

Precision Measurement of d_2^n : A Probe of the Color Force

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for the E06-014 Collaboration

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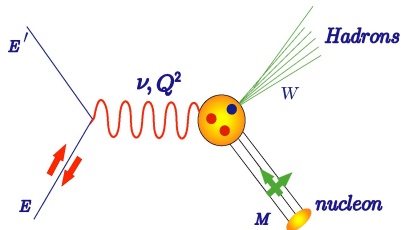
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Outline

- 1 Physics Motivation
- 2 The E06-014 Experiment
- 3 Data Analysis
- 4 Preliminary Results: Polarized Structure Functions

Polarized DIS

- Probes the spin content of the nucleon



$$\frac{d^2\sigma(\downarrow\uparrow-\uparrow\uparrow)}{dE'd\Omega} = \frac{4\alpha^2}{MQ^2} \frac{E'}{\nu E} \left[(E + E' \cos \theta) g_1(x, Q^2) - \frac{Q^2}{\nu} g_2(x, Q^2) \right]$$

$$\frac{d^2\sigma(\downarrow\Rightarrow-\uparrow\Rightarrow)}{dE'd\Omega} = \frac{4\alpha^2 \sin \theta}{MQ^2} \frac{E'^2}{\nu^2 E} [\nu g_1(x, Q^2) + 2E g_2(x, Q^2)]$$

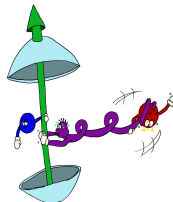
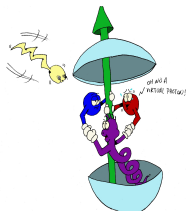
Probing Quark-Gluon Dynamics in the Nucleon

- d_2^n gives access to quark-gluon correlations

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

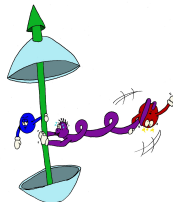
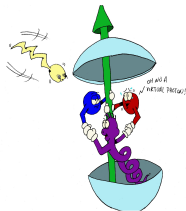
- What is d_2^n ?
 - Average **transverse Lorentz color force** acting on a quark immediately after being struck by a **virtual photon** (M. Burkardt, [hep-ph/0905.4079v1](https://arxiv.org/abs/hep-ph/0905.4079v1))
 - d_2^n is dominated by **large x** contributions

What is d_2^n ?



What is d_2^n ?

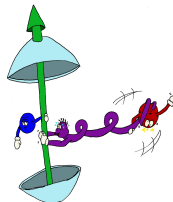
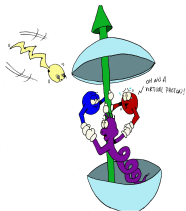
So d_2^n is ...



- A measure of **quark-gluon** correlations

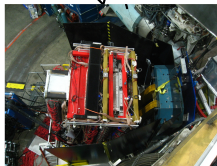
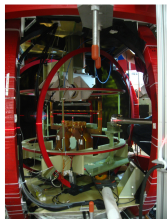
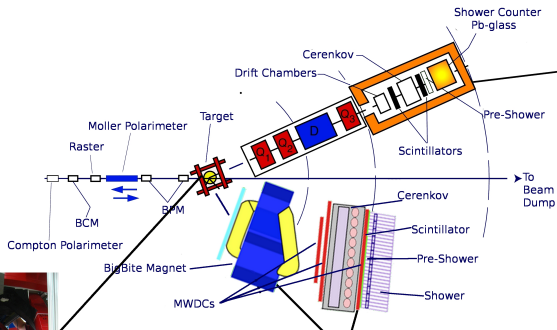
What is d_2^n ?

So d_2^n is ...



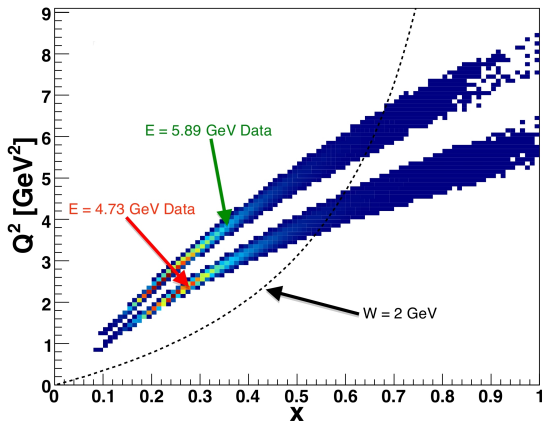
- A measure of **quark-gluon** correlations
- A **force** felt between the **quark** struck by the **virtual photon** and the **spectator quarks**

The E06-014 Experiment (1)



The E06-014 Experiment (2)

Kinematic Coverage



From Raw to Physics Asymmetries

- For the **physics** asymmetry, we have:

$$A_{\text{phys}} = \frac{1}{P_b P_t D} A_{\text{raw}}$$

where corrections are made for:

- Imperfect beam and target polarizations (P_b, P_t)
- Nitrogen dilution in the target (D)
- Pair-produced electrons

Electron Physics Asymmetries on ^3He

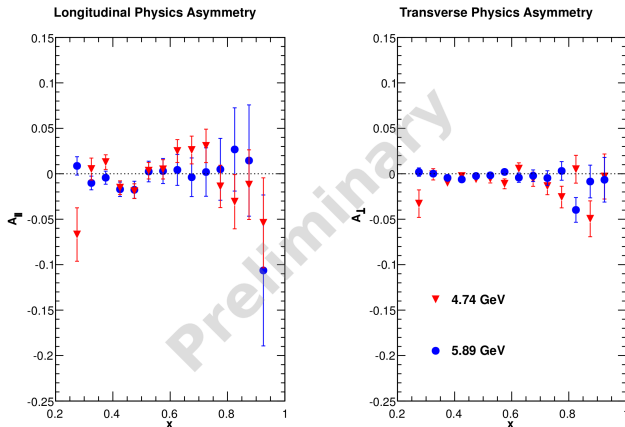
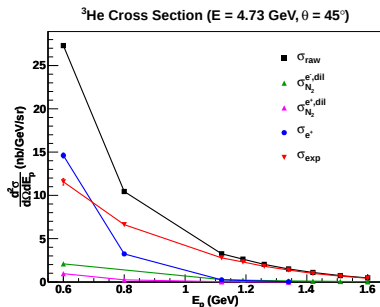
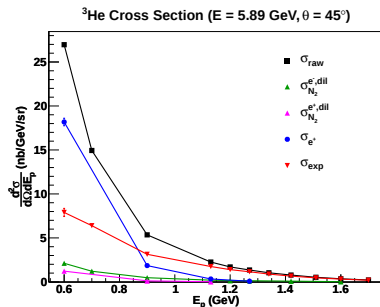


Figure: Preliminary electron asymmetries on ^3He in the DIS and resonance regions. $W = 2$ GeV for $E = 5.89$ GeV is at $x = 0.62$ and $x = 0.52$ for $E = 4.74$ GeV. Radiative corrections not yet applied.

Cross Sections



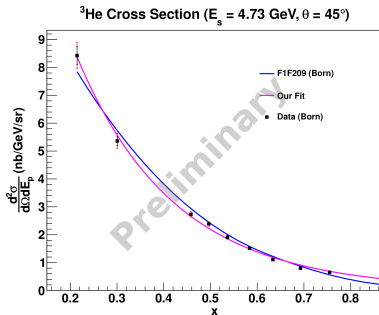
(a) E = 4.74 GeV



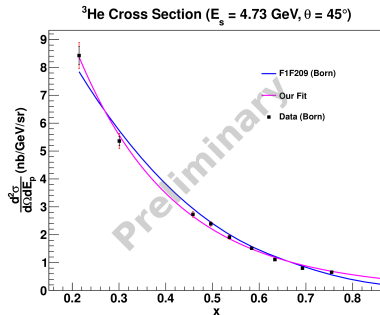
(b) E = 5.89 GeV

Figure: Raw ³He cross section and positron and nitrogen background cross sections. Background-subtracted cross section shown in red. Lines are drawn to help guide the eye. Statistical errors only.

Born Cross Sections



(a) $E = 4.74 \text{ GeV}$



(b) $E = 5.89 \text{ GeV}$

Figure: Born cross section. Error bars include statistical and systematic. Blue curve is P. Bosted's F1F209 inclusive cross section model. Magenta curve is our current fit used to extract cross section values.

$g_1^{3\text{He}}$ Compared to Selected World Data

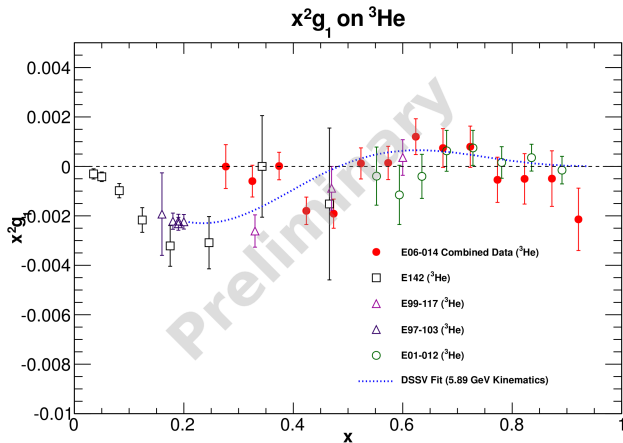


Figure: Preliminary $x^2 g_1$ structure function on ^3He in DIS and resonance regions. Radiative corrections to asymmetries not yet applied.

$g_2^{3\text{He}}$ Compared to Selected World Data

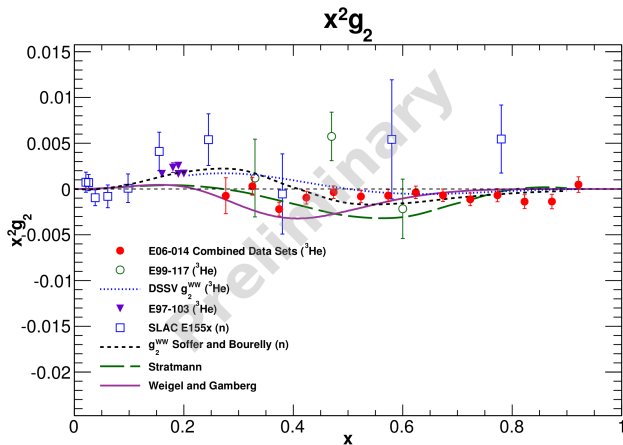


Figure: Preliminary $x^2 g_2$ structure function on ^3He in DIS and resonance regions. Radiative corrections to asymmetries not yet applied.

Current d_2 Uncertainty

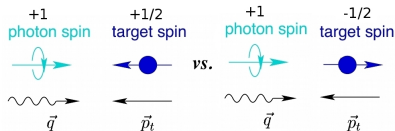
Data Set	Q^2 [GeV ²]	δd_2^{3He}
4.74 GeV	3.20	1.13×10^{-3}
5.89 GeV	4.32	8.26×10^{-4}
Combined	3.73	6.50×10^{-4}
Lattice QCD	5.00	1.50×10^{-3}

Table: Current [statistical uncertainty](#) on d_2^{3He} for $0.27 \leq x \leq 0.92$

But wait, there is [more...](#)

A_1 Asymmetry

$$A_1(x, Q^2) \equiv \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}}$$



- We measure A_1^n through the electron asymmetries $A_{\parallel}$ and $A_{\perp}$:

$$A_1^n = \frac{1}{D(1 + \eta\xi)} A_{\parallel}^n - \frac{\eta}{d(1 + \eta\xi)} A_{\perp}^n$$

- The asymmetries are given by:

$$A_{\parallel} \equiv \frac{\sigma_{\downarrow\uparrow} - \sigma_{\uparrow\uparrow}}{\sigma_{\downarrow\uparrow} + \sigma_{\uparrow\uparrow}} \quad \text{and} \quad A_{\perp} \equiv \frac{\sigma_{\downarrow\Rightarrow} - \sigma_{\uparrow\Rightarrow}}{\sigma_{\downarrow\Rightarrow} + \sigma_{\uparrow\Rightarrow}}$$

- D , η , ξ and d are kinematic factors

$A_1^3\text{He}$ Compared to World Data

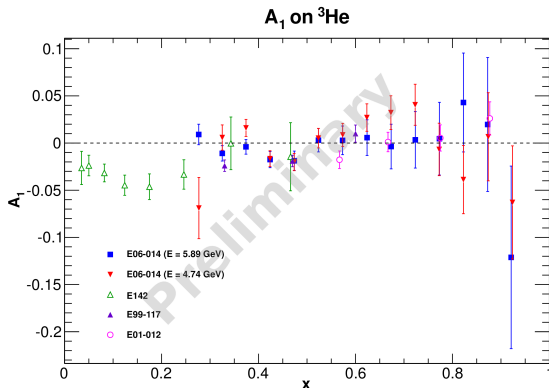


Figure: World $A_1^3\text{He}$ data with E06-014 DIS and resonance data. No radiative corrections to E06-014 data. E142: Phys. Rev. D **54**: 6620 (1996). E99-117: Phys. Rev. C **70**: 065207 (2004). E01-102: Phys. Rev. Lett. **101** 182502 (2008).

Summary

• Summary

- Exploit **transverse spin interactions** through g_2 structure function, to study higher twist effects
- Gain insight into the **Lorentz color force** inside the nucleon through the matrix element d_2
- Good statistical precision on the data will provide a **direct** test of **lattice QCD**

• Current/Future Work

- Radiative corrections to asymmetries are underway
- BigBite simulations also well underway
- Wally Melnitchouk is looking into neutron extraction of $d_2^{3He} \rightarrow d_2^n$ and $A_1^{3He} \rightarrow A_1^n$

Acknowledgements

- Thanks to the spokespeople X. Jiang, S. Choi, B. Sawatzky, and Z.-E. Meziani.
- Thanks to P. Solvignon, K. Slifer, V. Sulkosky, E. Schulte, C. Dutta, K. Allada, X. Qian and the rest of the d_2^n , Transversity and the Hall A Collaborations, and the Hall A Staff at Jefferson Lab for their advice, suggestions, and continued support.
- Thank you to Temple University and Carnegie Mellon University.
- Primary analysis team: B. Sawatzky, D. Parno, D. Flay, M. Posik, Y. Zhang, G. Franklin, Z.-E. Meziani
- This work is supported by:
DOE Award from Temple University #DE-FG02-94ER40844.

Backup

Pair Production Correction (1): Positron-Electron Ratio

$$R = \left(\frac{N_p^{e+}}{N_n^{raee-}} \right) = \kappa \left(\frac{N_n^{e+}}{N_n^{raee-}} \right)$$

$$\kappa = \left(\frac{N_p^+}{N_n^+} \right)$$

- κ measured during 4-pass running, assumed to have same values at 5-pass running (verifying with GEANT4)
- Where p, n mean BigBite is in positive or negative polarity. $raee-$ is measured electron with electron cuts applied
- We assume $\frac{N_p^{e+}}{N_n^{raee-}}$ is closer to reality based on LHRS $\frac{\sigma_{e+}}{\sigma_{e-}}$ measurements

Backup

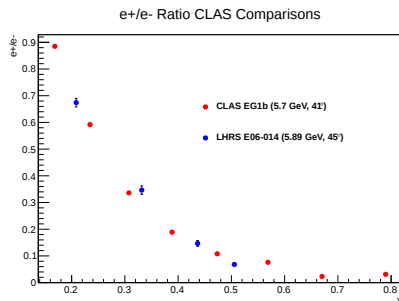
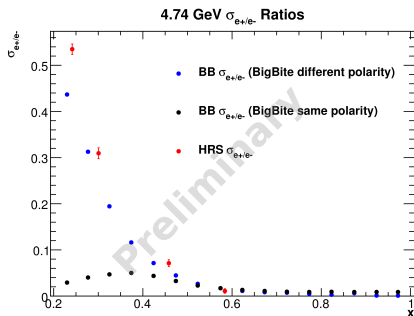
Pair Production Correction (2): Asymmetry Correction

$$\begin{aligned}
 N_n^{e-} &= N_n^{rawe-} - N_n^{e+} \\
 A_n^{e-} &= \left(\frac{N_n^{rawe-}}{N_n^{e-}} \right) A_n^{rawe-} - \left(\frac{N_n^{e+}}{N_n^{e-}} \right) A_n^{e+} \\
 \frac{N_n^{e-}}{N_n^{rawe-}} &= 1 - R \\
 A_n^{e-} &= \frac{A_n^{rawe-} - R A_n^{e+}}{1 - R} \\
 \delta A_n^{e-} &= \sqrt{\left(\frac{\delta A_n^{rawe-}}{1 - R} \right)^2 + \left(\frac{R \delta A_n^{e+}}{1 - R} \right)^2}
 \end{aligned}$$

assumes $\delta R = 0$

Backup

Pair Production Correction (4): Ratio Comparison



Backup

Pair Production Correction (4): 4.74 GeV Results

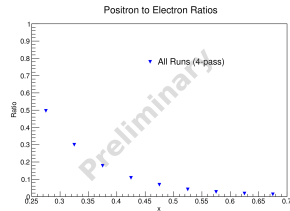
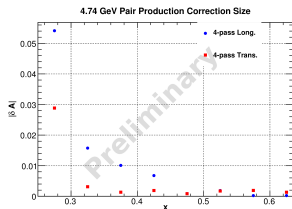
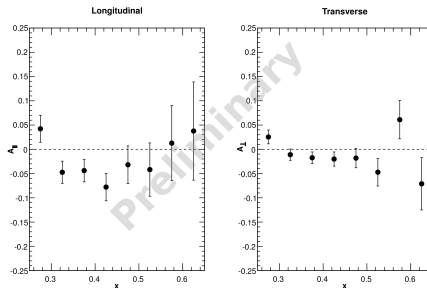


Figure: Positron asymmetries



Backup

Pair Production Correction (5): 5.89 GeV Results

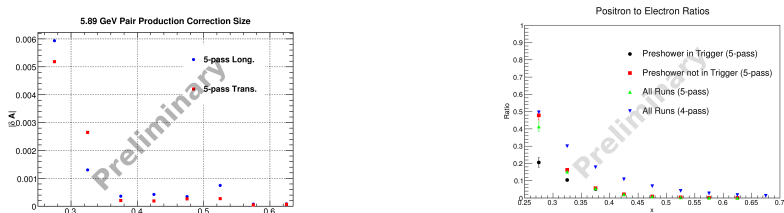
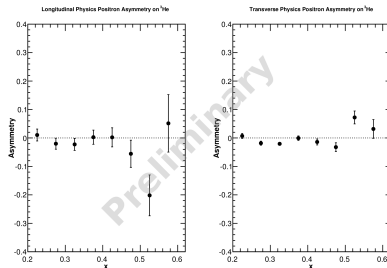
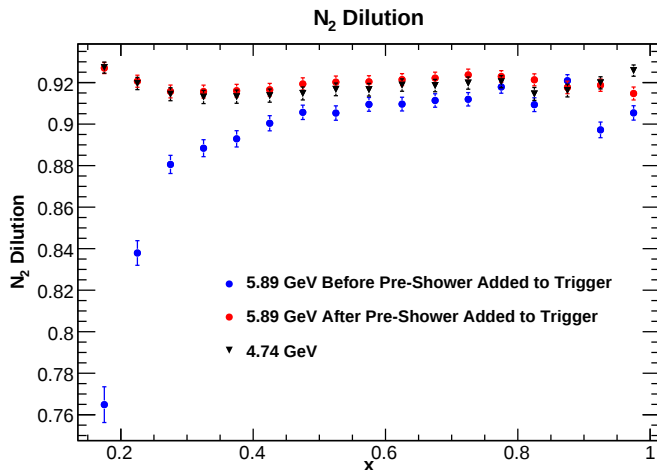


Figure: Positron asymmetries



Backup

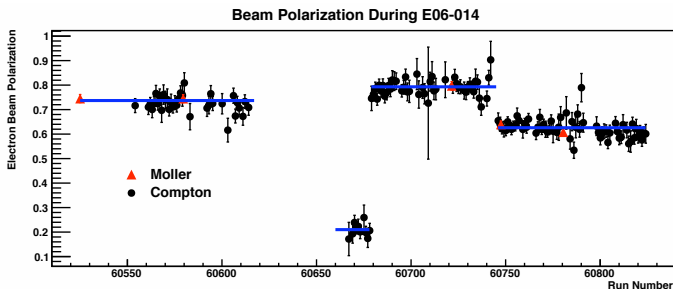
Nitrogen Dilution



Backup

Electron Beam Polarization

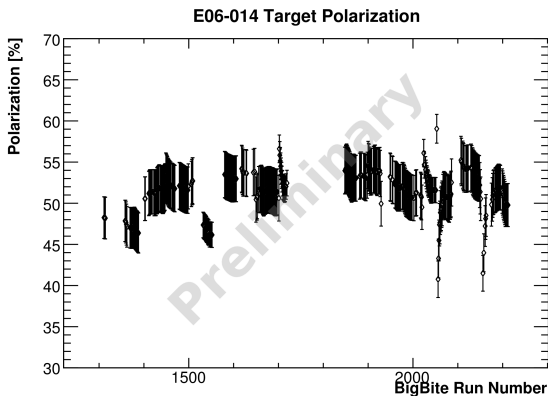
- Two methods: Møller and Compton measurements
- Combine both methods to achieve an error of $\sim 1.6\%$



Backup

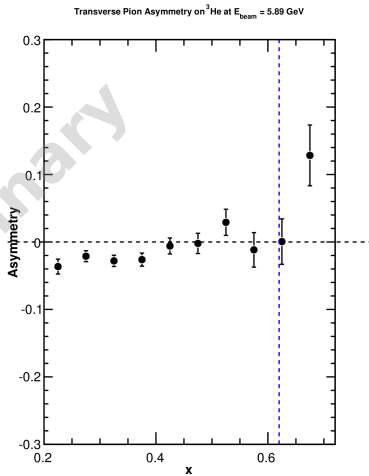
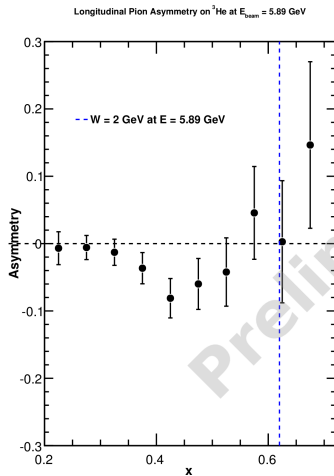
^3He Target Polarization

- NMR measurement every four hours (target chamber)
- EPR at every spin rotation (pumping chamber)



Backup

Pion Asymmetries



Backup

Spin Structure Functions

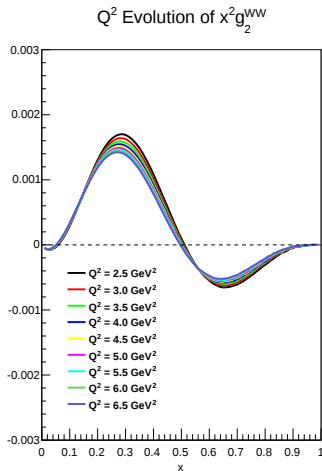
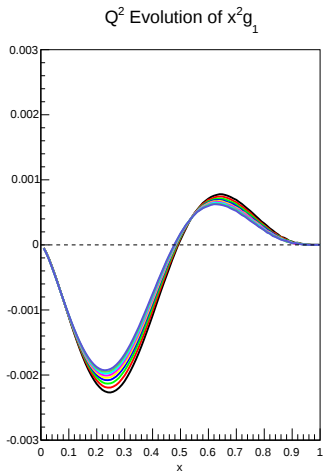
- The spin structure functions:

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

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

Backup

Q^2 Dependence: DSSV Fit



Backup

Q^2 Dependence: Selected Experiments

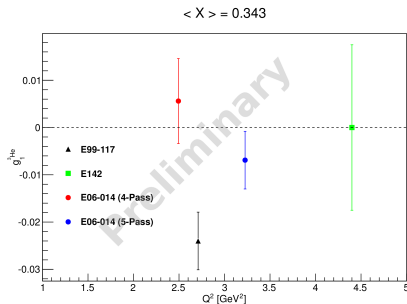


Figure: g_1^{He} vs. Q^2

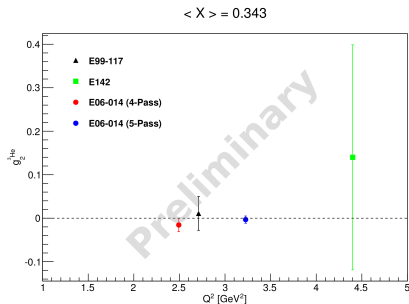


Figure: g_2^{He} vs. Q^2

Backup

Q^2 Dependence: Interpolation

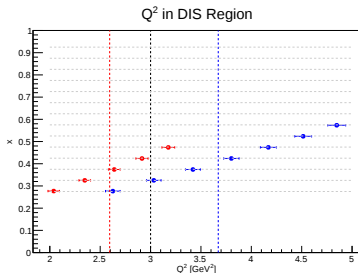


Figure: x vs Q^2 for 4 and 5 pass data. Red dashed line shows average Q^2 in the DIS region for the 4 pass data, the blue dashed line shows average Q^2 in the DIS region for the 5 pass data and the black dashed line shows the average Q^2 value in the DIS region over the entire data set.

- 3 overlapping data points
- $< Q^2 >$
 - 2.594 GeV^2 (4-pass)
 - 3.672 GeV^2 (5-pass)
 - 3.078 GeV^2 (4+5 pass)
- (4+5 pass) Drawn at $Q^2 = 3.0 \text{ GeV}^2$ here to get more data points for interpolation

Backup

Q^2 Dependence: Interpolation Comparison

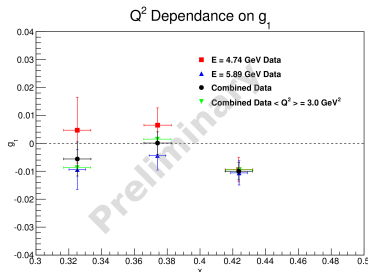


Figure: g_1 on ^3He as a function of x in a selected DIS region for various Q^2 treatments.

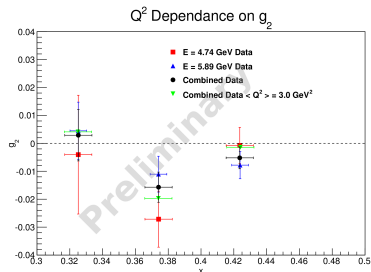


Figure: g_2 on ^3He as a function of x in a selected DIS region for various Q^2 treatments.

Backup

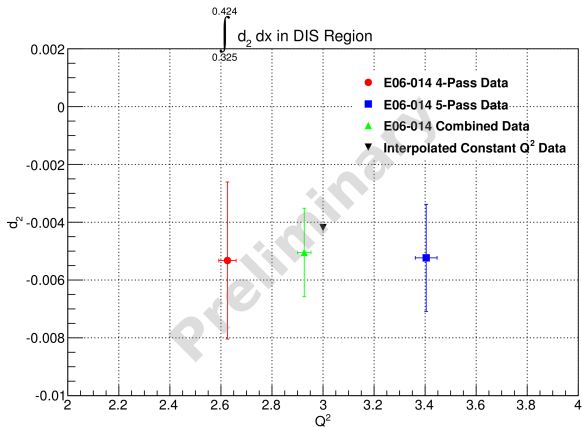
 Q^2 Dependence: d_2 Comparison

Figure: d_2 on ^3He as a function of x in a selected DIS region for various Q^2 treatments.