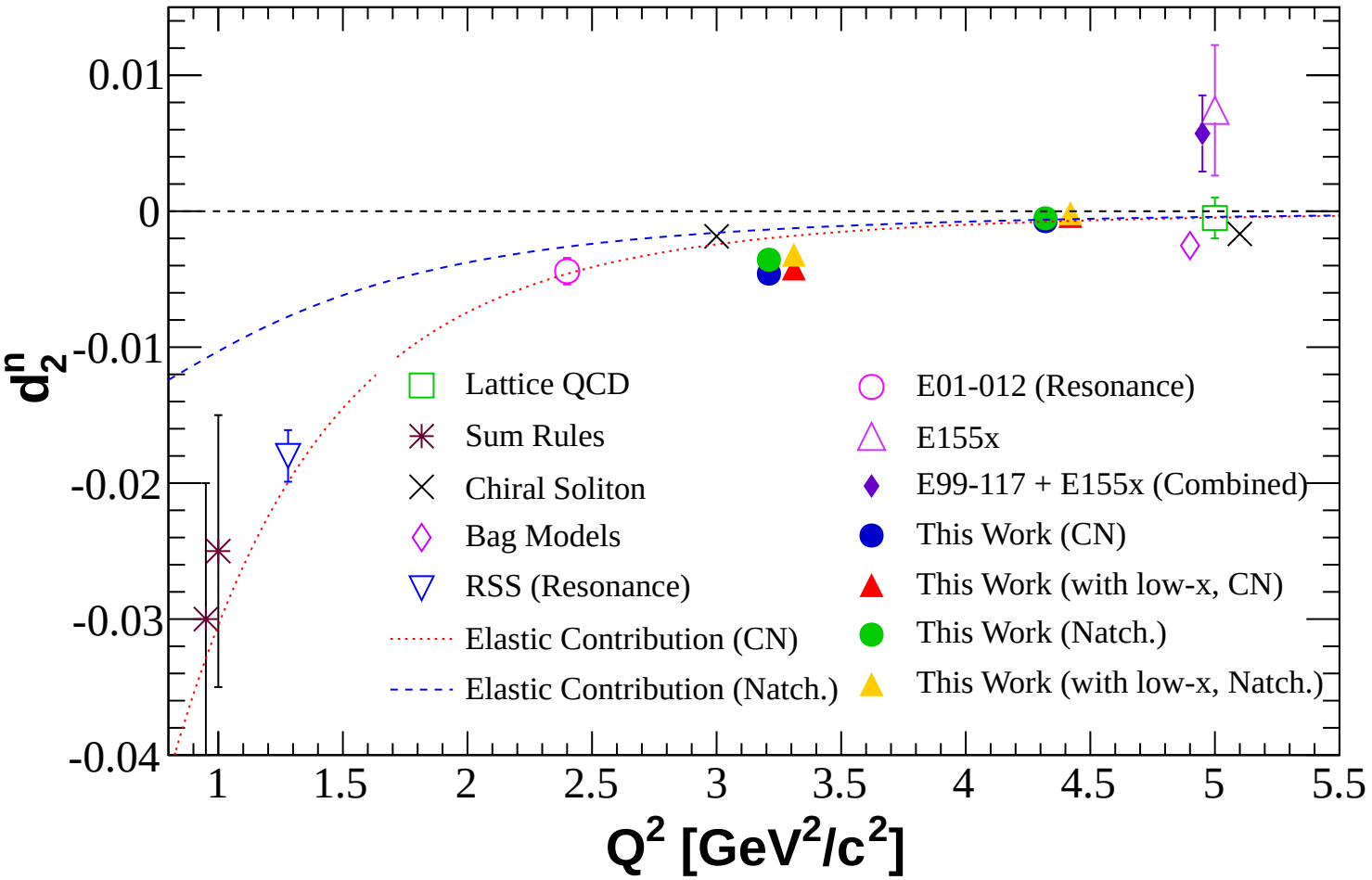
d_2 Results

Nachtmann



f_2^n Extraction

- Includes updated a_2^n, d_2^n, and f_2^n all at same Q^2
- Includes updated analysis from E94-010[5]
- Include analysis from RSS[6]

Table: Values listed are $\pm$ stat $\pm$ sys.

$\langle Q^2 \rangle$ (GeV^2)	$f_2^n \times 10^{-3}$	F_E^n (Mev/fm)	F_B^n (MeV/fm)
3.21	43.57 $\pm$ 0.79 $\pm$ 39.38	-26.17 $\pm$ 1.32 $\pm$ 29.35	44.99 $\pm$ 2.43 $\pm$ 29.43
4.32	39.80 $\pm$ 0.83 $\pm$ 39.38	-29.12 $\pm$ 1.38 $\pm$ 29.34	30.68 $\pm$ 2.55 $\pm$ 29.40

[5] K. Slifer et. al Phys. Rev. Lett 101, 022303 (2008).

[6] K. Slifer et. al Phys. Rev. Lett 105, 101601 (2010).

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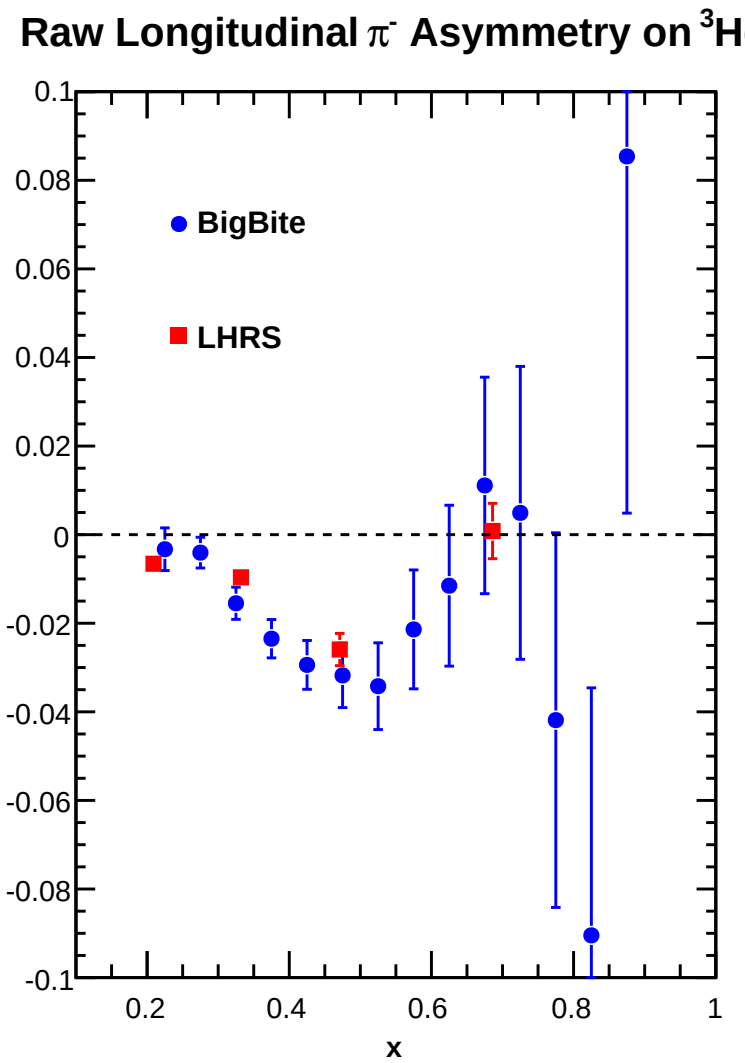
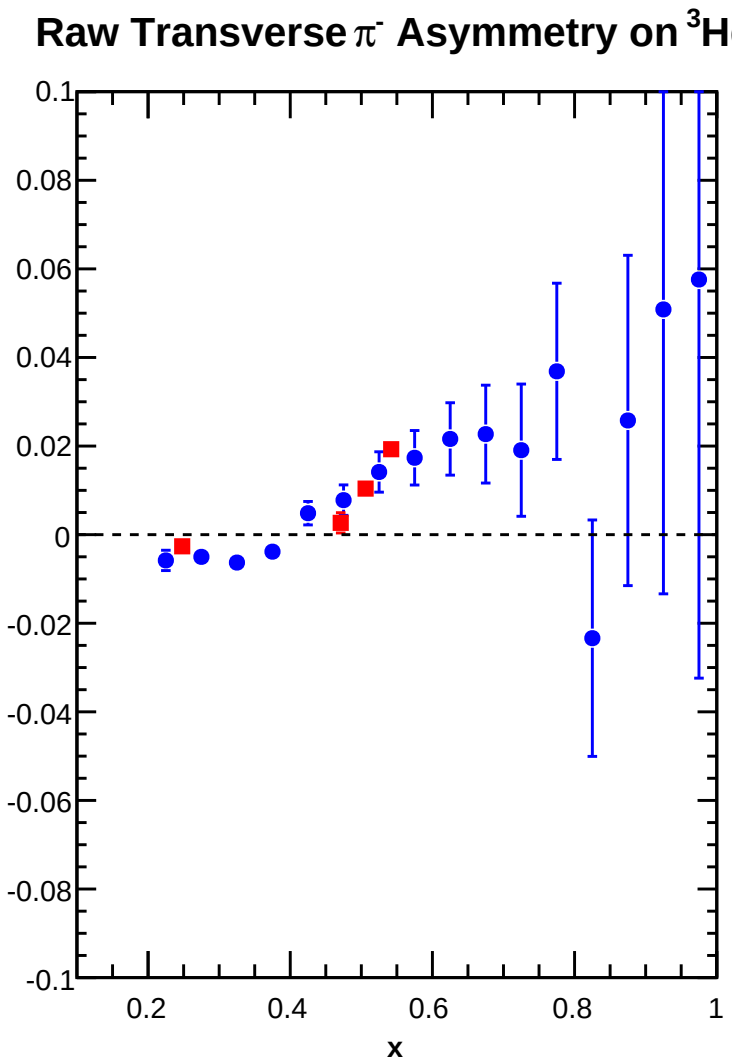
Raw π^- Asymmetries





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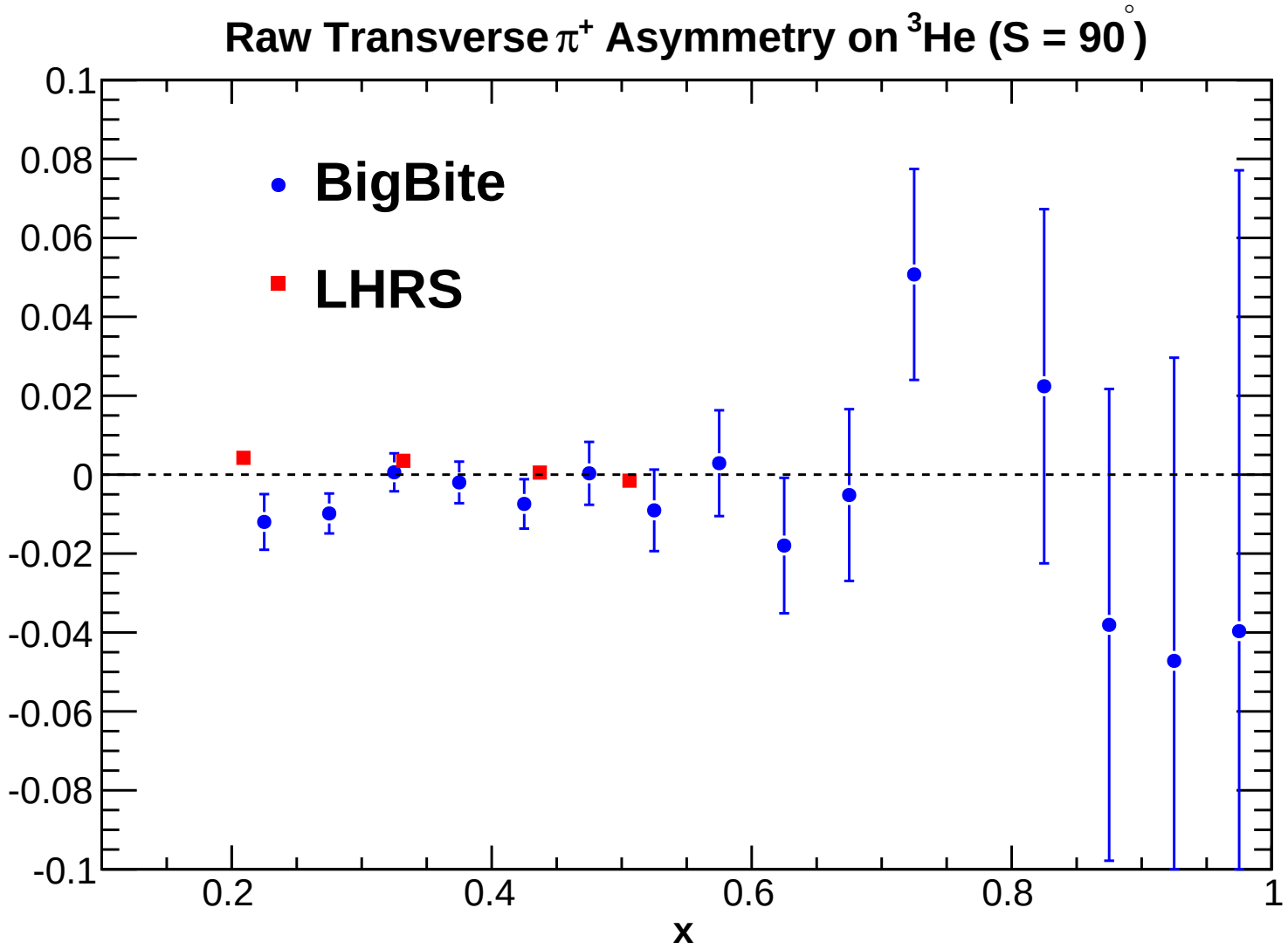
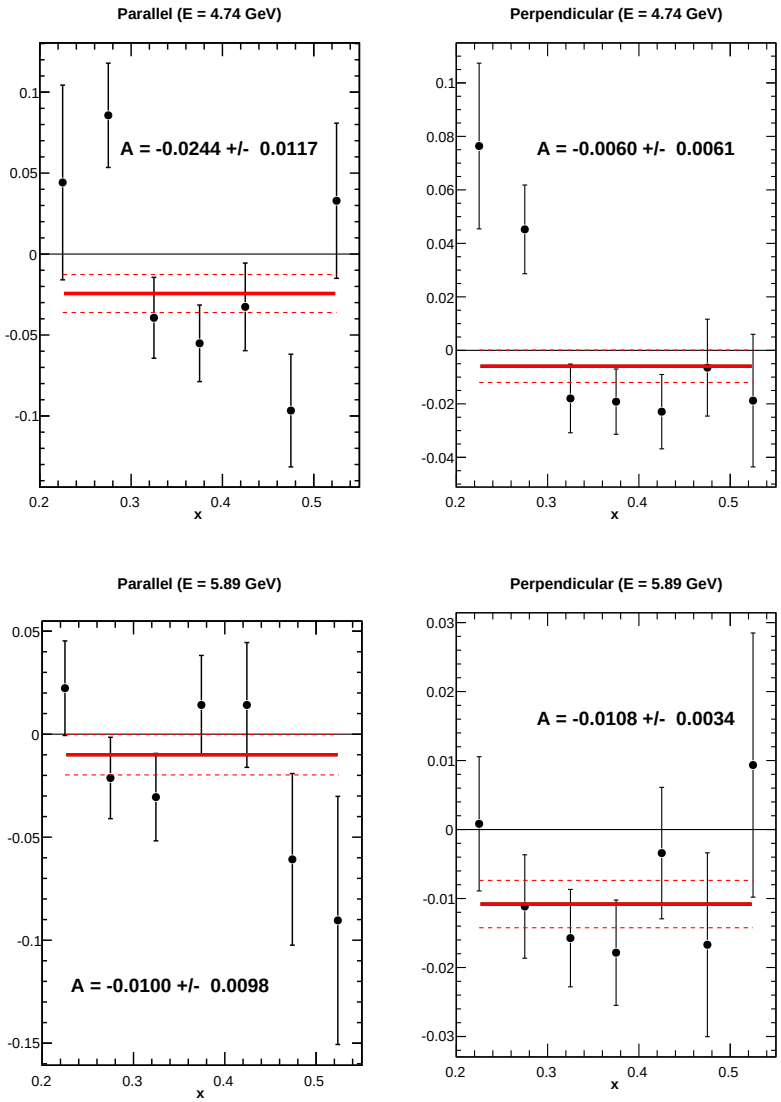
Raw π^+ Asymmetries



e^+ Asymmetries