# $d_2^n$ and $A_1^n$: Recent Results and Outlook
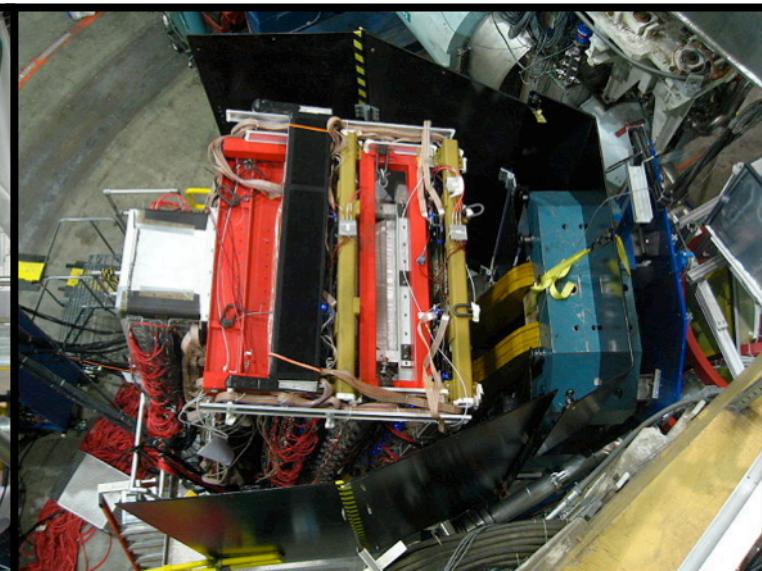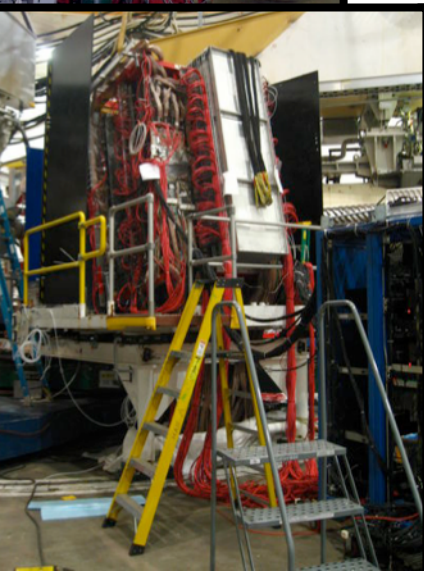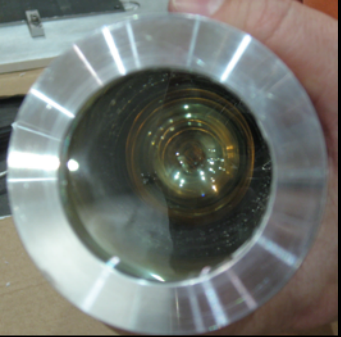
*Diana Parno*
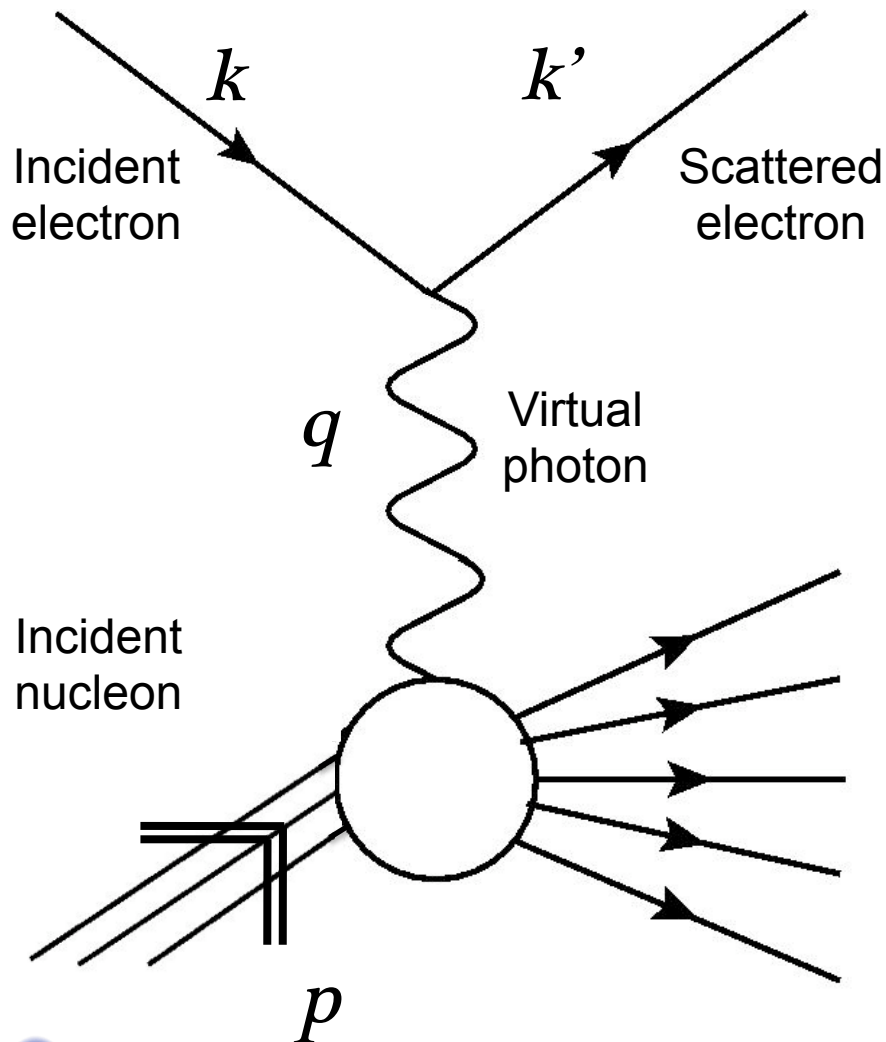
*CENPA, University of Washington*

2013 Users' Group Meeting, Jefferson Lab

# Outline

- Deep inelastic scattering and structure functions

- $d_2$ and $A_1$ for the neutron

- E06-014 in Hall A at 6 GeV

- Outlook at 12 GeV

# Deep Inelastic Scattering

$k$

$k'$

Incident electron

Scattered electron

$q$

Virtual photon

Incident nucleon

$p$

- Start with a polarized electron and a polarized nucleon

- They exchange a virtual photon

- Virtual photon-nucleon vertex contains nucleon structure information

- *Inclusive* measurement: only detect scattered electrons

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# DIS Vocabulary
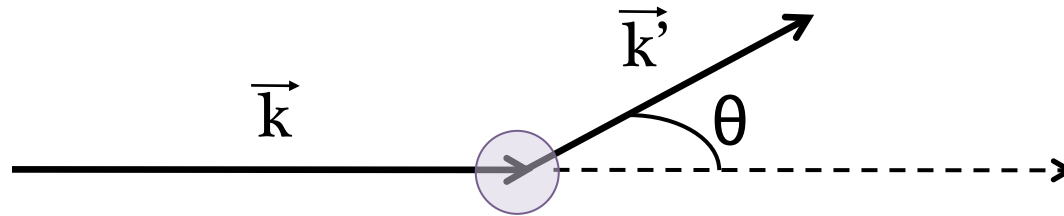


- Let's define some useful variables in the lab frame (nucleon rest frame)

$$Q^2 \equiv -q^2 = 2EE'(1-\cos\theta)$$  Four-momentum transfer
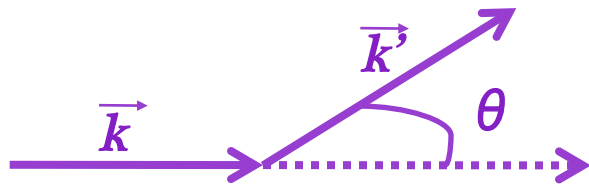
$$\nu \equiv \frac{p \cdot q}{M} = E - E'$$  Electron energy loss (lab frame)

$$x \equiv \frac{Q^2}{2p \cdot q} = \frac{Q^2}{2M\nu}$$  Bjorken $x$ (momentum fraction)

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# Nucleon Structure Functions

- Scattering from a point particle is straightforward:

$$\left(\frac{d\sigma}{d\Omega}\right)_{Mott} = \frac{\alpha^2 \cos^2{\theta/2}}{4E^2 \sin^4{\theta/2}}$$

- To describe scattering from a complex structure – like a nucleon – you need structure functions:

$$\frac{d^2\sigma}{d\Omega dE'} = \left(\frac{d\sigma}{d\Omega}\right)_{Mott}\left[\frac{1}{\nu}F_2\left(x,Q^2\right) + \frac{2}{M}F_1\left(x,Q^2\right)\tan^2{\frac{\theta}{2}}\right]$$

# Polarized Structure Functions

- Now add relative spin orientations to the picture

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

- $F_1(x, Q^2)$ and $g_1(x, Q^2)$ have a simple meaning in the quark-parton model:

$$F_1(x,Q^2) = \frac{1}{2}\sum_i e_i^2\left[q_i^{\uparrow}(x,Q^2) + q_i^{\downarrow}(x,Q^2)\right]$$

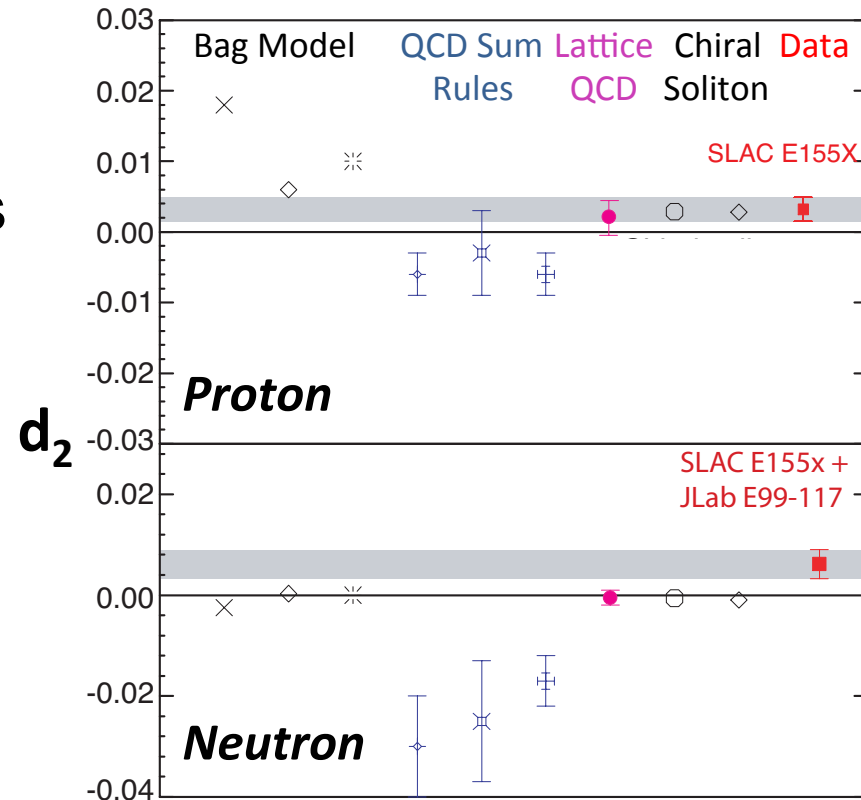$$g_1(x,Q^2) = \frac{1}{2}\sum_i e_i^2\left[q_i^{\uparrow}(x,Q^2) - q_i^{\downarrow}(x,Q^2)\right]$$

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# d$_2$

- From $g_1$ and $g_2$, we form the quantity $d_2$ for the nucleon:

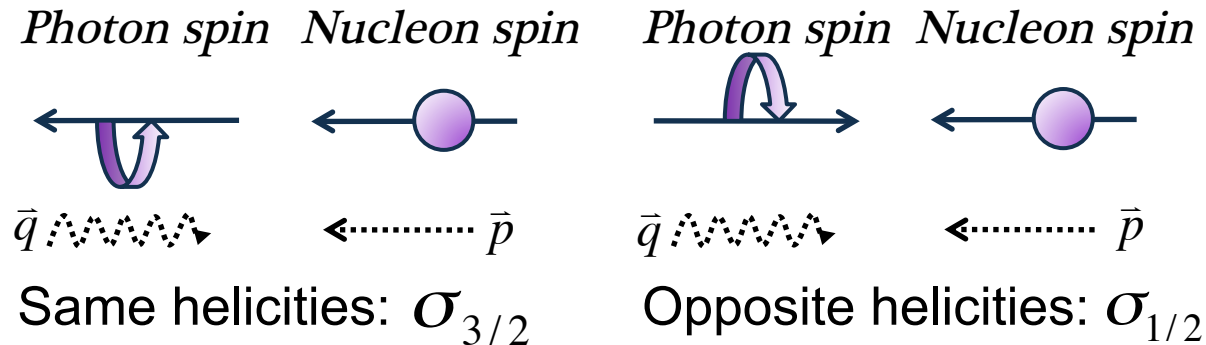$$d_2(Q^2) = \int_0^1 x^2 \left( 2g_1(x,Q^2) + 3g_2(x,Q^2) \right) dx$$

We need precise data at large $x$

- Clean probe of twist-3 physics (quark-gluon correlations)

- 2σ discrepancy between lattice prediction and measurement of neutron $d_2$



Bag Model    QCD Sum    Lattice    Chiral    Data
             Rules      QCD        Soliton

SLAC E155X

**Proton**

d$_2$

SLAC E155x + JLab E99-117

**Neutron**

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# A$_1$

- Picture the polarizations at the hadron vertex:

*Photon spin*  *Nucleon spin*     *Photon spin*  *Nucleon spin*

$\vec{q}$ ∿∿∿∿▸        ◂⋯⋯⋯ $\vec{p}$        $\vec{q}$ ∿∿∿∿▸        ◂⋯⋯⋯ $\vec{p}$

Same helicities: $\sigma_{3/2}$        Opposite helicities: $\sigma_{1/2}$

$$A_1\left(x,Q^2\right) \equiv \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}} = \frac{g_1(x,Q^2) - \dfrac{Q^2}{\nu^2} g_2(x,Q^2)}{F_1(x,Q^2)} \approx \frac{g_1\left(x,Q^2\right)}{F_1\left(x,Q^2\right)}$$
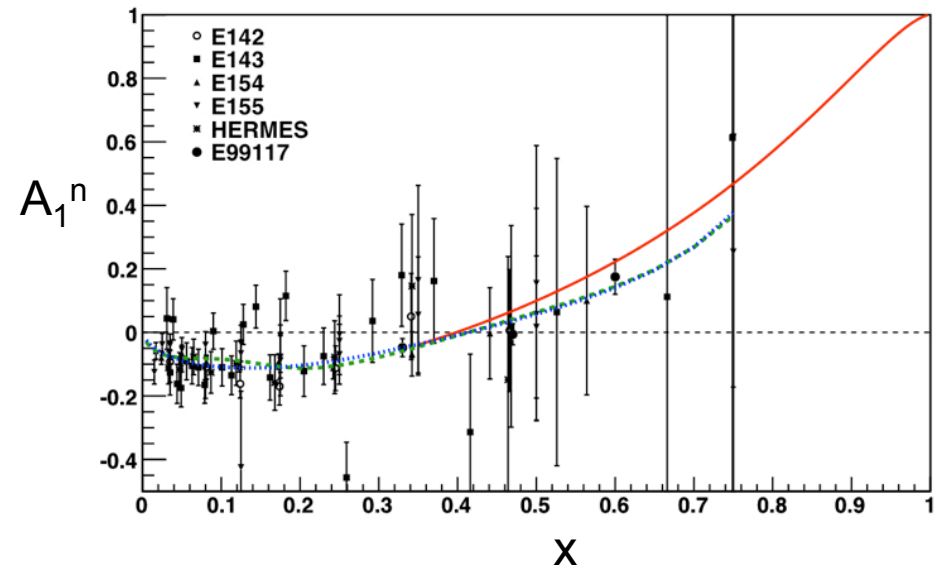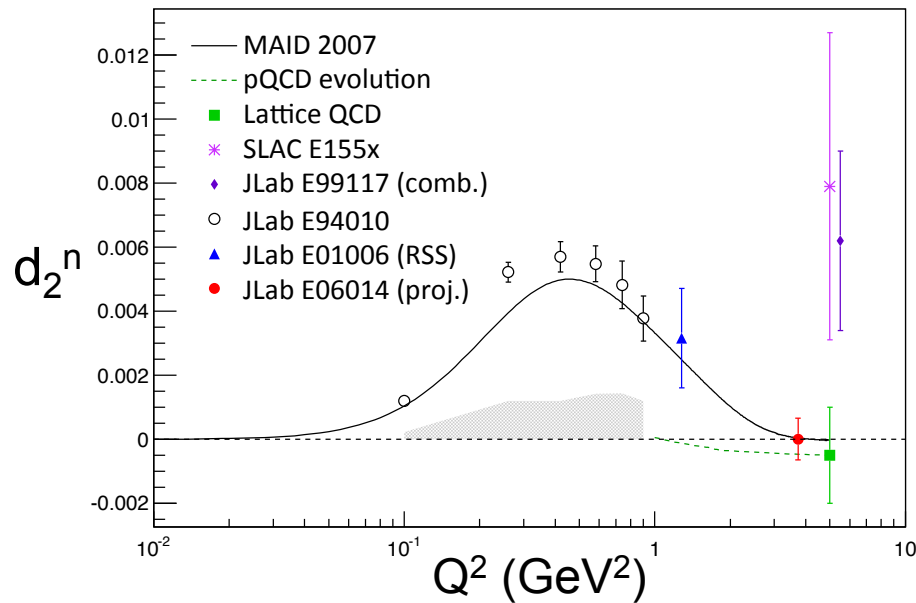
- Flavor decomposition of spin structure from $A_1^n$ and $A_1^p$ combined

# More Neutron DIS Data Needed

- ... at $Q^2 \approx 5$ GeV$^2$ and large $x$.

- ... at large $x$. pQCD predicts

$$\lim_{x \to 1} A_1^n(x, Q^2) = 1$$



Legend for left plot:
- MAID 2007
- pQCD evolution
- Lattice QCD
- SLAC E155x
- JLab E99117 (comb.)
- JLab E94010
- JLab E01006 (RSS)
- JLab E06014 (proj.)

$d_2^n$ vs $Q^2$ (GeV$^2$)



Legend for right plot:
- E142
- E143
- E154
- E155
- HERMES
- E99117

$A_1^n$ vs $x$

- - - - - Leader, Sidorov and Stamenov,
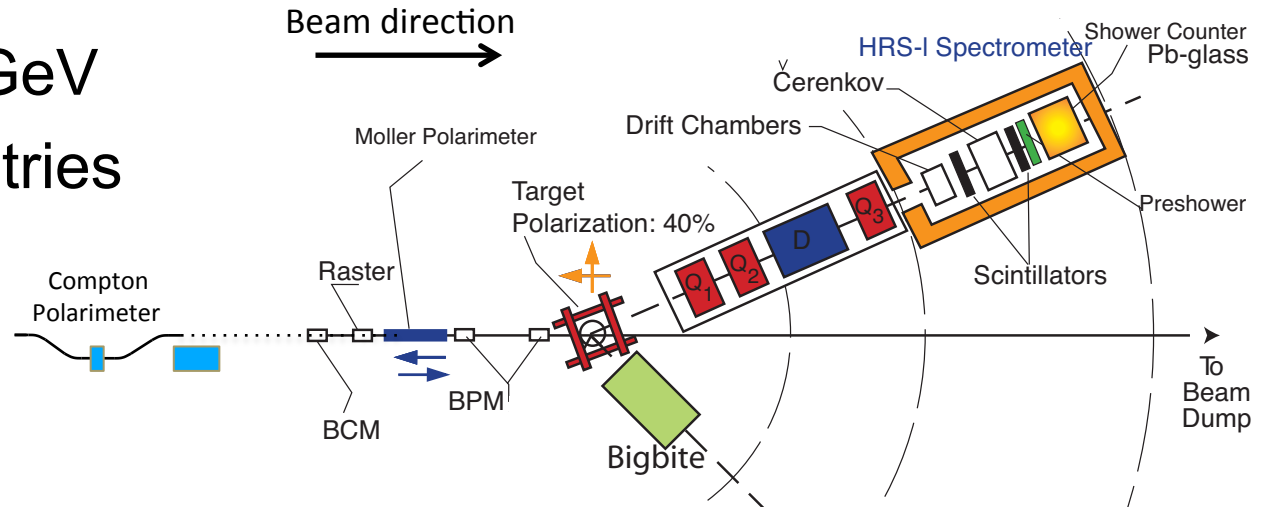· · · · · PRD **75**: 074027 (2007)

——— Avakian et al, PRL **99**: 082001 (2007)

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# E06-014 in Hall A

- Feb-Mar 2009
- $E_e$ = 4.7 and 5.9 GeV
- Inclusive asymmetries
- Inclusive cross sections

Beam direction

Moller Polarimeter

Compton Polarimeter

Raster

BPM

BCM

Target Polarization: 40%

Bigbite

HRS-I Spectrometer

Shower Counter Pb-glass

Čerenkov

Drift Chambers

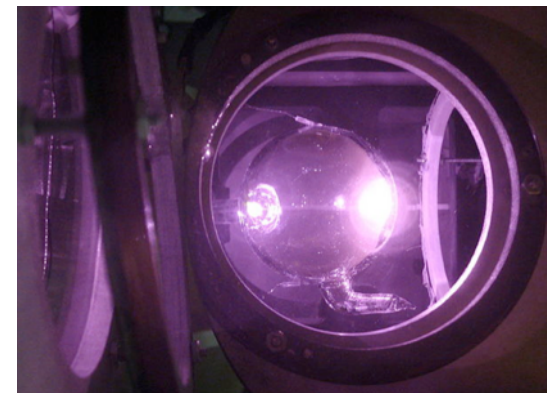$Q_1$ $Q_2$ $Q_3$ D

Preshower
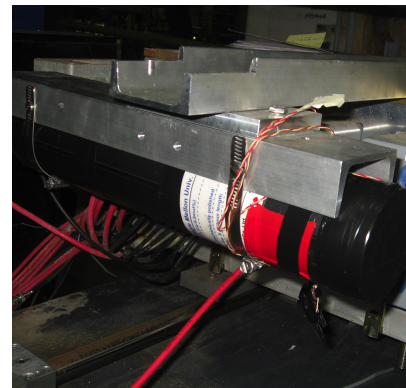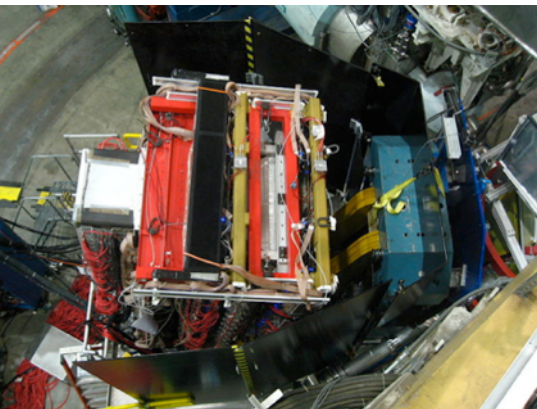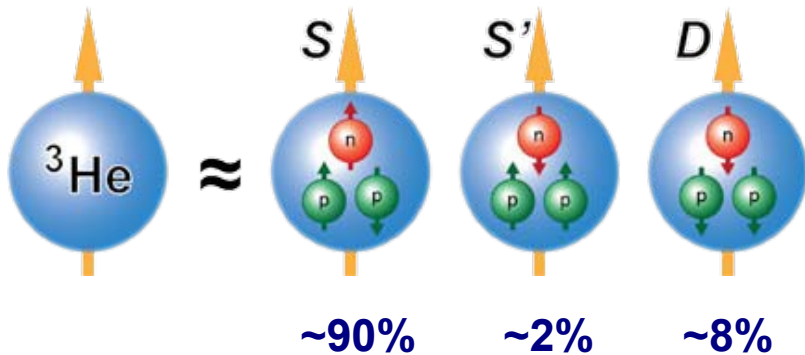
Scintillators

To Beam Dump

BigBite spectrometer

Left high-resolution spectrometer

Polarized electron beam

Polarized $^3$He target

# Polarized $^3$He Target



$S$  $S'$  $D$

~90%  ~2%  ~8%
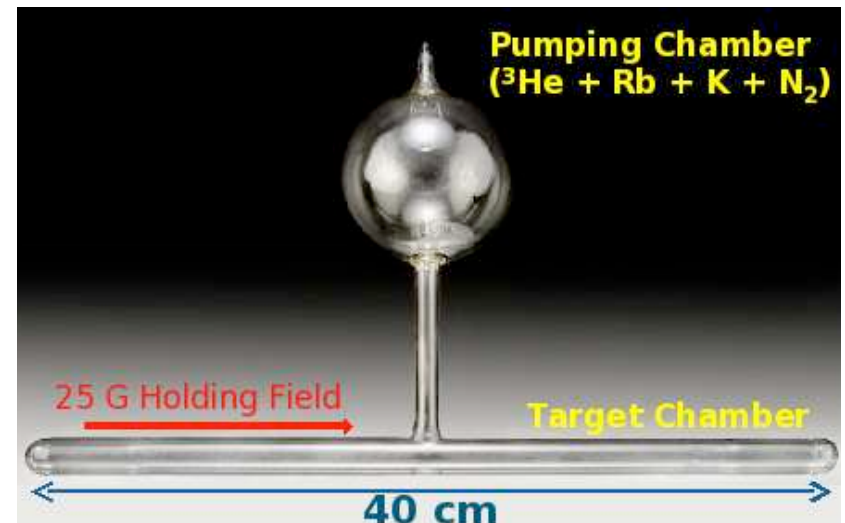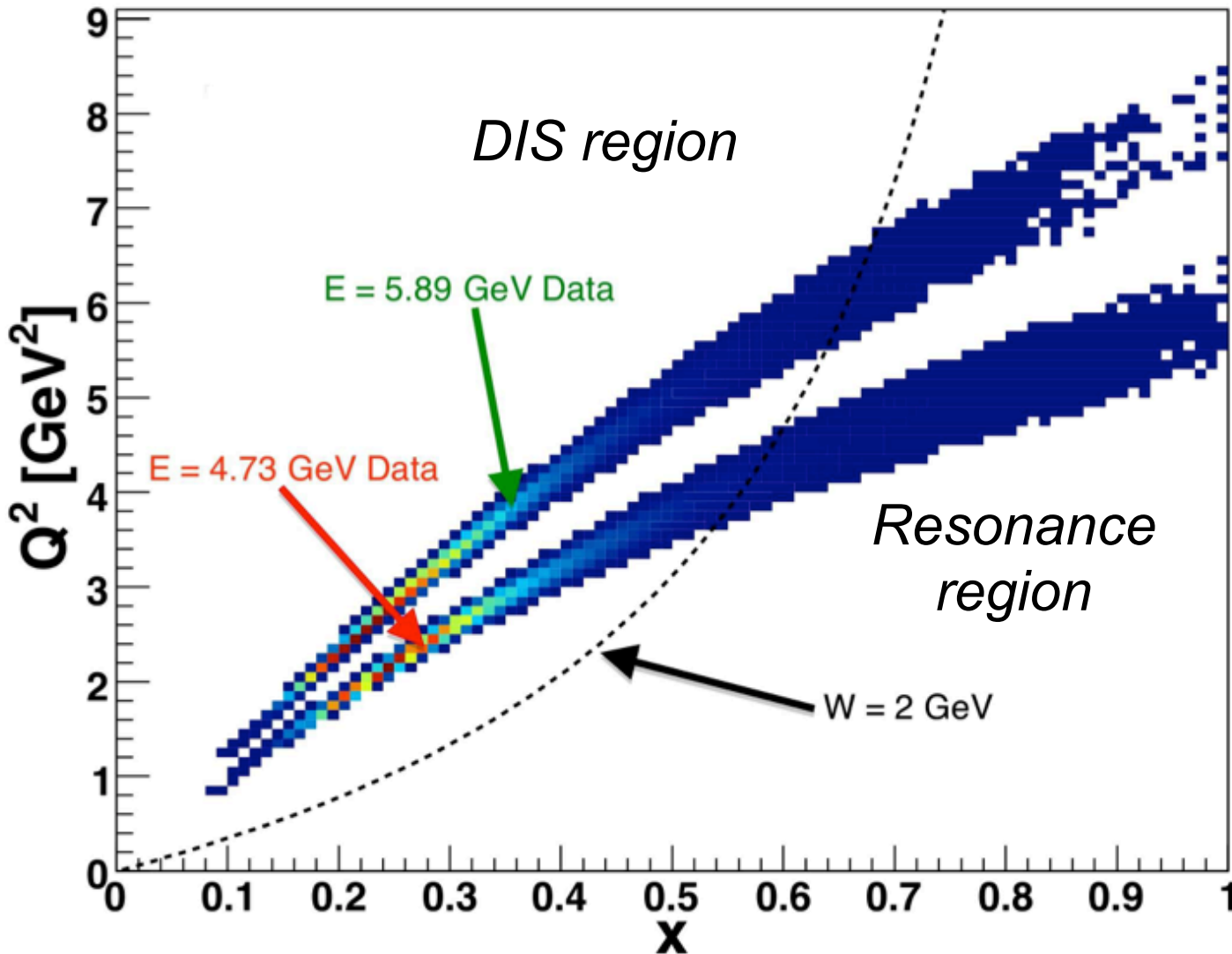
- 87% of the time, the neutron carries the $^3$He nuclear spin
- Polarized $^3$He target ≈ polarized neutron target

- Hybrid spin-exchange optical pumping

1. Polarize Rb via optical pumping

2. Rb-K interactions polarize K

3. K-$^3$He interactions polarize $^3$He



Pumping Chamber
($^3$He + Rb + K + N$_2$)

25 G Holding Field

Target Chamber
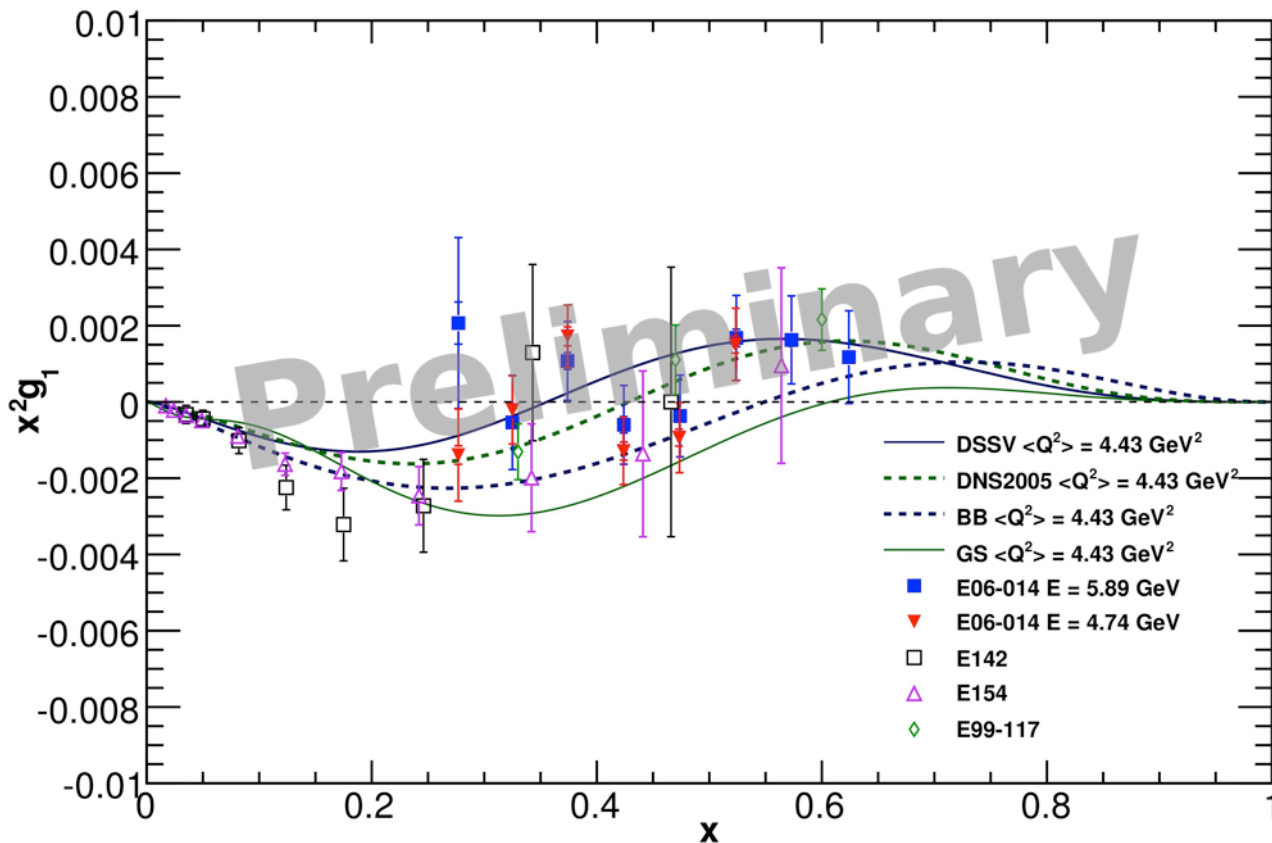
40 cm

Ameya Kolarkar, PhD thesis, 2008

# E06-014 Kinematics

# Preliminary E06-014 Results

- What you *will* see accounted for:
  - Beam polarization
  - Target polarization
  - $N_2$ dilution in target cell
  - Dilution from $e^+/e^-$ pairs produced in $\pi^0$ decay
  - Basic nuclear corrections (effective polarization model)

- What you *won't* see accounted for:
  - Radiative corrections (nearly complete)
  - Asymmetries from $e^+/e^-$ pairs
  - Some systematics (cut selection, kinematics)
  - More sophisticated nuclear corrections

Deconvolution method in progress – Melnitchouk et al.

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# $x^2 g_1^n$ ($d_2^n$ integrand)



- Lacks radiative / pair-production corrections

- Systematic error bars will grow

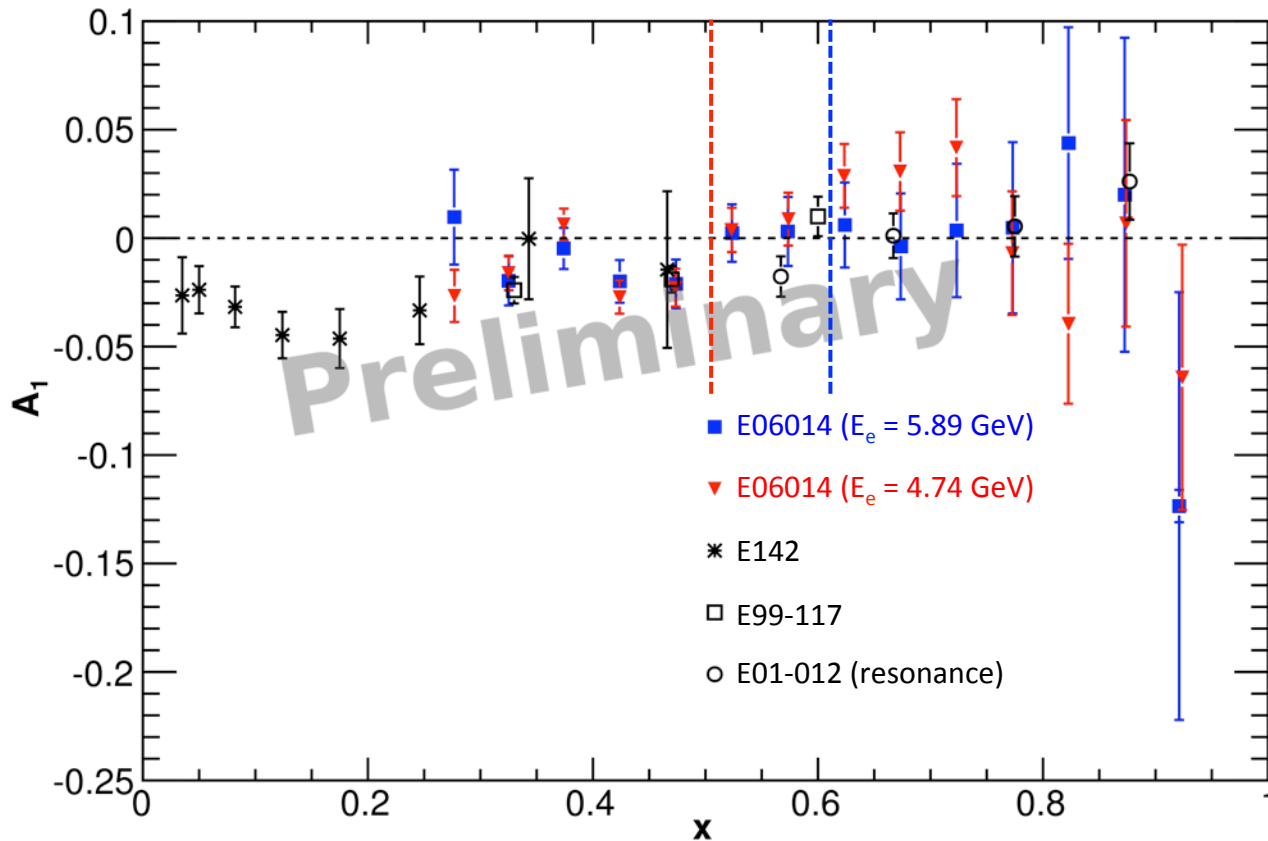- Preliminary nuclear-correction method

# $x^2 g_2^n$ ($d_2^n$ integrand)
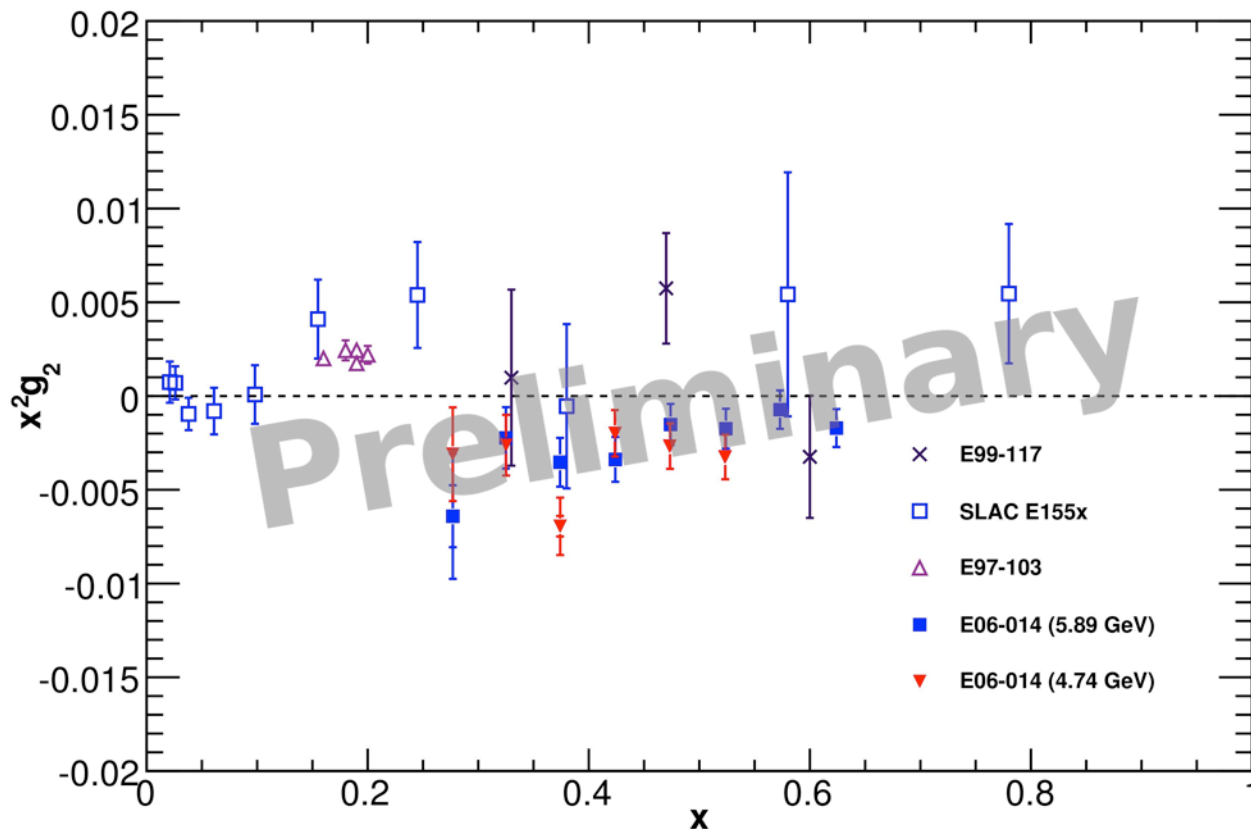


- Lacks radiative / pair-production corrections
- Systematic error bars will grow
- Preliminary nuclear-correction method

# $A_1^{He-3}$



*DIS*                    *Resonance*

- Lacks radiative / pair-production corrections

- Systematic error bars will grow

- No nuclear correction yet

Legend within figure:
- ■ E06014 ($E_e$ = 5.89 GeV)
- ▼ E06014 ($E_e$ = 4.74 GeV)
- ✳ E142
- □ E99-117
- ○ E01-012 (resonance)

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# E12-06-121: $d_2^n$ at 12 GeV

- $E_e = 11$ GeV, upgraded $^3$He target
- SHMS: large $x$ range at nearly constant $Q^2$
- HMS: fill in gaps at low $x$
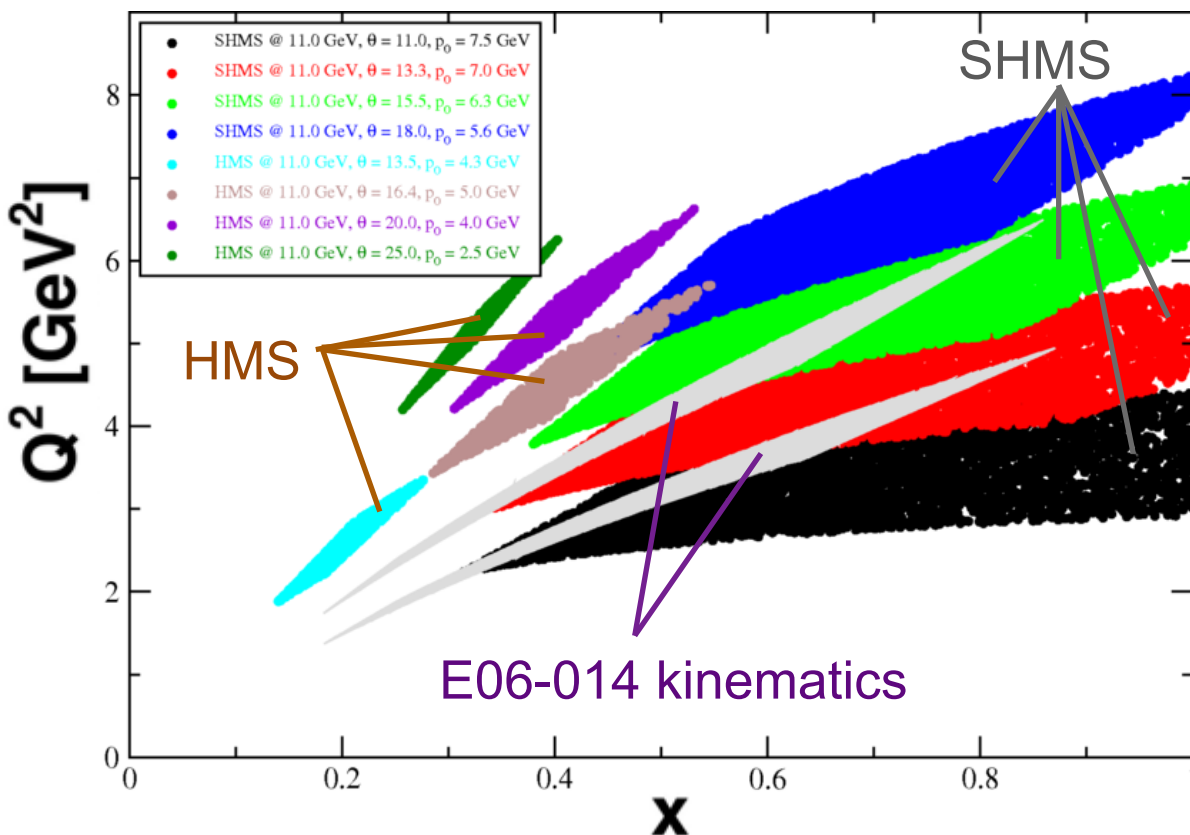


- Measure $d_2^n$ at 4 constant $Q^2$ values
- Error at each point will be comparable to E06-014

**Spokespeople:**
T. Averett
W. Korsch
Z.-E. Meziani
B. Sawatzky

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# E12-06-110: $A_1^n$ at 12 GeV

- $E_e$=11 GeV, upgraded $^3$He target
- Simultaneous HMS, SHMS measurements improve statistics
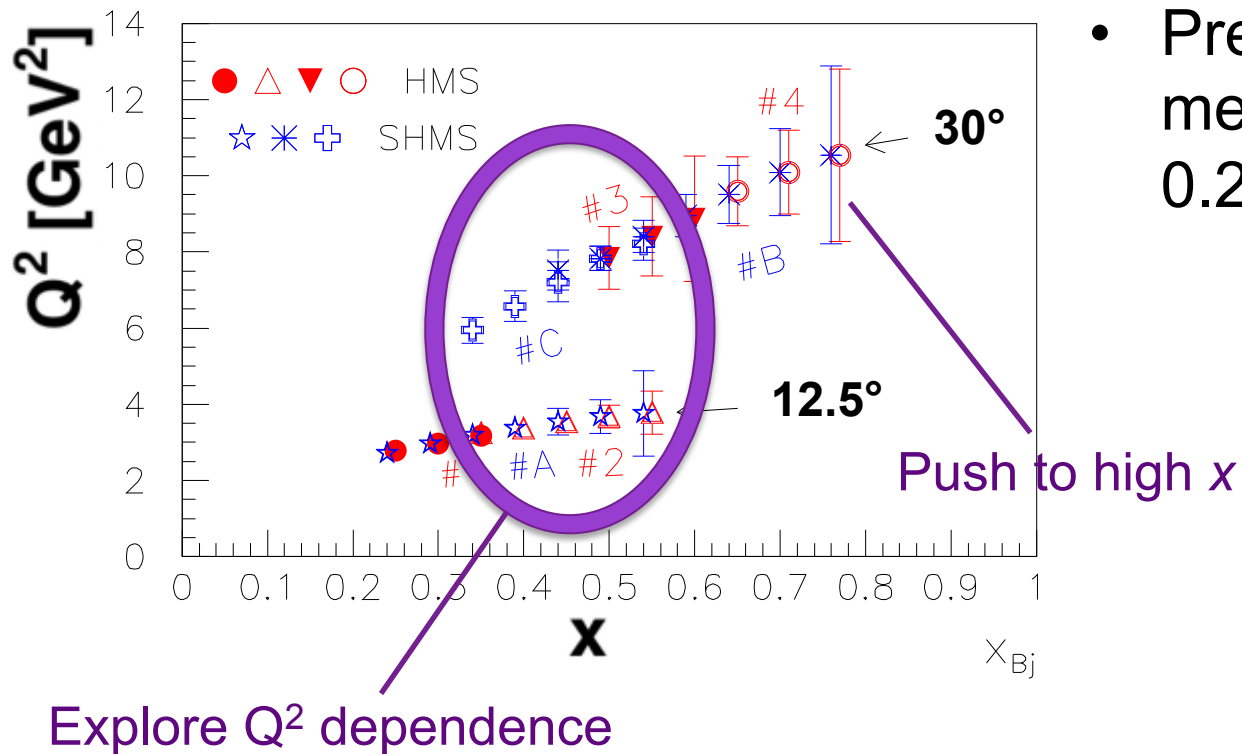
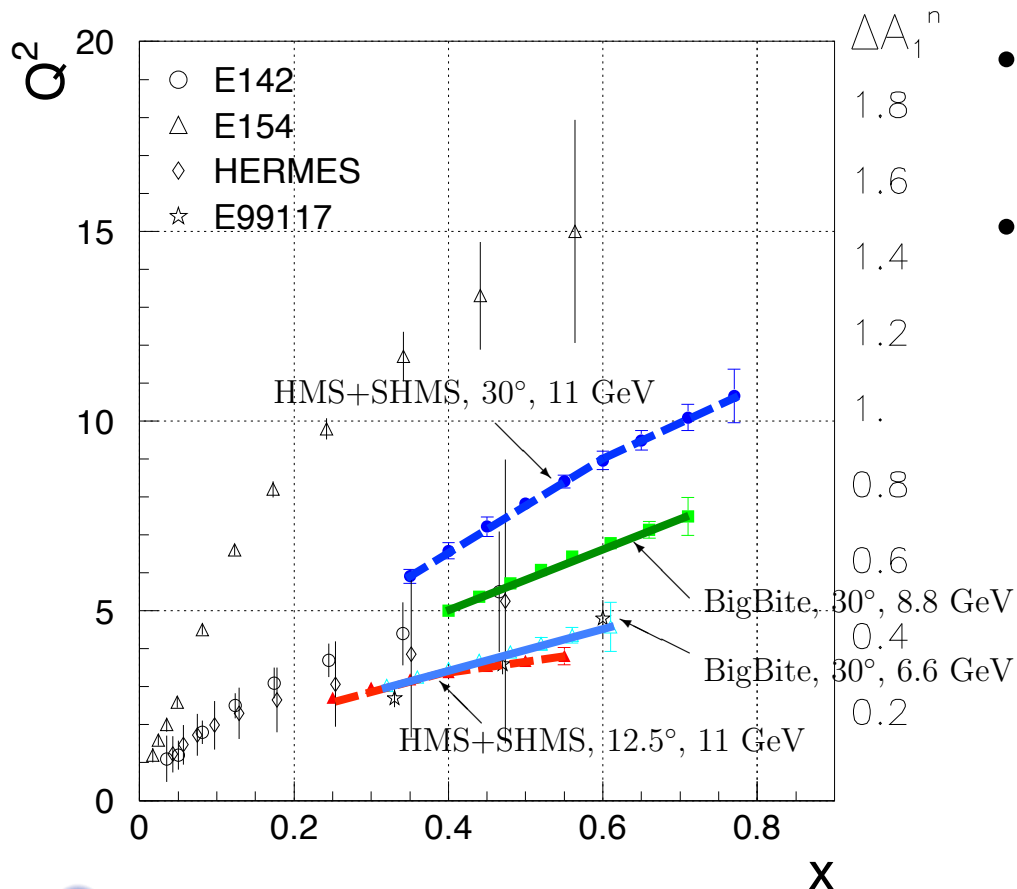- Precise DIS $A_1^n$ measurements from $0.25 \leq x \leq 0.77$



Explore $Q^2$ dependence

Push to high *x*

*Spokespeople:*
G. Cates
J.-P. Chen
Z.-E. Meziani
X. Zheng

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# E12-06-122: $A_1^n$ at 12 GeV

- $E_e$=6.6, 8.8 GeV; upgraded $^3$He target
- BigBite: Primary measurement
- Left HRS: Cross-check (lower statistics)



- Third set of $Q^2$ values for interpolation
- Test of open-geometry measurement technique

**Spokespeople:**
T. Averett
G. Cates
N. Liyanage
G. Rosner
B. Wojtsekhowski
X. Zheng

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# Conclusions

- DIS measurements of $d_2^n$ and $A_1^n$ at large $x$ will
  - test Lattice QCD and pQCD
  - probe higher-twist effects
  - explore nucleon spin structure

- E06-014 data will address these questions
  - Stay tuned for final results

- The 12-GeV program will improve the picture even further
  - Push to higher $x$
  - Explore $Q^2$ evolution

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# Acknowledgments

- The E06-014 collaboration*, especially* David Flay, Matthew Posik, Brad Sawatzky, Gregg Franklin, and Zein-Eddine Meziani

- The Accelerator Division for making the measurements possible

- The Transversity collaboration for setup help and many of the pictures used in this talk
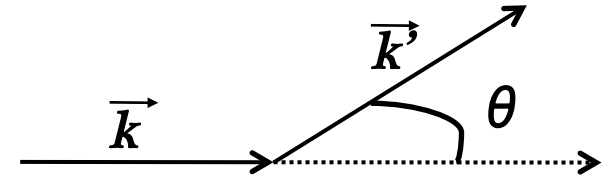
*Thank you!*

# Backup Slides

CENPA
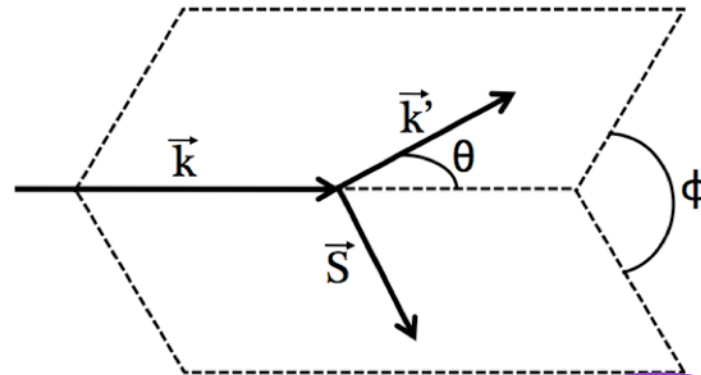Center for Experimental Nuclear Physics and Astrophysics

# Polarized Structure Functions

- Longitudinally polarized beam and target



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

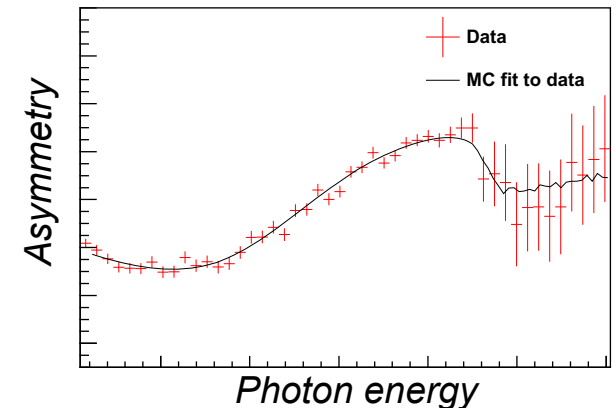- Longitudinally polarized beam and transversely polarized target



$$\frac{d^2\sigma^{\downarrow\Rightarrow}}{d\Omega dE'} - \frac{d^2\sigma^{\uparrow\Rightarrow}}{d\Omega dE'} = \frac{4\alpha^2 E'^2}{Q^2 E}\sin\theta\cos\phi\left[\frac{g_1\left(x,Q^2\right)}{M\nu} - \frac{2Eg_2\left(x,Q^2\right)}{M\nu^2}\right]$$
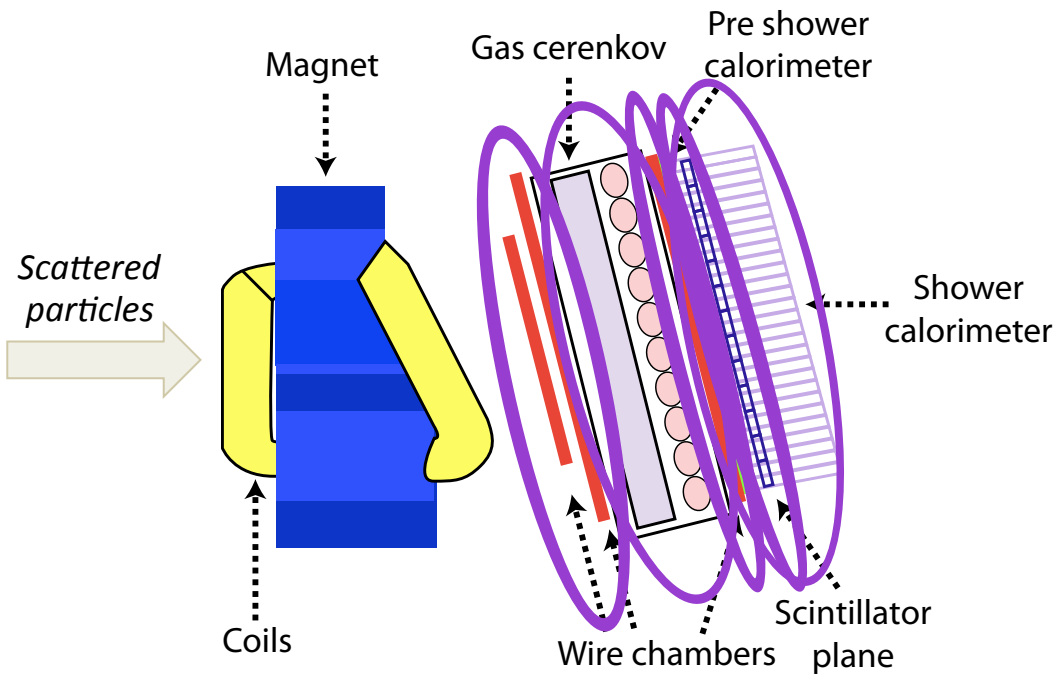
# Polarized Electron Beam

- The electrons on target are longitudinally polarized…
  but how well polarized are they?

$$P_e = \left| \frac{N^\uparrow - N^\downarrow}{N^\uparrow + N^\downarrow} \right|$$

- Two measurement methods for E06-014:

  - **Møller scattering** (e⁻e⁻ ➔ e⁻e⁻)
    - Destructive measurement

  - **Compton scattering** (e⁻γ ➔ e⁻γ)
    - Non-destructive measurement
    - Circularly polarized photons
    - Longitudinally polarized electrons

# BigBite



Magnet

Gas cerenkov

Pre shower calorimeter

Scattered particles

Shower calorimeter

Coils

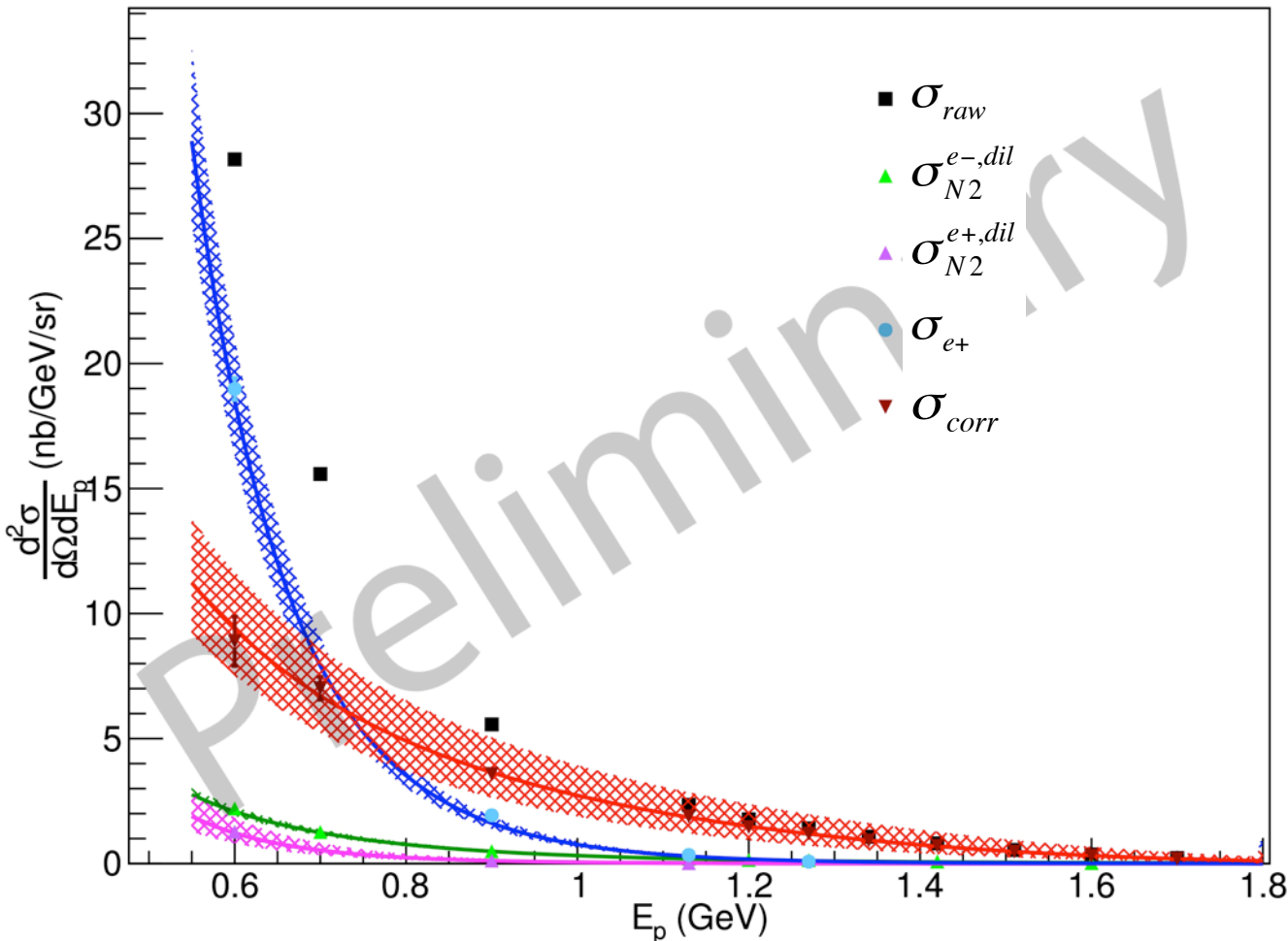Wire chambers

Scintillator plane

Adapted from Xin Qian, PhD thesis, 2010

- 3 multiwire drift chambers
  - Tracking
  - Momentum
- Gas Čerenkov
  - Exclude pions from trigger
- 2 lead-glass calorimeters
  - Energy
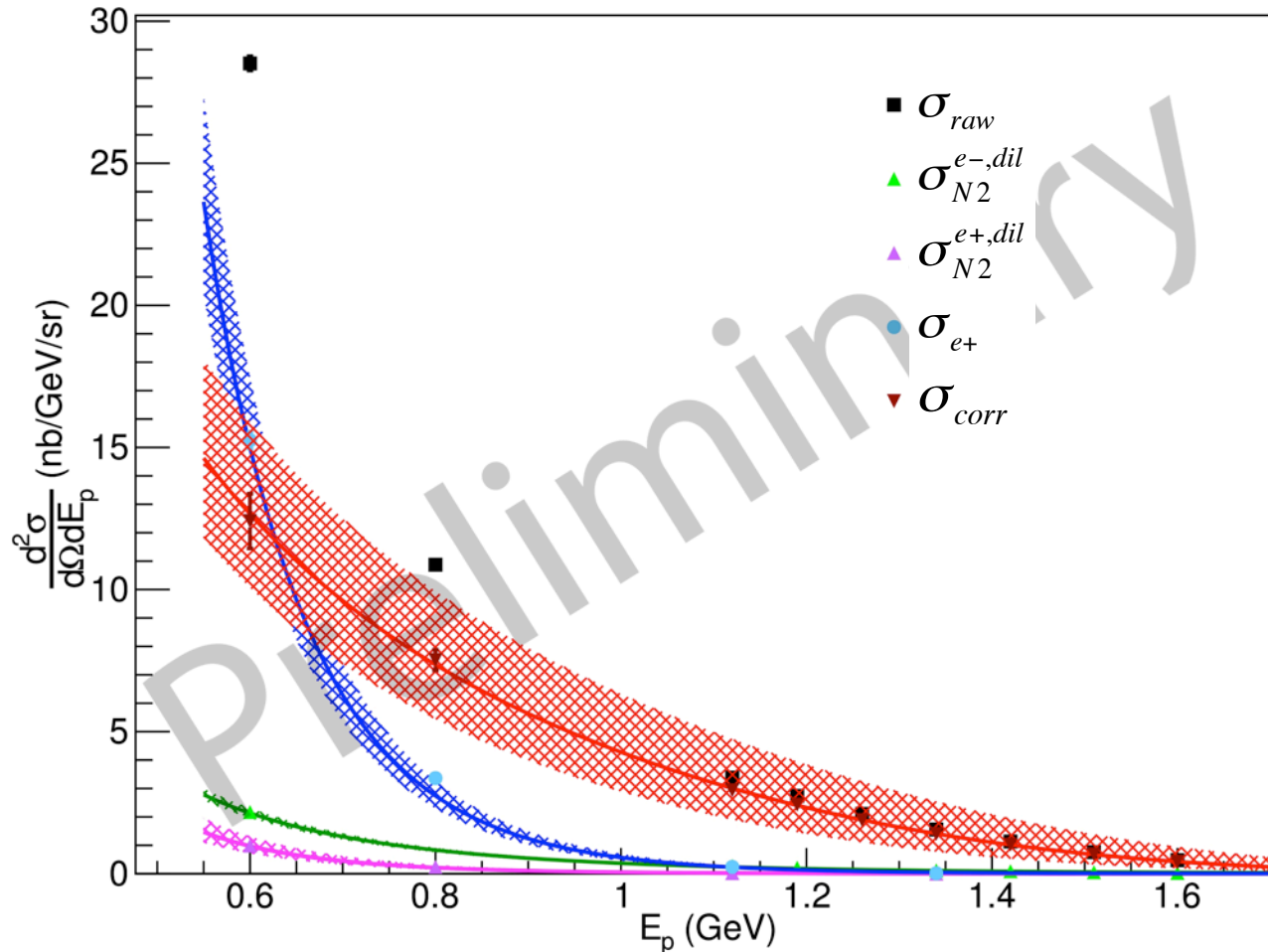  - Particle identification
- Scintillator plane
  - Timing

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# 5.9-GeV Cross Sections



$^3$He Cross Section (E = 5.89 GeV, θ = 45°)

Legend:
- $\sigma_{raw}$
- $\sigma_{N2}^{e-,dil}$
- $\sigma_{N2}^{e+,dil}$
- $\sigma_{e+}$
- $\sigma_{corr}$

- Radiative corrections have not been applied

# 4.7-GeV Cross Sections



$^3$He Cross Section (E = 4.73 GeV, θ = 45°)

- Radiative corrections have not been applied