# 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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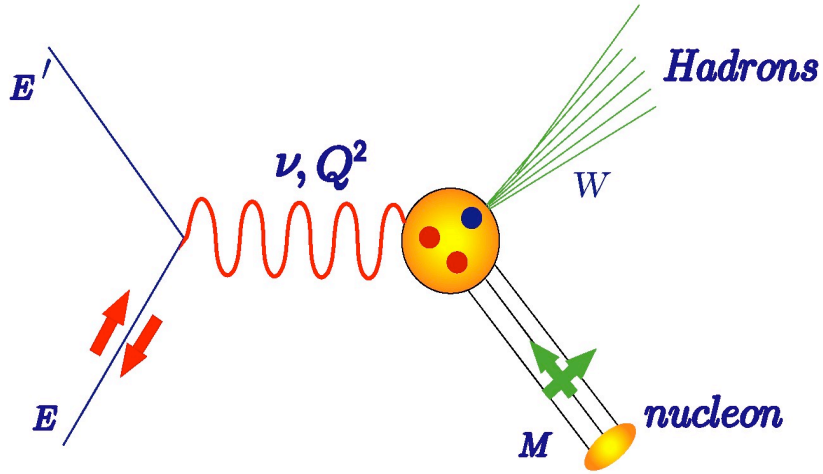
12/10/12

# Outline

# Polarized DIS

- Probes the spin content of the nucleon




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

$$\frac{d^2\sigma^{(\downarrow\Rightarrow-\uparrow\Rightarrow)}}{dE'd\Omega} = \frac{4\alpha^2\sin\theta}{MQ^2}\frac{E'^2}{\nu^2 E}\left[\nu g_1\left(x,Q^2\right)+2Eg_2\left(x,Q^2\right)\right]$$

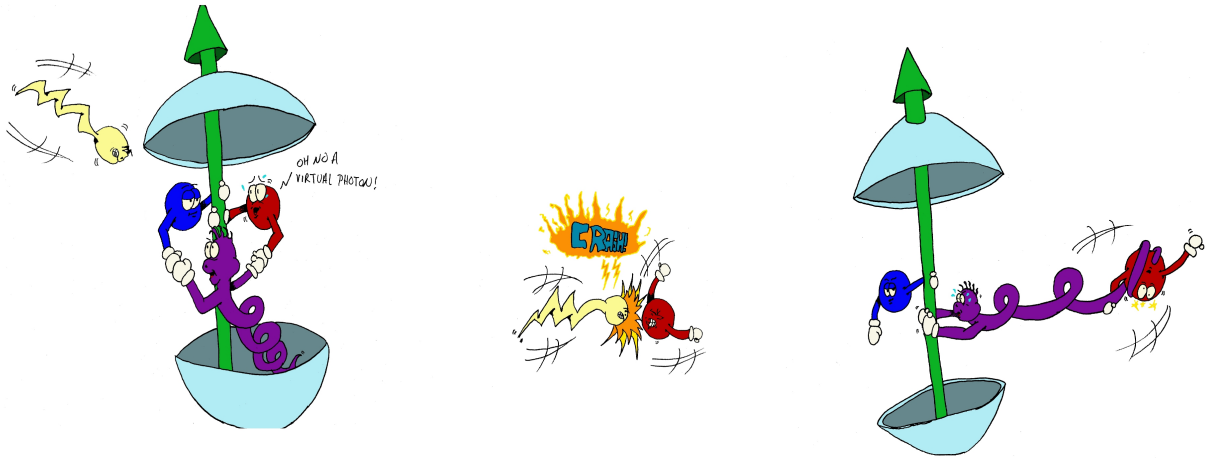
# Probing Quark-Gluon Dynamics in the Nucleon

- $d_2^n$ gives access to quark-gluon correlations

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

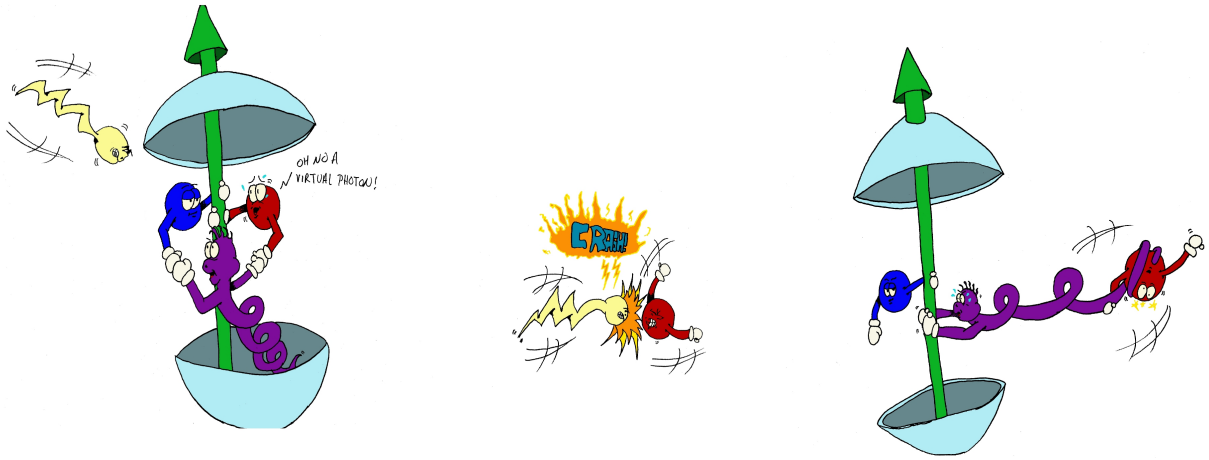
- What is $d_2^n$?
  - Average transverse Lorentz color force acting on a quark immediately after being struck by a virtual photon (M. Burkardt, hep-ph/0905.4079v1)
  - $d_2^n$ is dominated by large x contributions

# What is $d_2^n$?



# What is $d_2^n$?

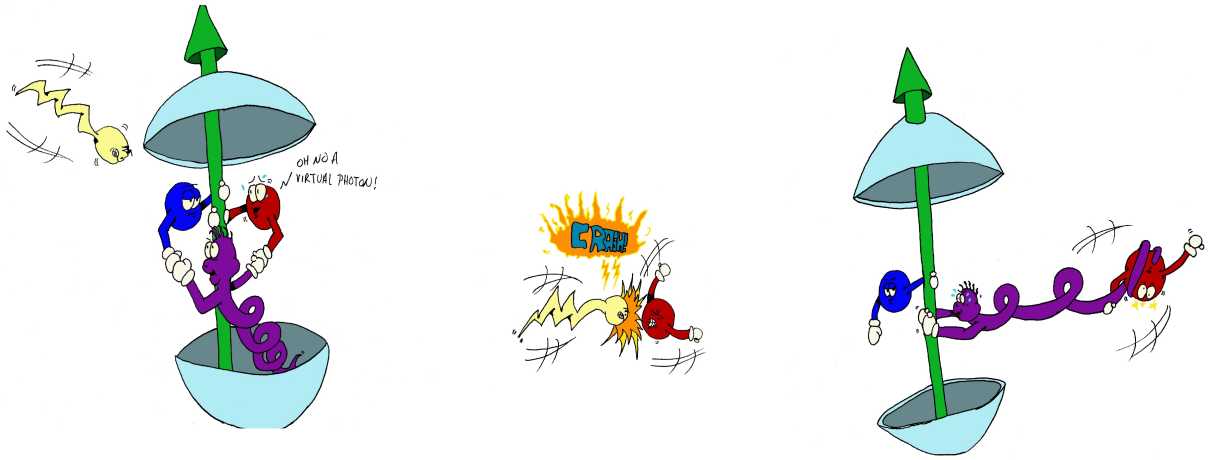
So $d_2^n$ is...




- A measure of quark-gluon correlations

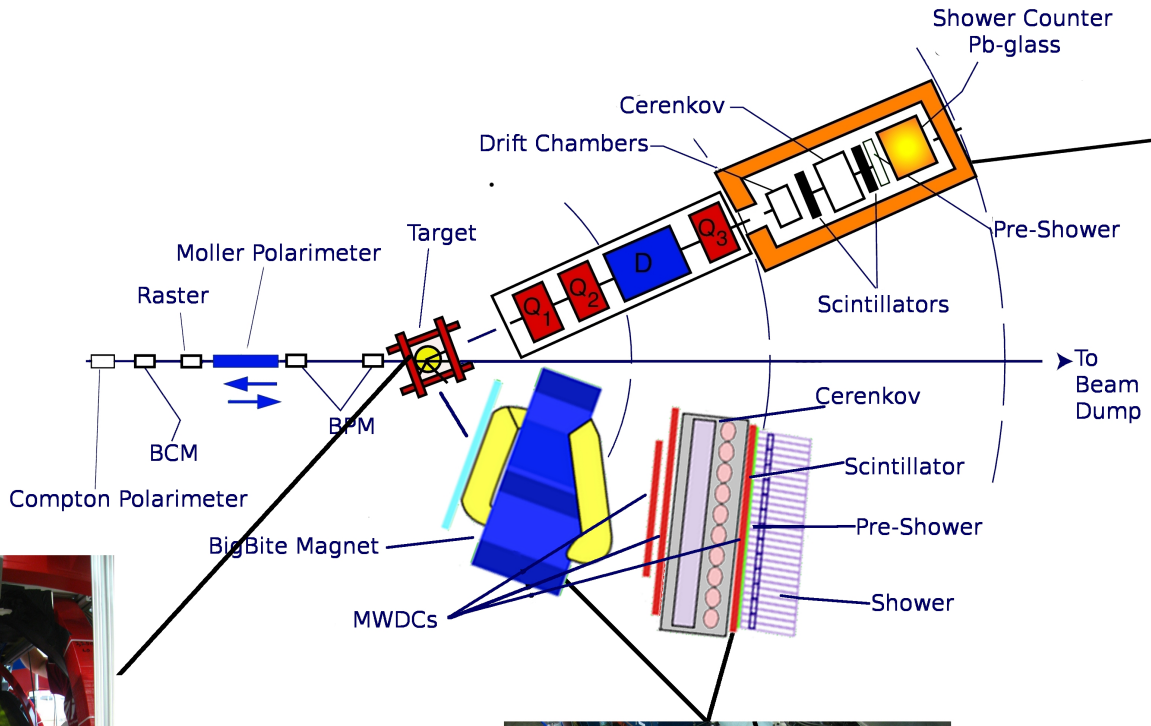
# What is $d_2^n$?

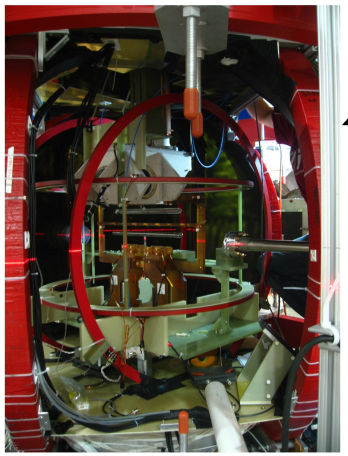
So $d_2^n$ is...

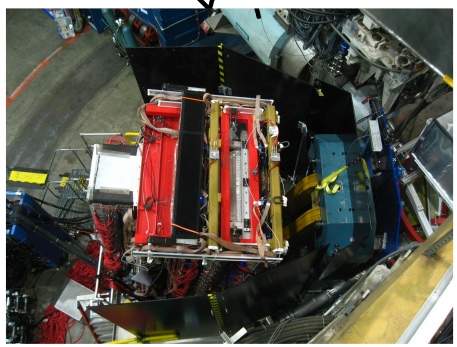



- A measure of quark-gluon correlations
- A force felt between the quark struck by the virtual photon and the spectator quarks

# The E06-014 Experiment (1)

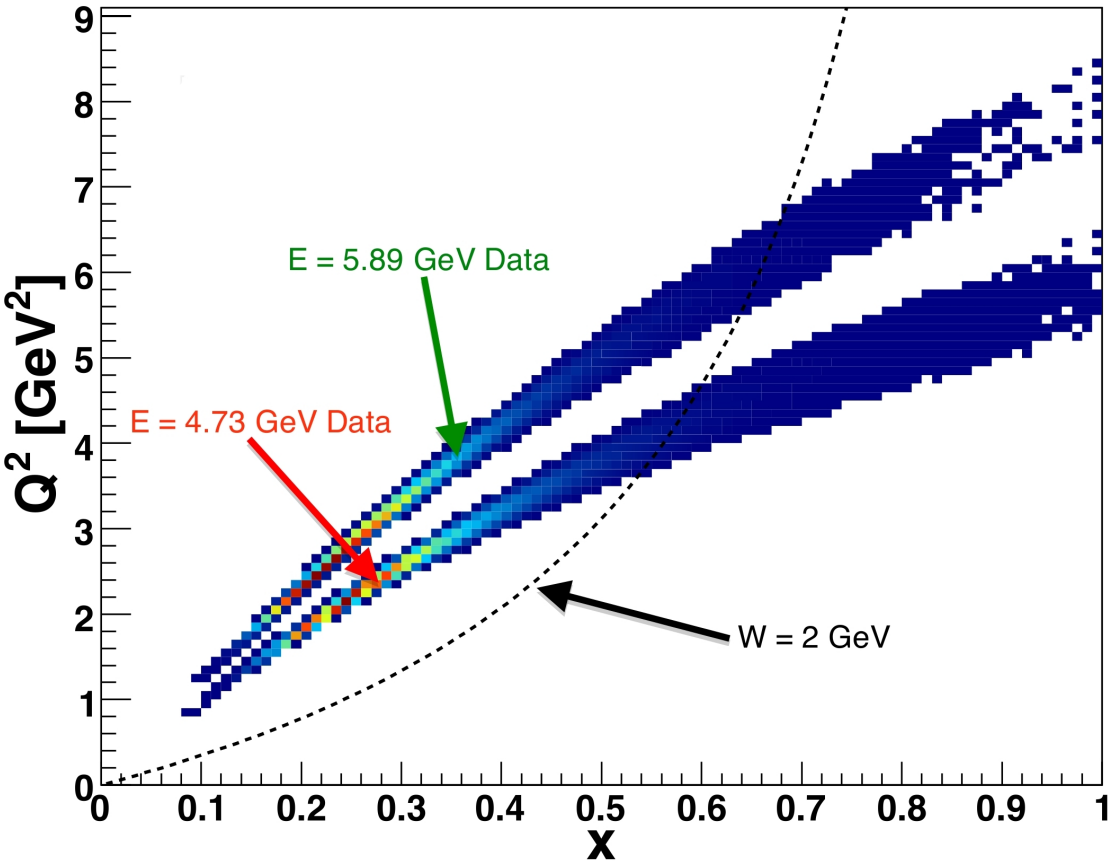




# The E06-014 Experiment (2)

## 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

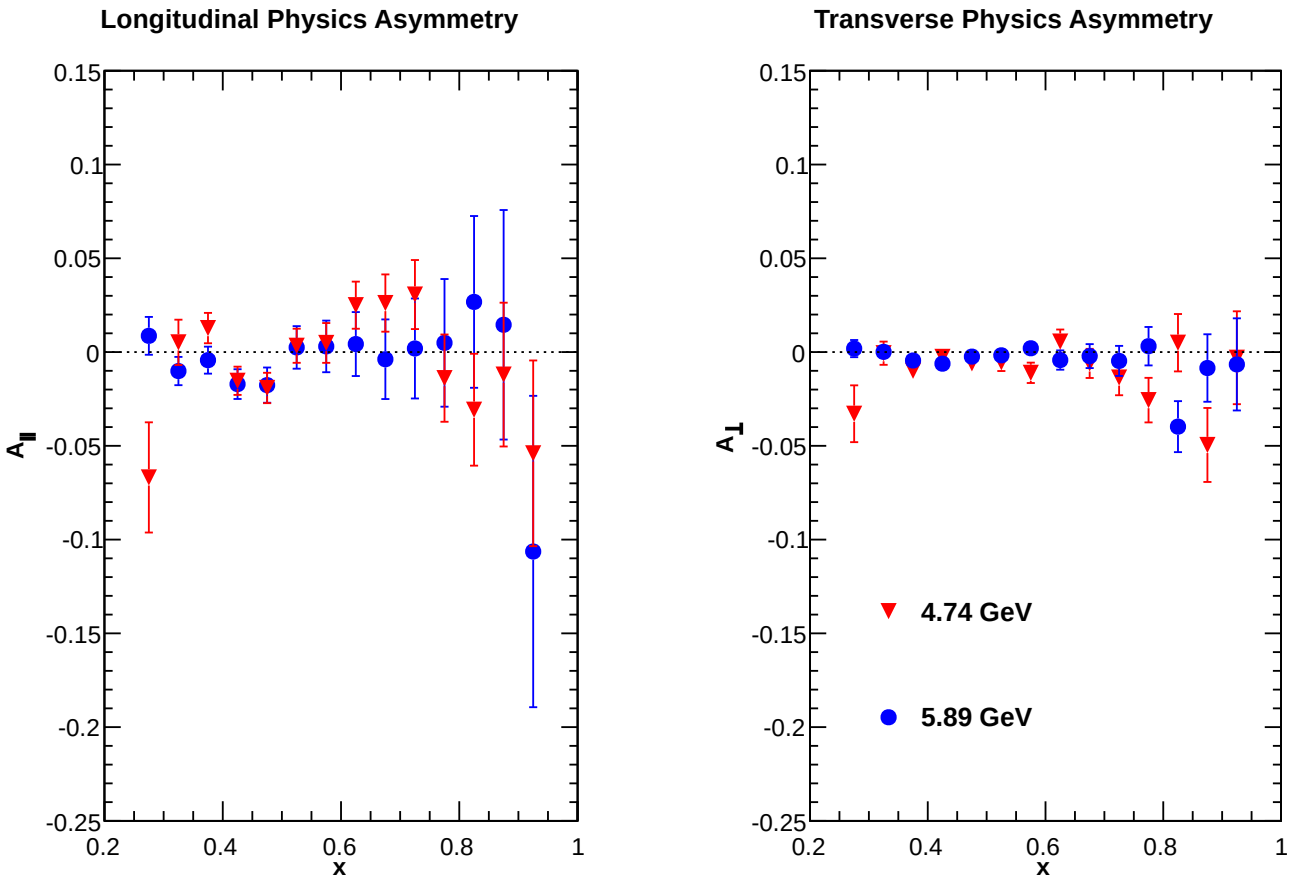
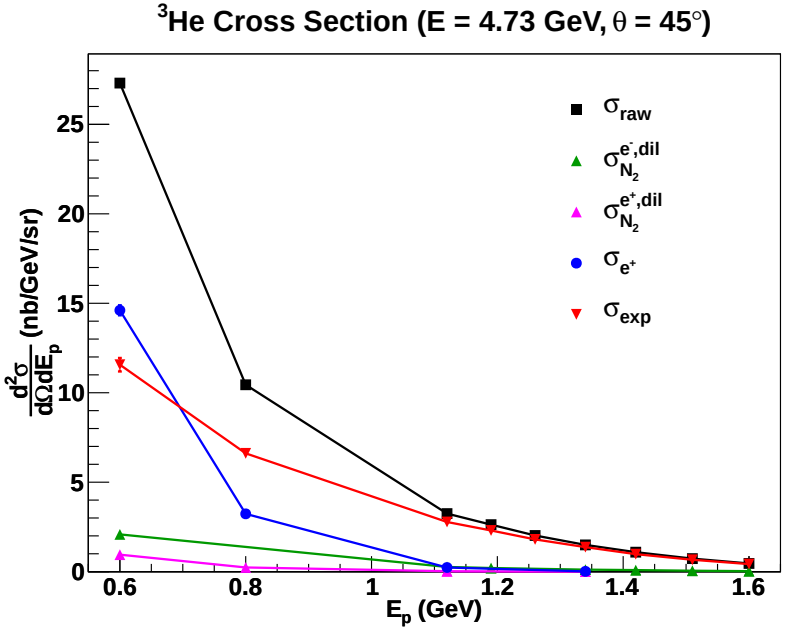
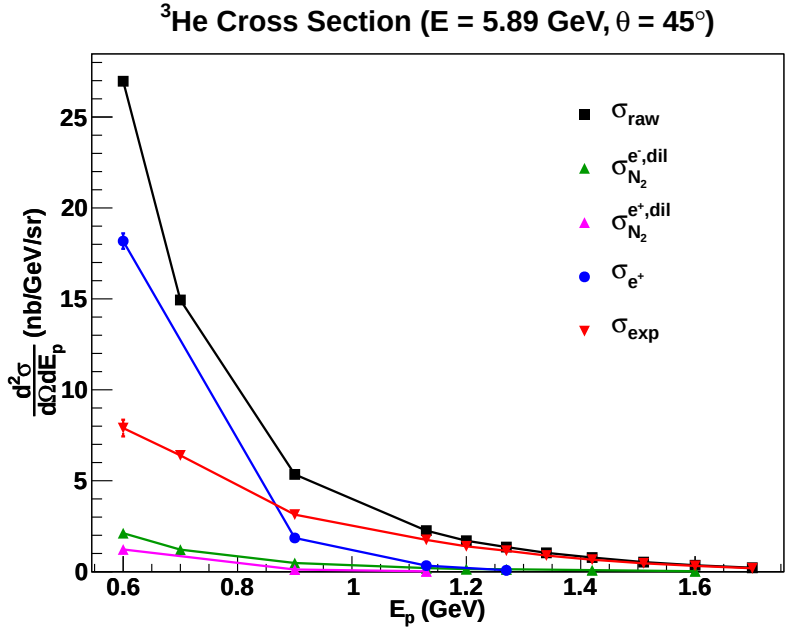



Figure: Preliminary electron asymmetries in the DIS and resonance regions. W = 2 GeV for E = 5.89 GeV is at $x$ = 0.62 and $x$ = 0.52 for E = 4.74 GeV. Radiative corrections not yet applied.

# Cross Sections



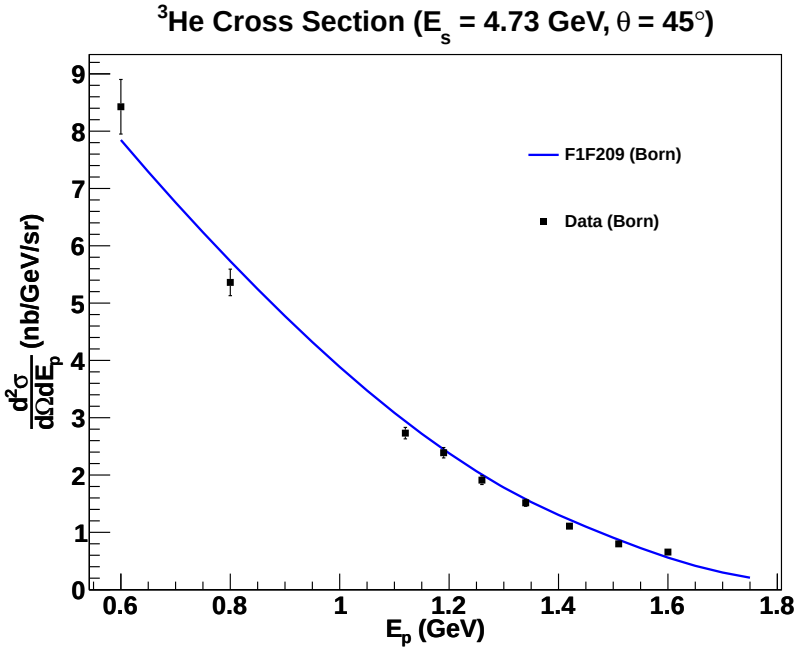

(a) E = 4.74 GeV



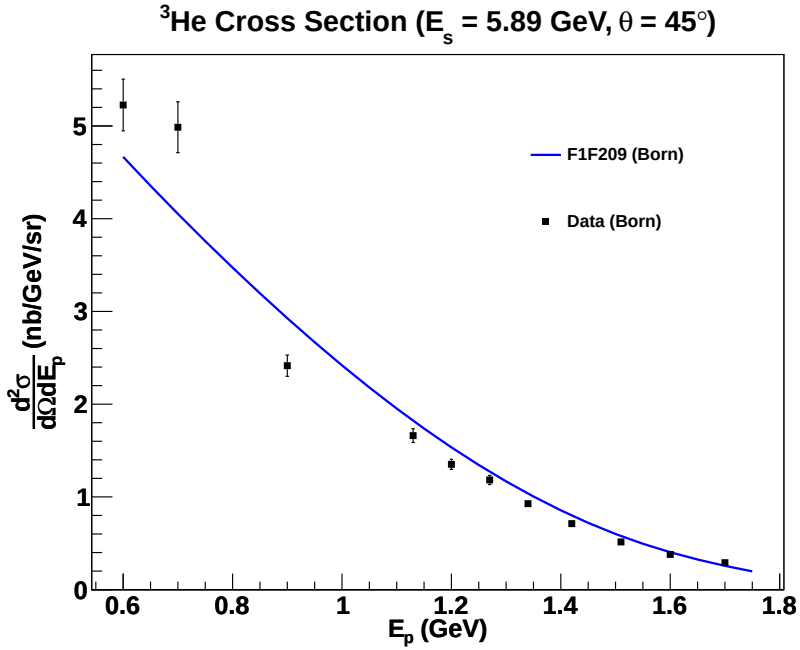

(b) E = 5.89 GeV

Figure: Raw $^3$He cross section and positron and nitrogen background cross sections. Background-subtracted cross section shown in red. Statistical errors only.

# Born Cross Sections




(a) E = 4.74 GeV




(b) E = 5.89 GeV

Figure: Born cross section. Error bars include statistical and systematic. Blue curve is P. Bosted's F1F209 inclusive cross section model.

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

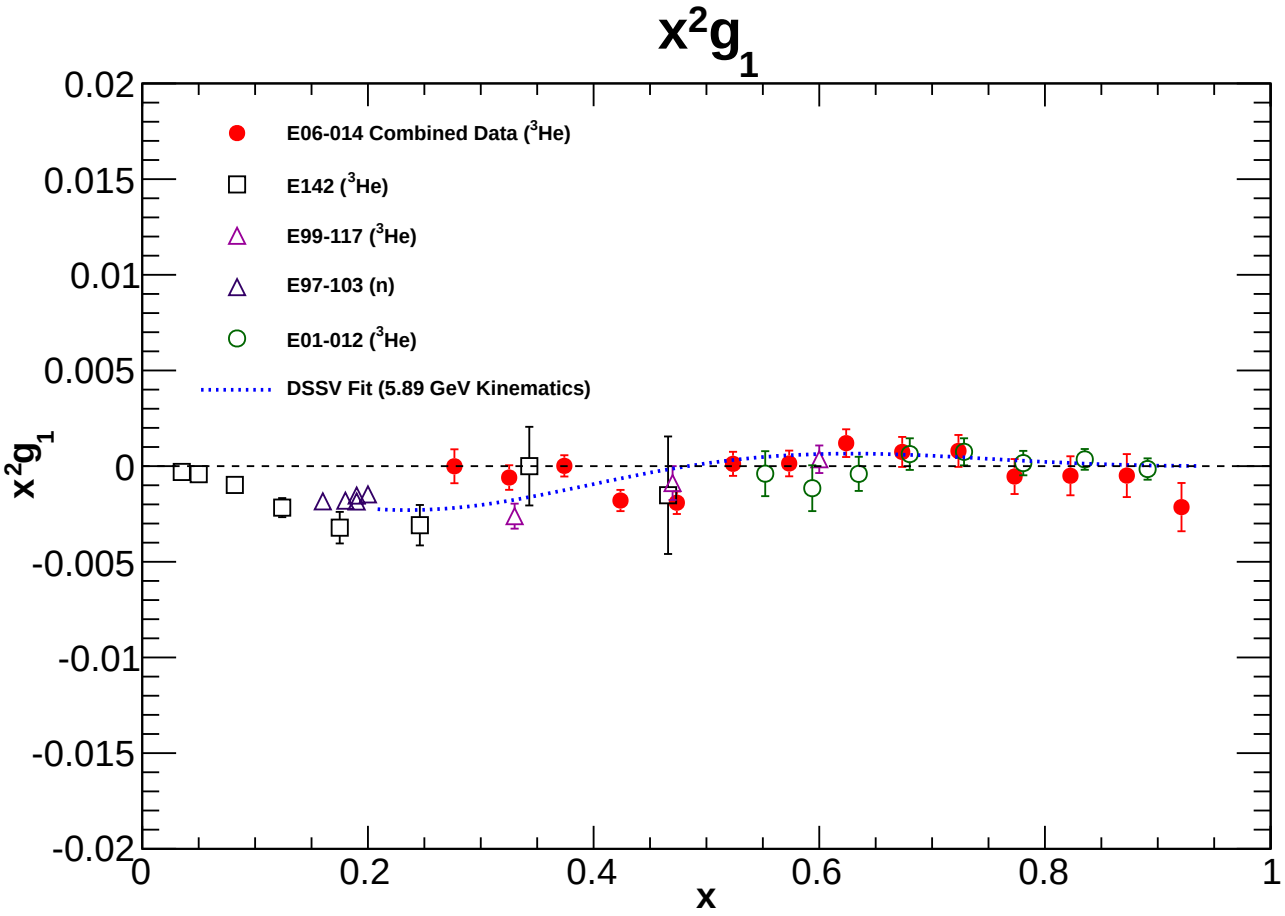



Figure: Preliminary $x^2 g_1$ structure function on $^3$He in DIS and resonance regions. Radiative corrections to asymmetries not yet applied.

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

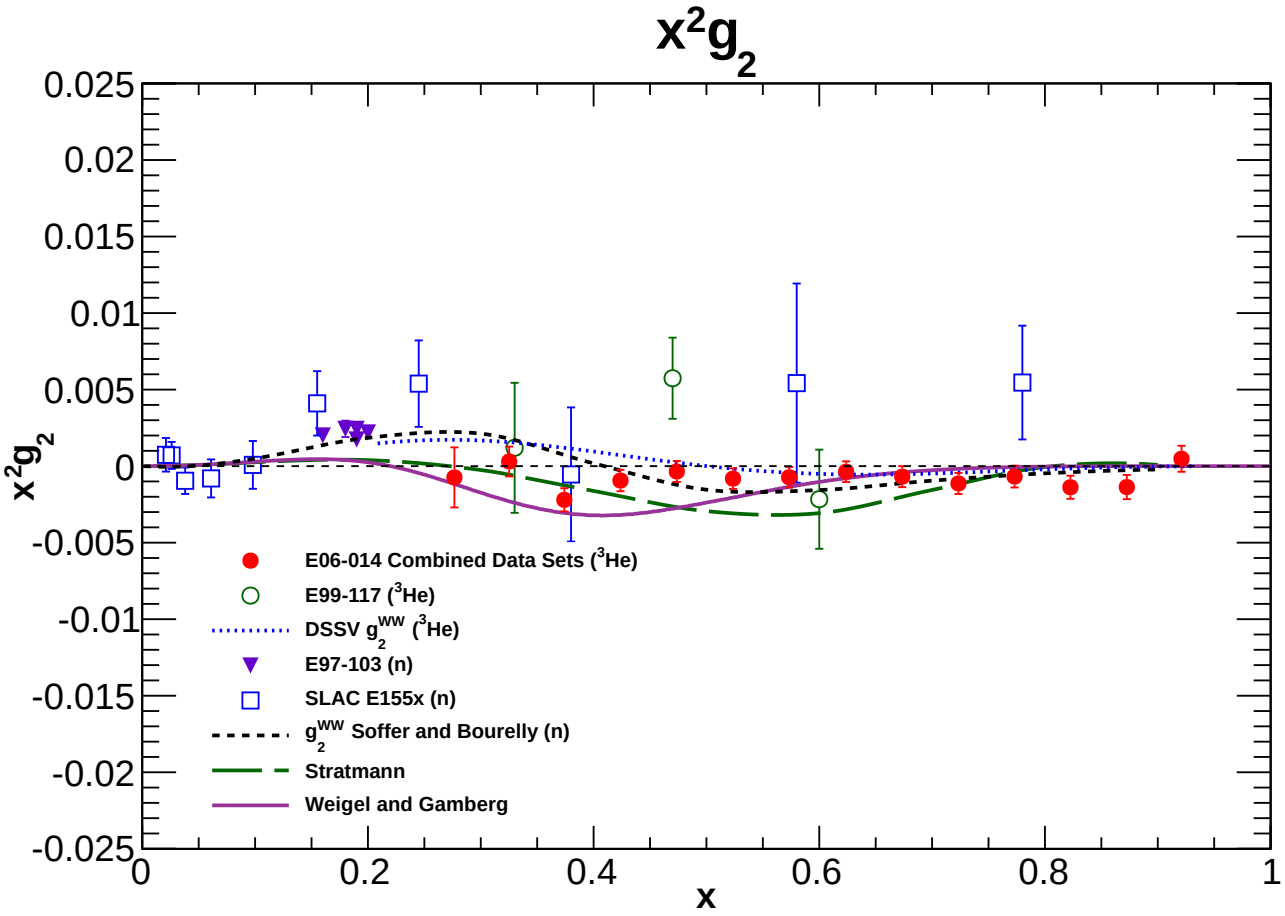



Figure: Preliminary $x^2 g_2$ structure function on $^3$He in DIS and resonance regions. Radiative corrections to asymmetries not yet applied.

# Current $d_2$ Uncertainty

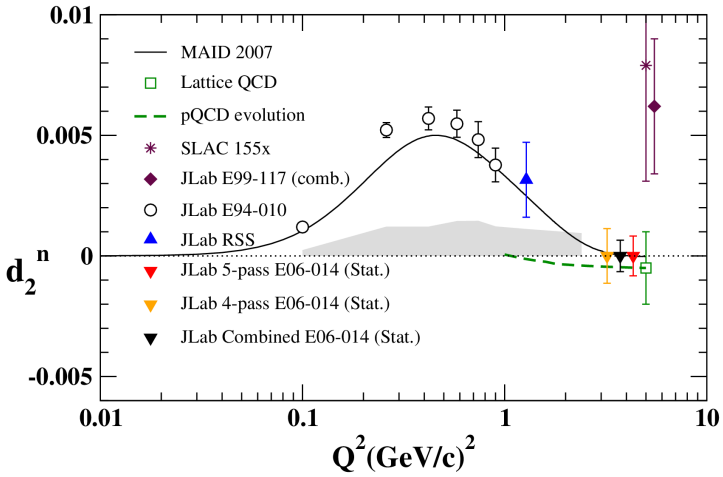



Figure: E06-014 statistical uncertainty on $d_2^n$.

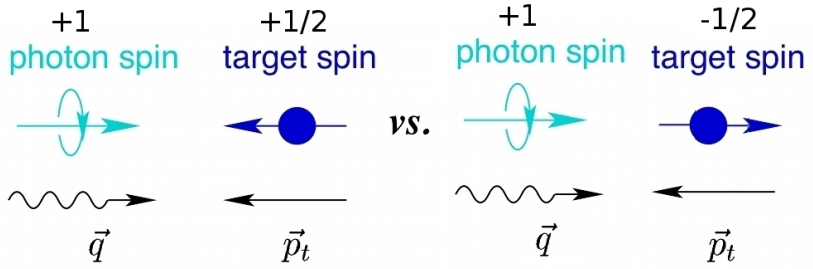
| Data Set | $Q^2$ [GeV$^2$] | $\delta d_2^{^3He}$ |
|---|---|---|
| 4.74 GeV | 3.20 | $1.13\times10^{-3}$ |
| 5.89 GeV | 4.32 | $8.26\times10^{-4}$ |
| Combined | 3.73 | $6.50\times10^{-4}$ |

Table: Current statistical uncertainty on $d_2^3$ for $0.27 \leq x \leq 0.92$

But wait, there is more...

# $A_1$ Asymmetry

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




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

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

  - The asymmetries are given by:

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

  - $D$, $\eta$, $\xi$ and $d$ are kinematic factors

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

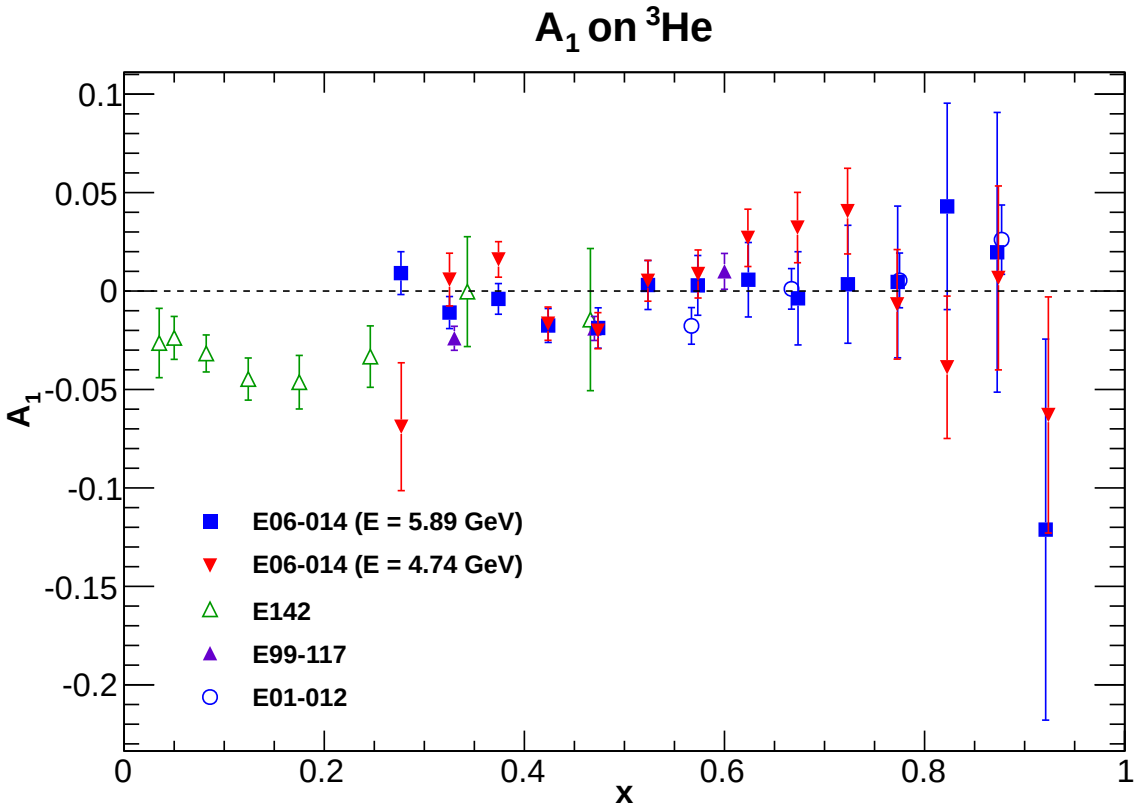



Figure: World $A_1^{^3\mathrm{He}}$ data with E06-014 DIS and resonance data. No radiative corrections to E06-014 data.E142: Phys. Rev. D **54**: 6620 (1996). E99-117: Phys. Rev. C **70**: 065207 (2004). E01-102: Phys. Rev. Lett. **101** 182502 (2008).

# 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 neutron through the matrix element $d_2^n$
  - Good statistical precision on the data will provide a direct test of lattice QCD
  - Born cross sections are finalized
- 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 $A_1^{^3\mathrm{He}} \rightarrow A_1^n$

# 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

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

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

- $\kappa$ 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. $rawe-$ is measured electron with electron cuts applied
- We assume $\frac{N_p^{e+}}{N_n^{rawe-}}$ is closer to reality based on LHRS $\frac{\sigma_{e^+}}{\sigma_{e^-}}$ measurements

# Backup

## Pair Production Correction (2): Asymmetry Correction

$$N_n^{e-} = N_n^{rawe-} - N_n^{e+}$$

$$A_n^{e-} = \left(\frac{N_n^{rawe-}}{N_n^{e-}}\right) A_n^{rawe-} - \left(\frac{N_n^{e+}}{N_n^{e-}}\right) A_n^{e+}$$

$$\frac{N_n^{e-}}{N_n^{rawe-}} = 1 - R$$

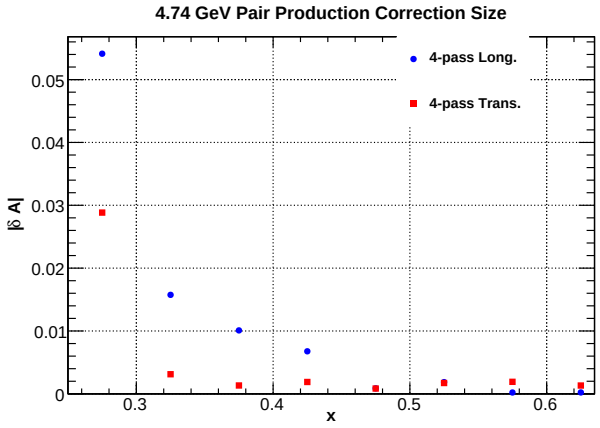
$$A_n^{e-} = \frac{A_n^{rawe-} - R A_n^{e+}}{1 - R}$$

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

assumes $\delta R = 0$

# Backup

## Pair Production Correction (3): 4.74 GeV Results



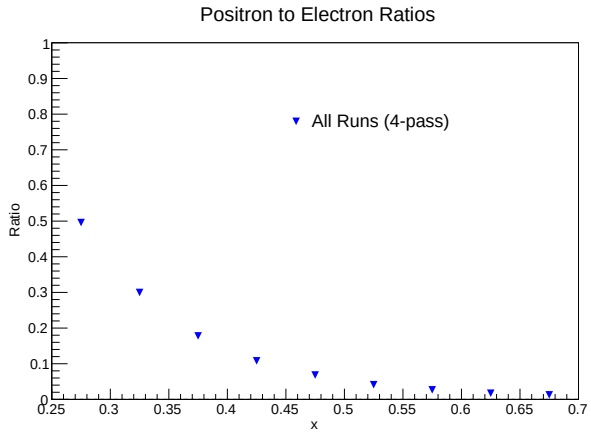
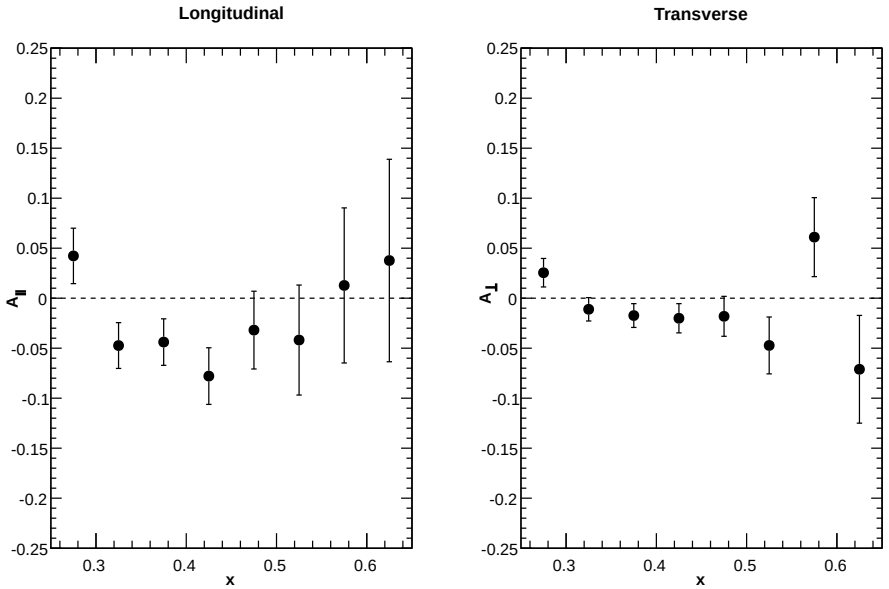
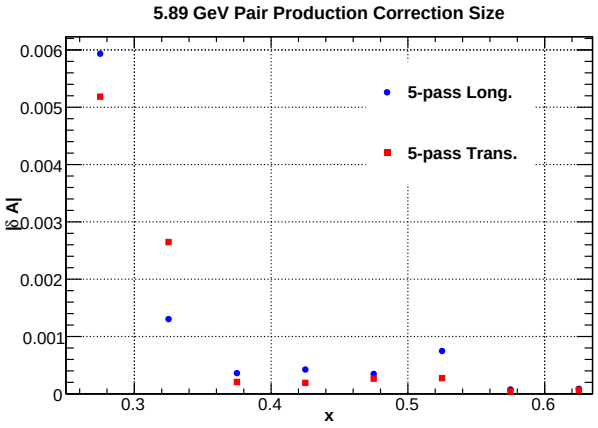




Figure: Positron asymmetries



# Backup

## Pair Production Correction (4): 5.89 GeV Results



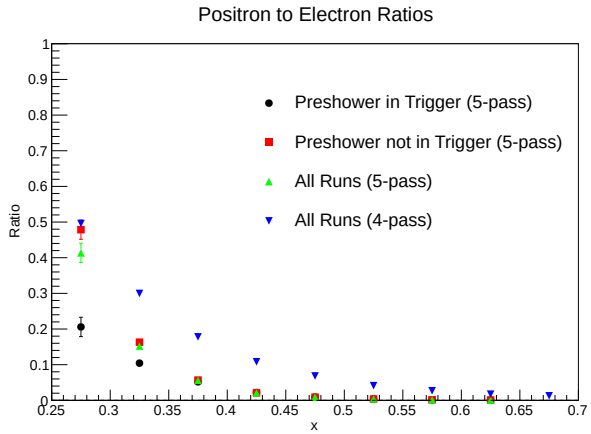
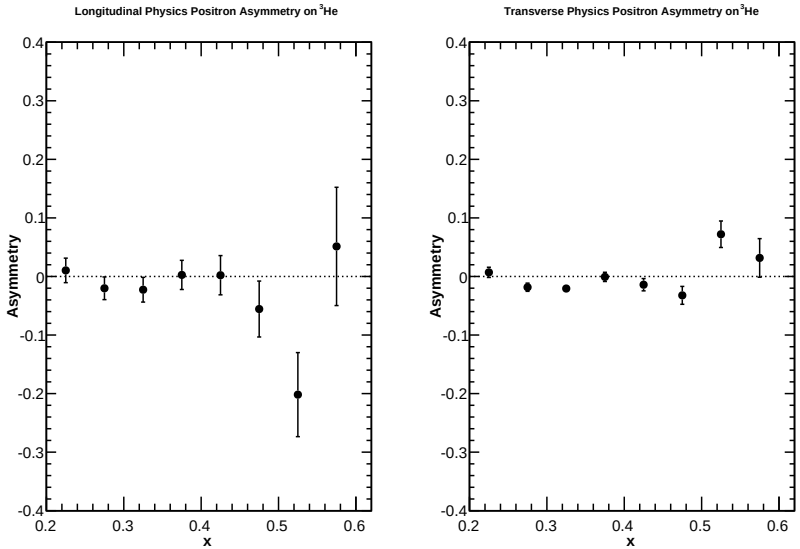
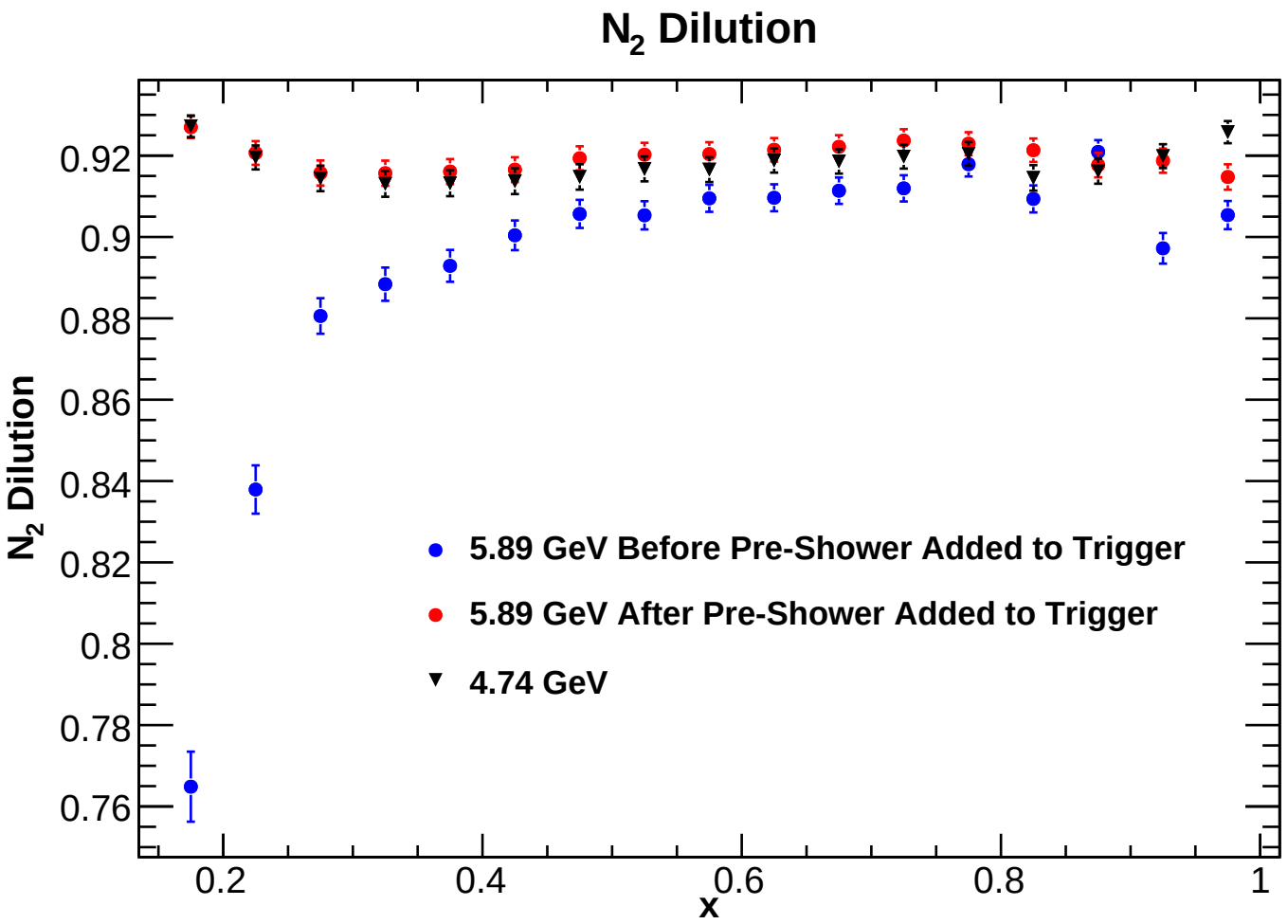




Figure: Positron asymmetries



# Backup

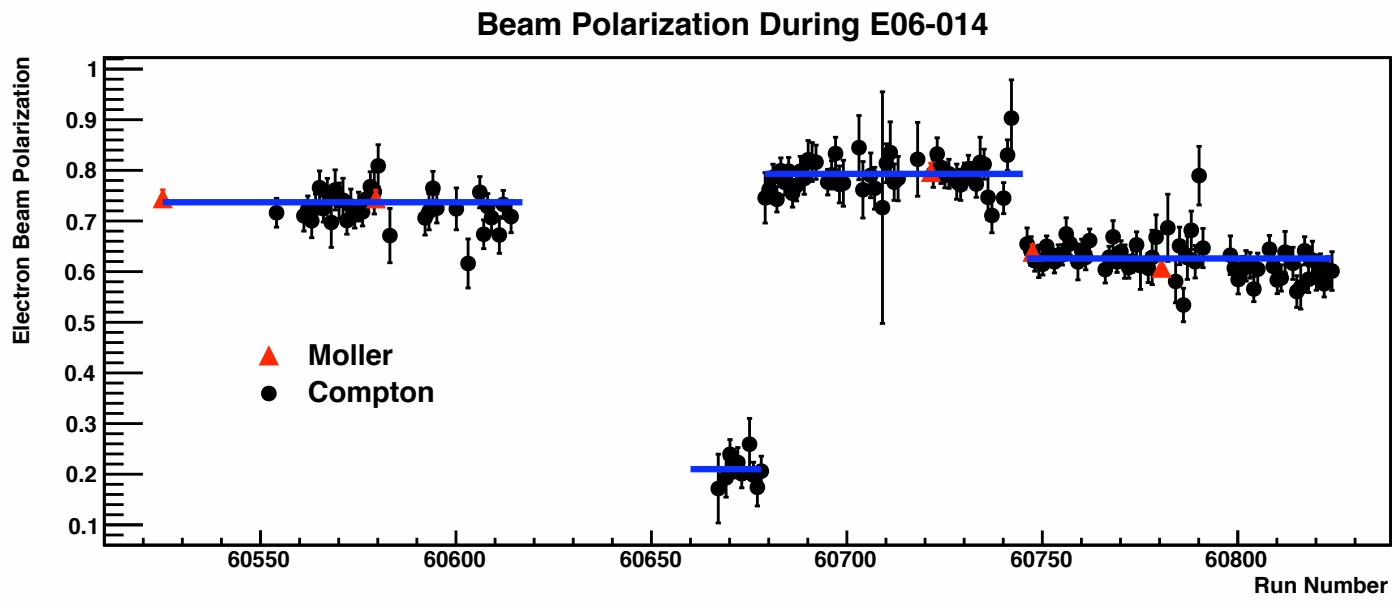
## Nitrogen Dilution



# Backup

## Electron Beam Polarization

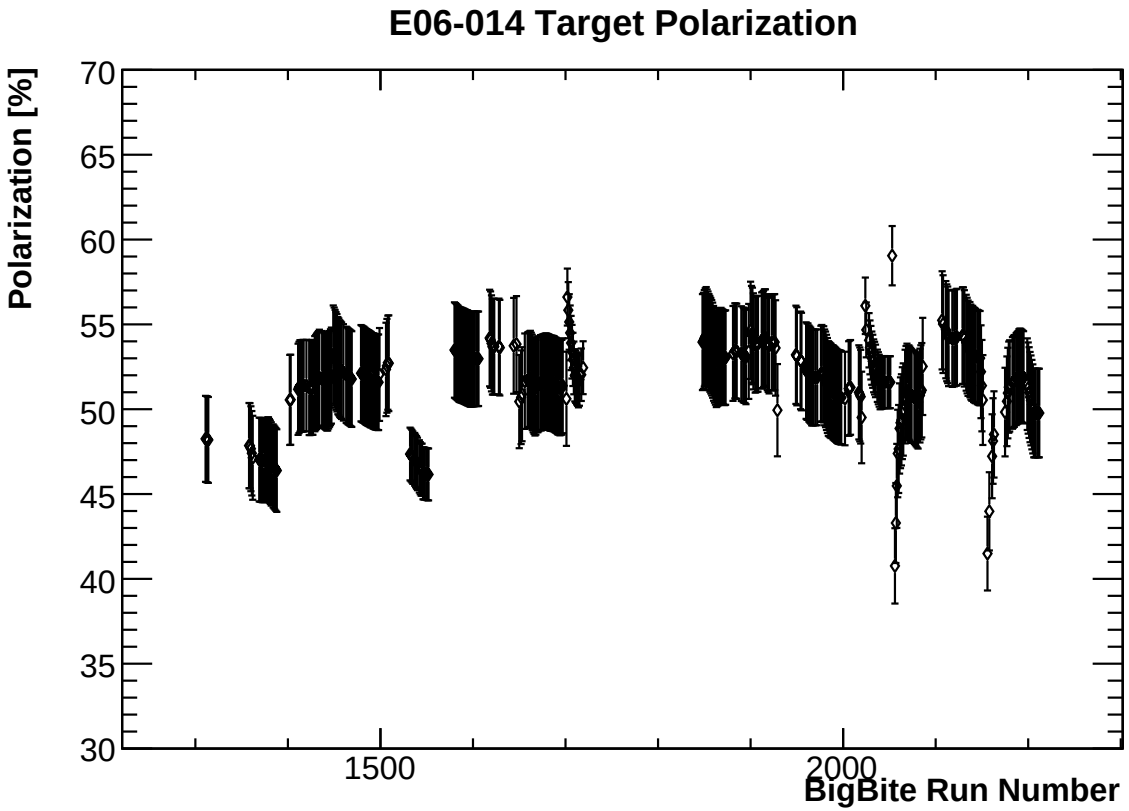
- Two methods: Møller and Compton measurements
- Combine both methods to achieve an error of $\sim 1.6\%$



# Backup

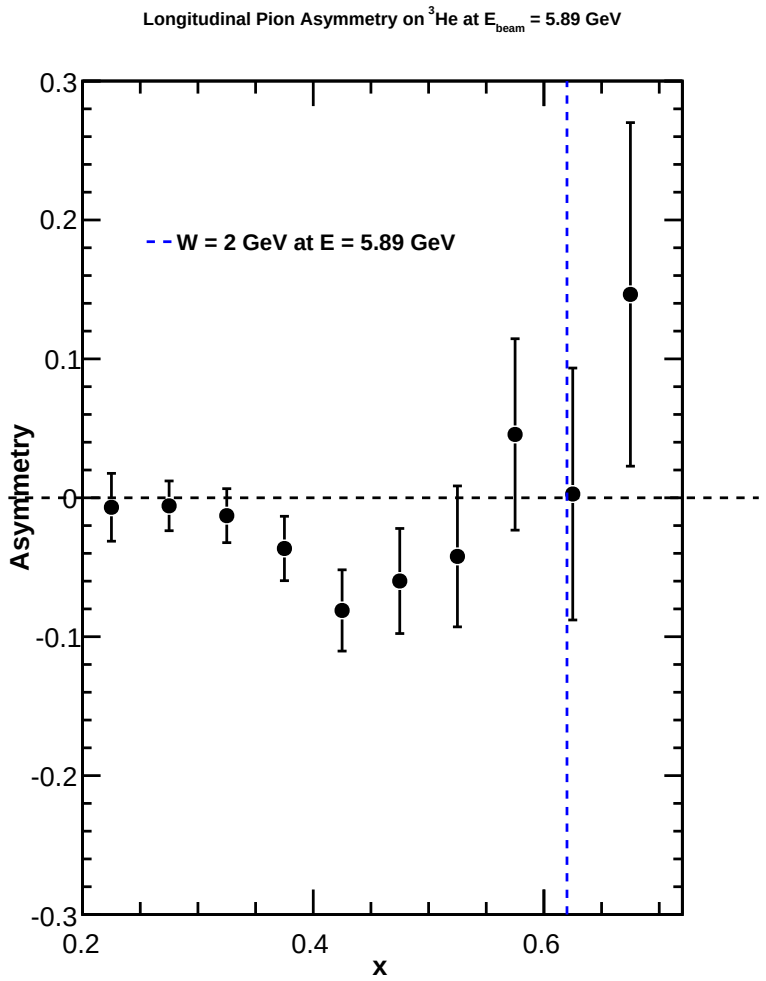
## $^3$He Target Polarization

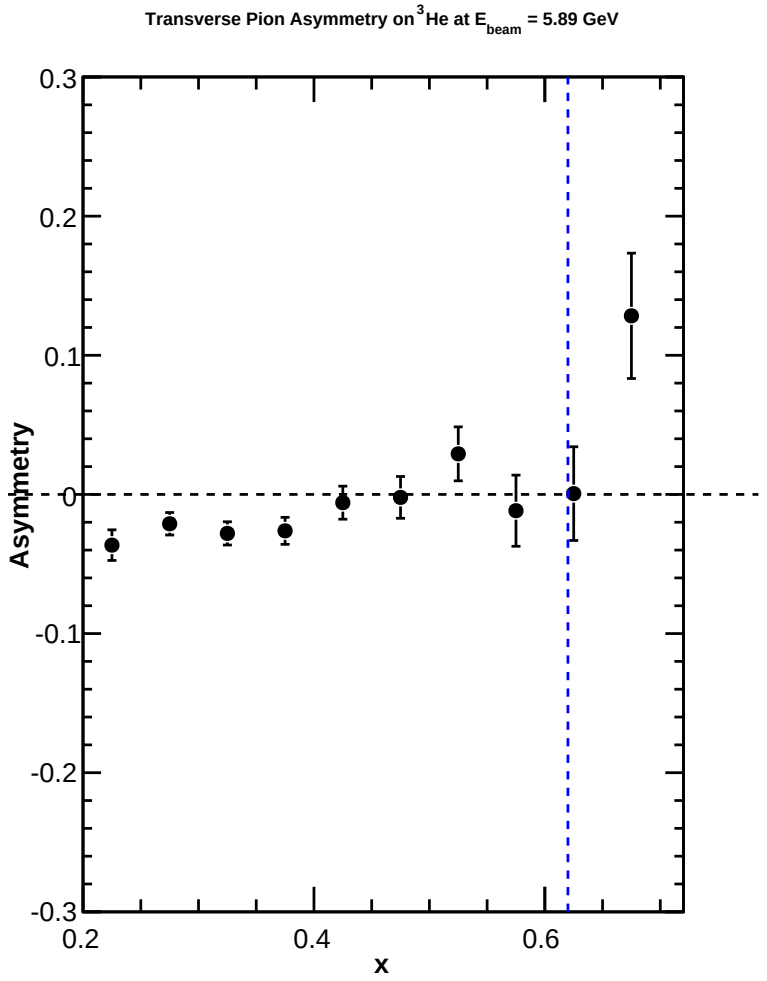
- NMR measurement every four hours (target chamber)
- EPR at every spin rotation (pumping chamber)



# Backup

## Pion Asymmetries



# Backup

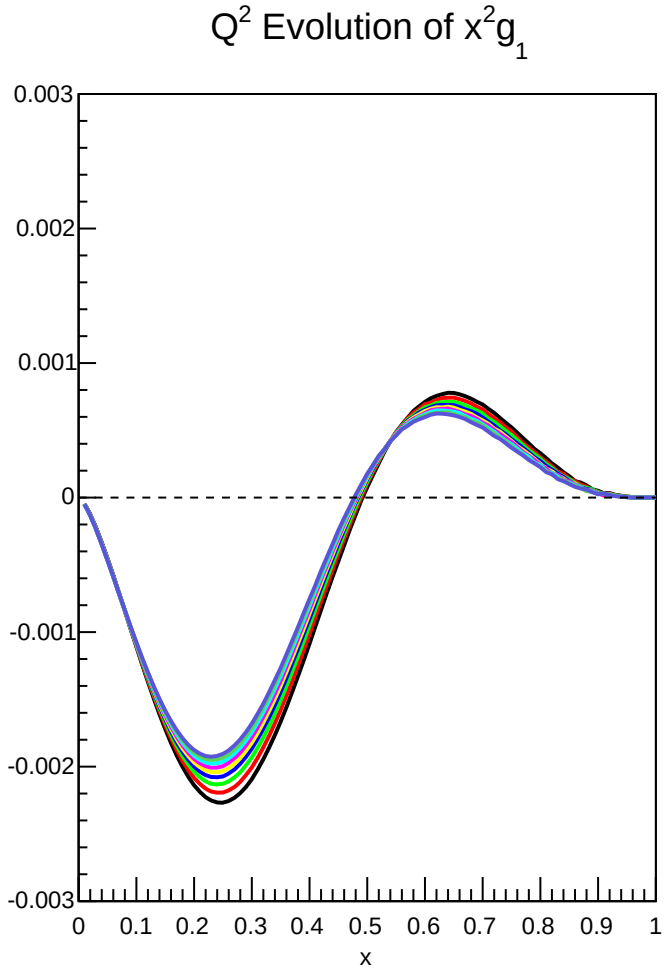
## Spin Structure Functions

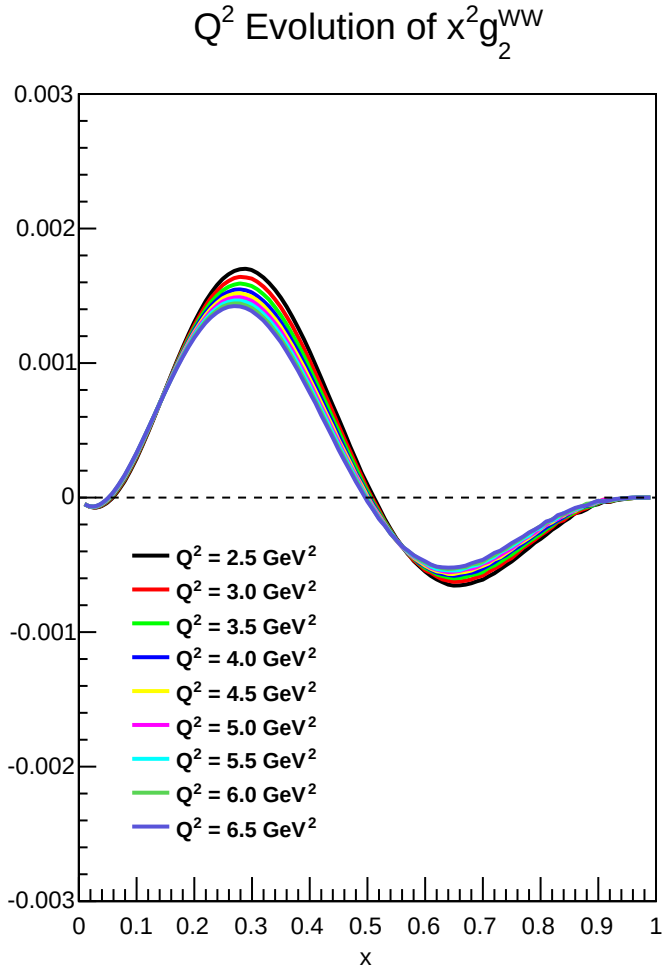
- The spin structure functions:

$$
\begin{aligned}
g_1 &= \frac{MQ^2}{4\alpha^2}\frac{2y}{(1-y)(2-y)}\sigma_0\left[A_{\parallel}+\tan(\theta/2)\,A_{\perp}\right] \\
g_2 &= \frac{MQ^2}{4\alpha^2}\frac{y^2}{(1-y)(2-y)}\sigma_0\left[-A_{\parallel}+\frac{1+(1-y)\cos\theta}{(1-y)\sin\theta}A_{\perp}\right]
\end{aligned}
$$

# Backup

## $Q^2$ Dependence: DSSV Fit



# Backup

## $Q^2$ Dependence: Selected Experiments

< X > = 0.343

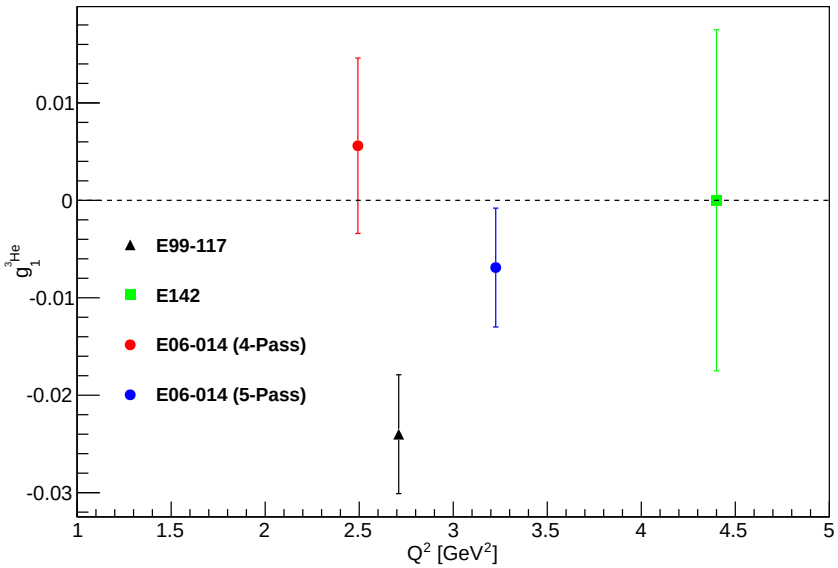



Figure: $g_1^{^3He}$ vs. $Q^2$

< X > = 0.343

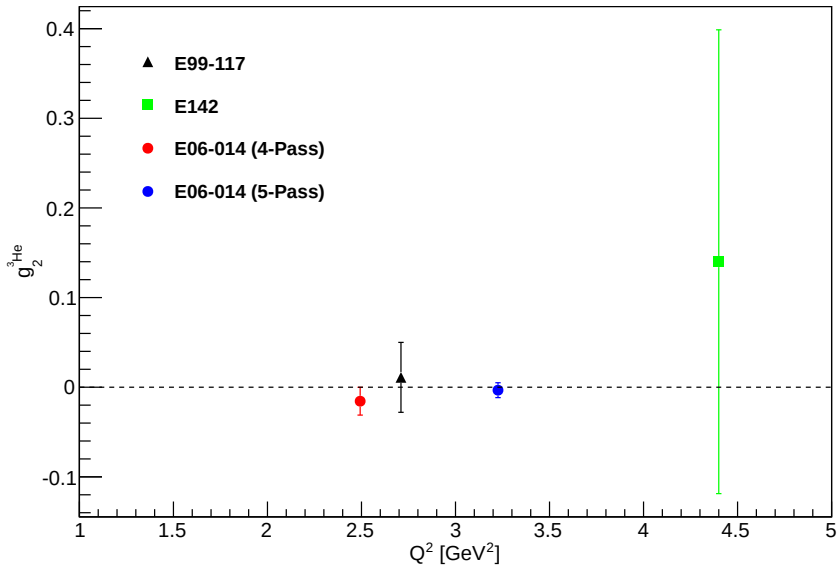



Figure: $g_2^{^3He}$ vs. $Q^2$

# Backup

## $Q^2$ Dependence: Interpolation

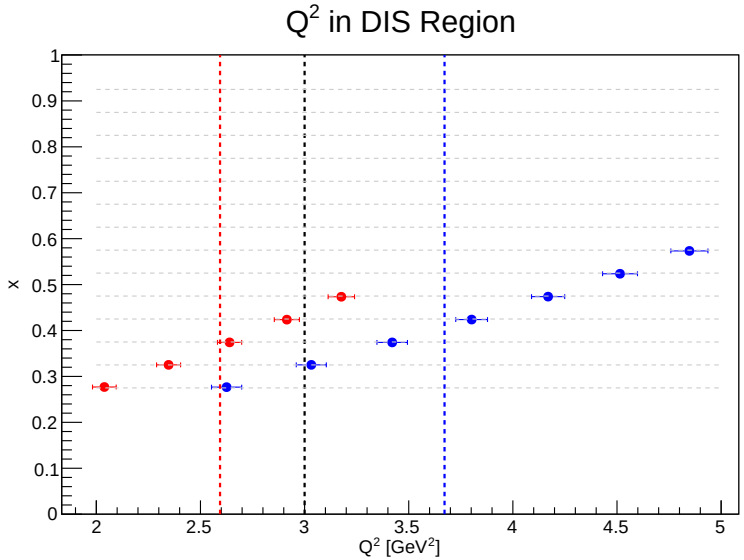



Figure: x vs $Q^2$ for 4 and 5 pass data. Red dashed line shows average $Q^2$ in the DIS region for the 4 pass data, the blue dashed line shows average $Q^2$ in the DIS region for the 5 pass data and the black dashed line shows the average $Q^2$ value in the DIS region over the entire data set.

- 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 GeV$^2$ here to get more data points for interpolation

# Backup

## $Q^2$ Dependence: Interpolation Comparison

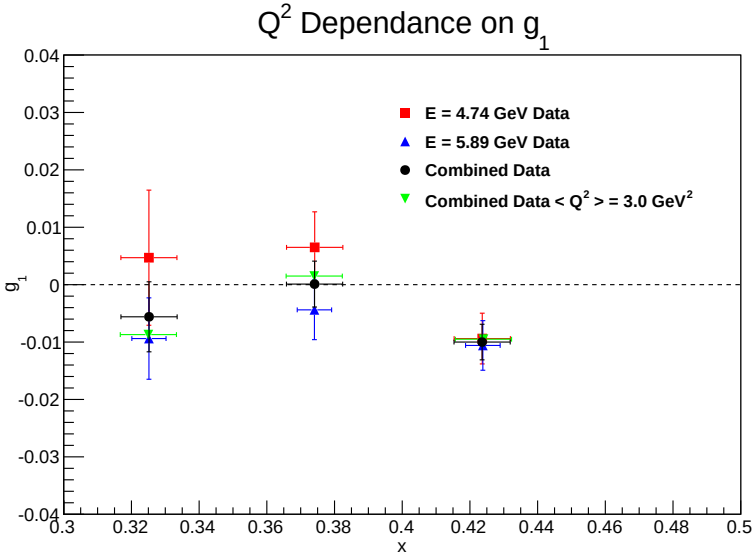



Figure: $g_1$ on $^3$He as a function of x in a selected DIS region for various $Q^2$ treatments.

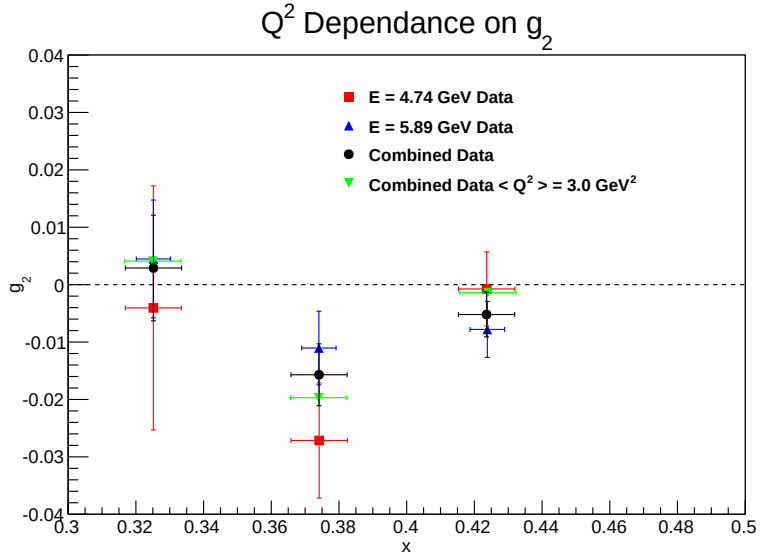



Figure: $g_2$ on $^3$He as a function of x in a selected DIS region for various $Q^2$ treatments.

# Backup

## $Q^2$ Dependence: $d_2$ Comparison

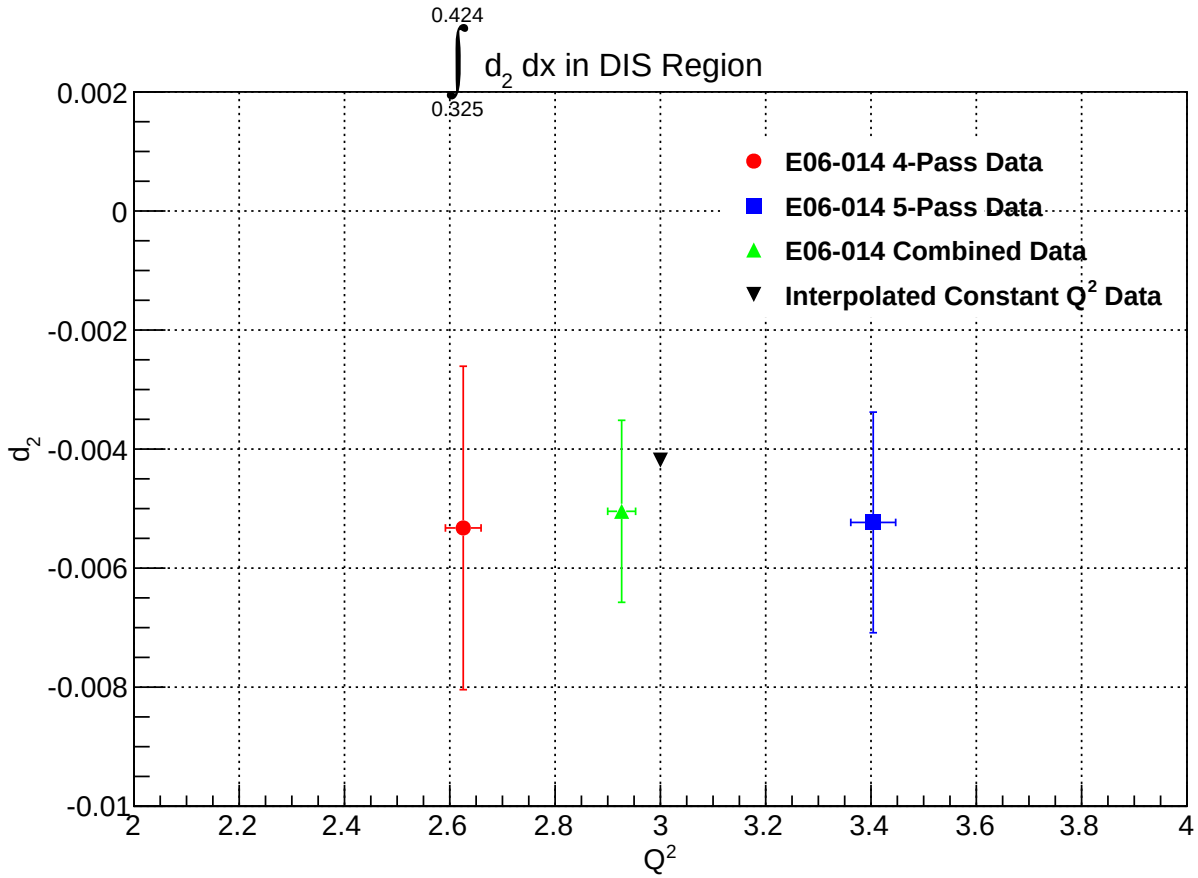



Figure: $d_2$ on $^3$He as a function of x in a selected DIS region for various $Q^2$ treatments.