Measurements of the Neutron Longitudinal Spin Asymmetry A_1 in the Valence Quark Region

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for the E06-014 Collaboration

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Outline

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2. The Virtual Photon-Nucleon Asymmetry A_1
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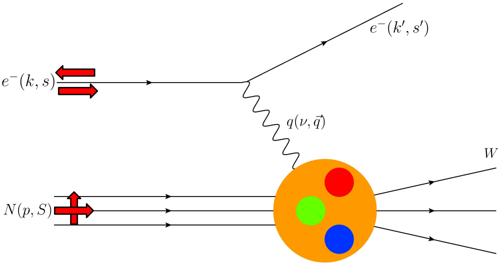
   - Theoretical Models
   - Theoretical and Experimental Status
3. The E06-014 Experiment
   - Setup and Kinematics
4. Preliminary Results
   - A_1
   - Flavor Decomposition
5. Summary

Polarized DIS

- Probes the spin content of the nucleon

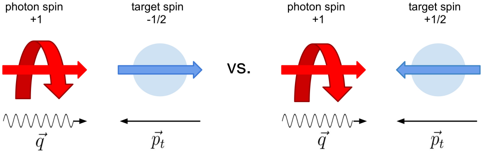


$$\frac{d^2\sigma^{(\downarrow\Uparrow-\uparrow\Uparrow)}}{dE'd\Omega} = \frac{4\alpha^2}{MQ^2}\frac{E'}{\nu E}\left[\left(E + E'\cos\theta\right) g_1\left(x, Q^2\right) - \frac{Q^2}{\nu} g_2\left(x, Q^2\right)\right]$$

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

What is A_1? (1)

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



- We measure A_1 through the double-spin asymmetries $A_\parallel$ and $A_\perp$:

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

  - 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

What is A_1? (2)

In Terms of Structure Functions

- In terms of the unpolarized structure function F_1 and the spin structure functions g_1 and g_2:

$$A_1\left(x,Q^2\right)=\frac{g_1\left(x,Q^2\right)-\gamma^2 g_2\left(x,Q^2\right)}{F_1\left(x,Q^2\right)}\approx\frac{g_1\left(x,Q^2\right)}{F_1\left(x,Q^2\right)} \quad (\text{large } Q^2)$$

$$\begin{aligned}
F_1\left(x,Q^2\right) &= \frac{1}{2}\sum_i e_i^2 q_i\left(x,Q^2\right)\\
g_1\left(x,Q^2\right) &= \frac{1}{2}\sum_i e_i^2 \Delta q_i\left(x,Q^2\right)\\
q\left(x,Q^2\right) &= q^{\uparrow}\left(x,Q^2\right)+q^{\downarrow}\left(x,Q^2\right)\\
\Delta q\left(x,Q^2\right) &= q^{\uparrow}\left(x,Q^2\right)-q^{\downarrow}\left(x,Q^2\right)
\end{aligned}$$

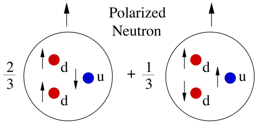
- Important for flavor decomposition to obtain $\Delta u/u$, $\Delta d/d$
  - Need p, n data

Theoretical Models (1)

SU(6) Symmetry

Constituent Quark Model (CQM)

- Non-relativistic
- Simplest possible model: no dynamics
- ‘Bare’ valence quarks are dressed by q-$\bar{q}$ pairs, gluons
- Choose a symmetric SU(6) wave function for the nucleon
  - Spin and isospin are both 1/2
  - Three flavors: u, d, s



- These assumptions lead to the diquark states for which S = 0, S = 1 to contribute equally
  - Prediction: $A_1^n = 0$

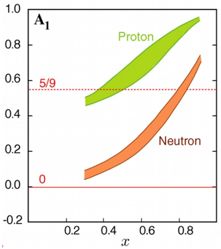
Theoretical Models (2)

SU(6) Breaking Mechanism

Relativistic CQM (Close, Thomas, Isgur)

- Utilize the hyperfine interaction: $\vec{S}_i \cdot \vec{S}_j \delta^3 \left(\vec{r}_{ij} \right)$

$$
\begin{aligned}
|n \uparrow\rangle &= \boxed{\frac{1}{\sqrt{2}} |d \uparrow (ud)_{S=0, S_z=0}\rangle} \text{ dominant component} \\
&+ \frac{1}{\sqrt{18}} |d \uparrow (ud)_{S=1, S_z=0}\rangle - \frac{1}{3} |d \downarrow (ud)_{S=1, S_z=1}\rangle \\
&- \frac{1}{3} |u \uparrow (dd)_{S=1, S_z=0}\rangle - \frac{\sqrt{2}}{3} |u \downarrow (dd)_{S=1, S_z=1}\rangle
\end{aligned}
$$



As $x \to 1$

$$
\begin{aligned}
A_1^{n,p} &\to 1 \\
\frac{\Delta u}{u} &\to 1 , \frac{\Delta d}{d} \to -\frac{1}{3}
\end{aligned}
$$

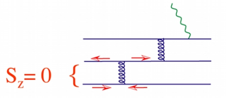
Theoretical Models (3)

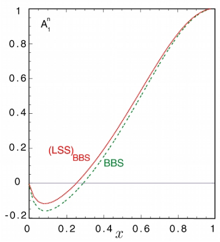
SU(6) Breaking Mechanism

Perturbative Gluon Exchange (Farrar and Jackson; Brodsky *et al.*)

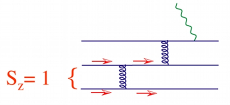
- As $x \to 1$, scattering from a relativistic quark

- Exchange transverse gluon $\Rightarrow$ flip both spins





- Suppressed mode: Longitudinal gluons only $\Rightarrow$ no spin flip



As $x \to 1$

$$A_1^{n,p} \to 1$$

$$\frac{\Delta u}{u} \to 1\,, \quad \frac{\Delta d}{d} \to 1$$

Theoretical Models (4)

Predictions at Large x

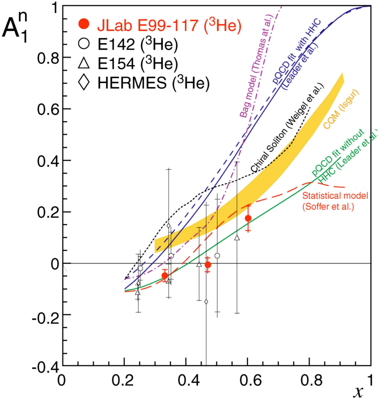
- Summary of selected model predictions as x $\to$ 1:

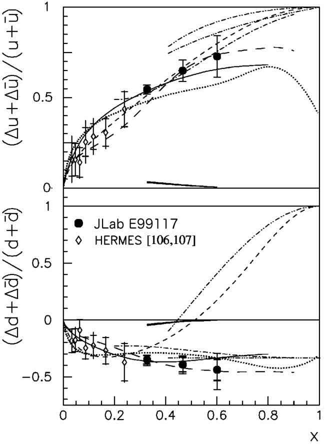
Quantity / Model	A_1^n	A_1^p	$\Delta u/u$	$\Delta d/d$	d/u
SU(6)	0	$\frac{5}{9}$	$\frac{2}{3}$	$-\frac{1}{3}$	$\frac{1}{2}$
rCQM	1	1	1	$-\frac{1}{3}$	0
pQCD	1	1	1	1	$\frac{1}{5}$
DSE (Realistic)	0.17	0.59	0.65	-0.26	0.28
DSE (Contact)	0.34	0.88	0.88	-0.33	0.18

DSE calculations from: C. Roberts, R. Holt and S. M. Schmidt, arXiv:1308.1236v3 [nucl-th]

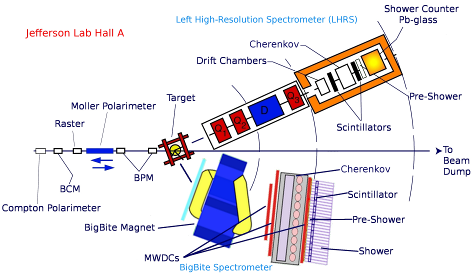
Theoretical and Experimental Status

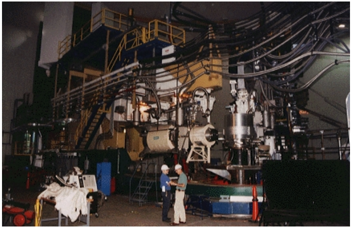
Theoretical Models and Current World Data

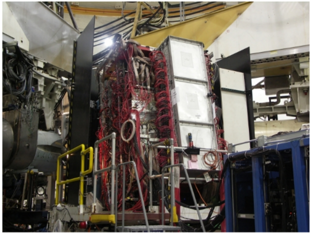




The E06-014 Experiment (1)

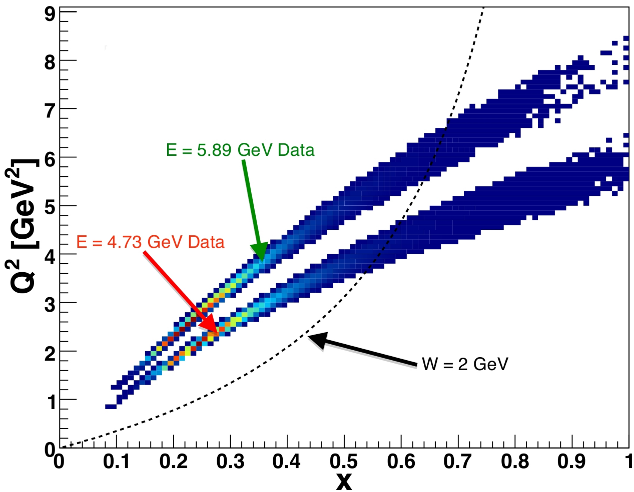






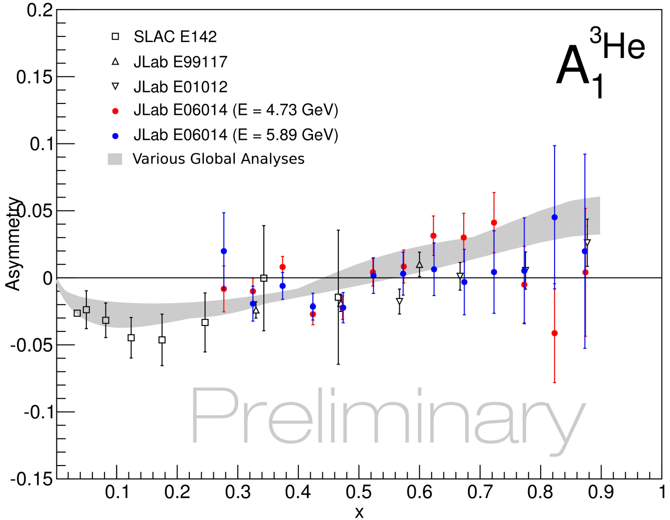
The E06-014 Experiment (2)

Kinematic Coverage



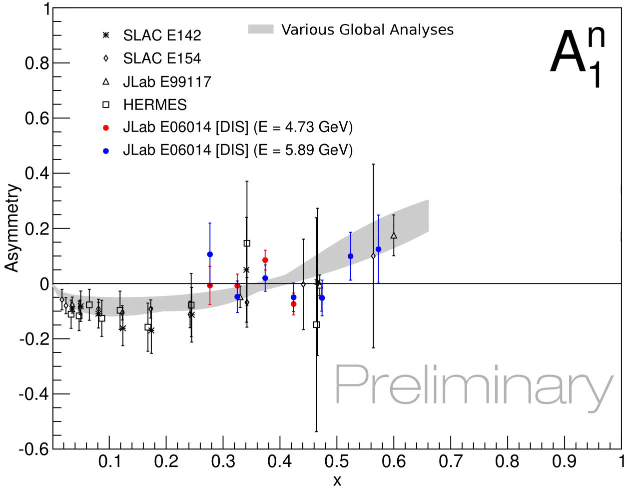
A_1 Preliminary Results (1)

Compared to World Data



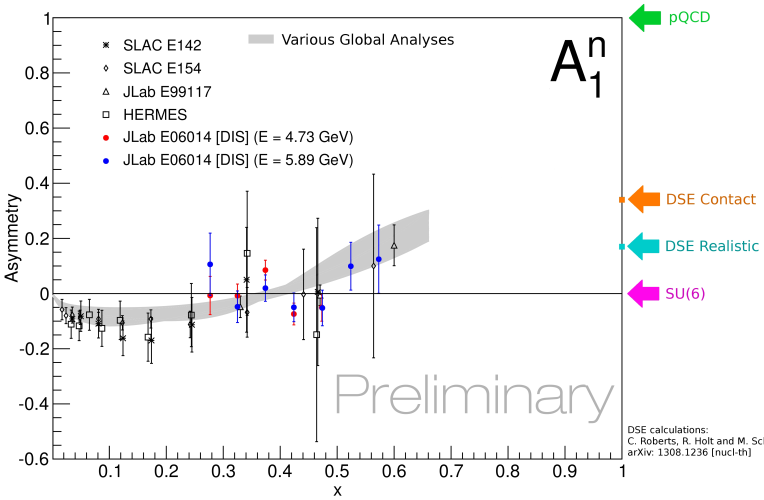
A_1 Preliminary Results (2)

Compared to World Data



A_1 Preliminary Results (2)

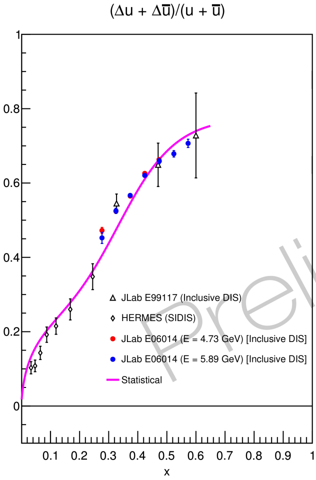
Compared to World Data

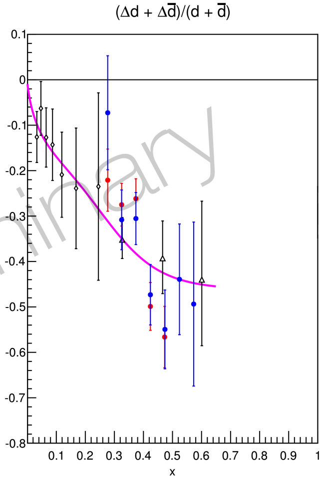


DSE calculations:
C. Roberts, R. Holt and M. Schmidt
arXiv: 1308.1236 [nucl-th]

Flavor Decomposition Prelim. Results

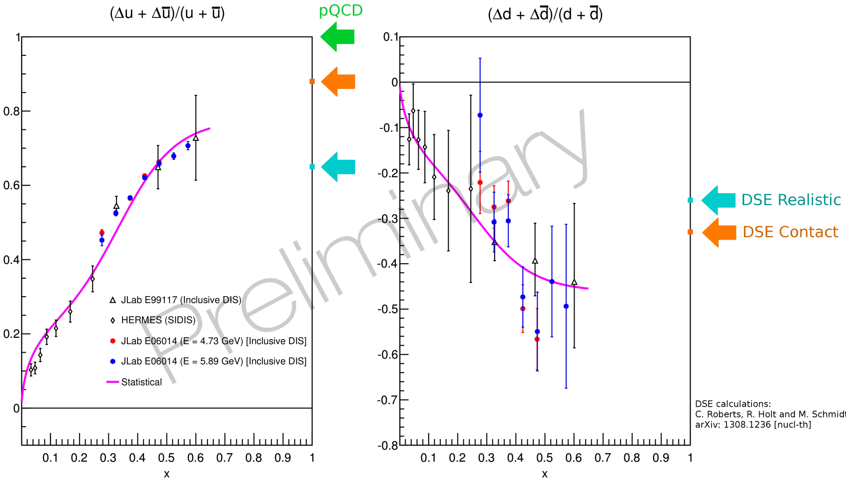
Compared to World Data





Flavor Decomposition Prelim. Results

Compared to World Data



DSE calculations:
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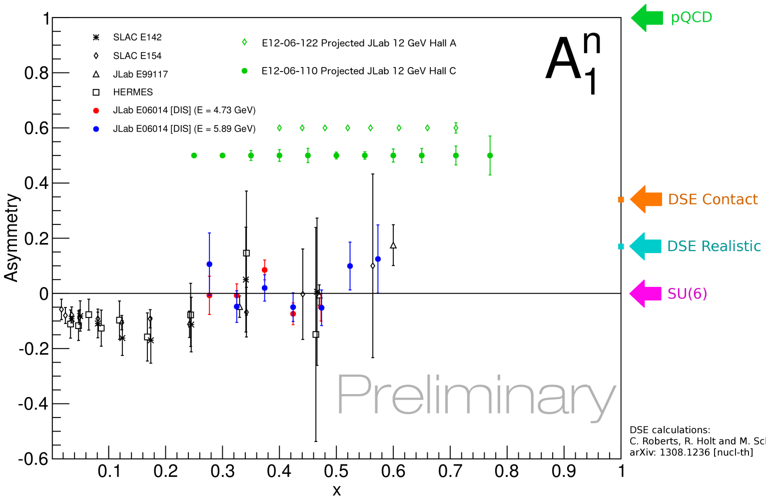
A_1^n at 12 GeV

Pushing to Larger x



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Summary and What's Next

- Extracted preliminary $A_1^{^3He}$, A_1^n, $\Delta d/d$ and $\Delta u/u$
  - A_1 data: we see a similar trend as shown in existing world data
  - $\Delta d/d$ data confirms the sign seen with JLab E99117
- Current and Future Work
  - Extracting A_1^n in the resonance region
  - Systematic errors for A_1 data, $\Delta d/d$ and $\Delta u/u$ data

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Ph.D. (complete)
Ph.D. (in progress)

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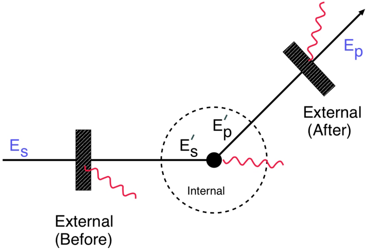
Backup (1)

Radiative Corrections: Description

- In principle, the measured cross section is: $\sigma_{\mathrm{exp}} = \sigma_0 + \sigma_{\mathrm{RC}}$
- External radiation: Various materials in the path of the incident (scattered) electron causes energy loss
  - Causes a change in the incident (E_s) and scattered (E_p) energies, changing the cross section
  - Characterized by ionization and bremsstrahlung
- Internal radiation: At the interaction vertex, bremsstrahlung can also occur
- These types of radiation can be visualized as:



- The goal of RCs is to remove these effects to obtain σ_0

Backup (2)

Radiative Corrections: Procedure

- Use the program RADCOR for the radiative corrections
- Convert our physics asymmetries to polarized cross section differences:

$$\Delta\sigma^{r}_{\parallel,\perp} = 2\sigma^{r}_{0} A^{r}_{\parallel,\perp}$$

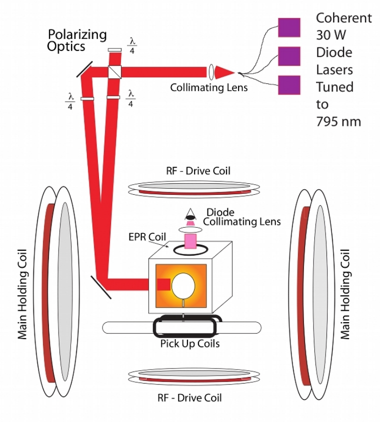
- Build an input grid of $\Delta\sigma_{\parallel,\perp}$ that contains contributions from the DIS, quasi-elastic and resonance regions
- Using the grid and our data, RADCOR unfolds the Born $\Delta\sigma_{\parallel,\perp}$
- Convert the $\Delta\sigma_{\parallel,\perp}$ back to asymmetries:

$$A^{b}_{\parallel,\perp} = \frac{\Delta\sigma^{b}_{\parallel,\perp}}{2\sigma^{b}_{0}}$$

  - $r \Rightarrow$ radiated
  - $b \Rightarrow$ Born
  - $\sigma_0 \Rightarrow$ unpolarized cross section

Backup (3)

^{3}He Target



- Vaporized Rb is optically pumped using circularly polarized light to polarize its electrons
- Through hybrid spin-exchange the Rb electrons transfer their spin to K atoms, then K to ^{3}He nuclei

- 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 (5)

Nuclear Corrections: Description

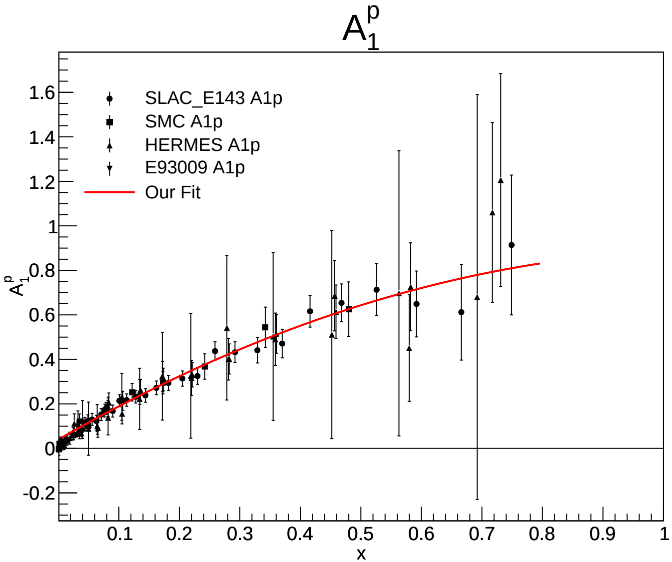
- Bounded nucleons behave differently than free ones
- Need to correct for:
  1. Spin depolarization
  2. Nuclear binding
  3. Fermi motion of nucleons
  4. Off-shellness of nucleons
- To extract A_1^n, we compute:

$$A_1^n = \frac{F_2^{^3\mathrm{He}}}{\tilde{P}_n F_2^n} \left[A_1^{^3\mathrm{He}} - \tilde{P}_p \left(\frac{F_2^p}{F_2^{^3\mathrm{He}}} \right) A_1^p \right]$$

- $\tilde{P}_i$ terms include Δ isobar effects:
  - $\tilde{P}_n$ = 0.879 + 0.056
  - $\tilde{P}_p$ = 2(-0.021) - 0.014

Backup (6)

Nuclear Corrections: A_1^p Fit



Flavor Decomposition: Description

- We need g_1^n/F_1^n
  - Compute nuclear corrections on $g_1^{^3\mathrm{He}}$ data, then divide the resulting g_1^n by F_1^n
- Fits to $(d+\bar{d})/(u+\bar{u}) \approx d/u$, g_1^p/F_1^p
- Compute $(\Delta q + \Delta\bar{q})/(q+\bar{q})$ for u and d as:

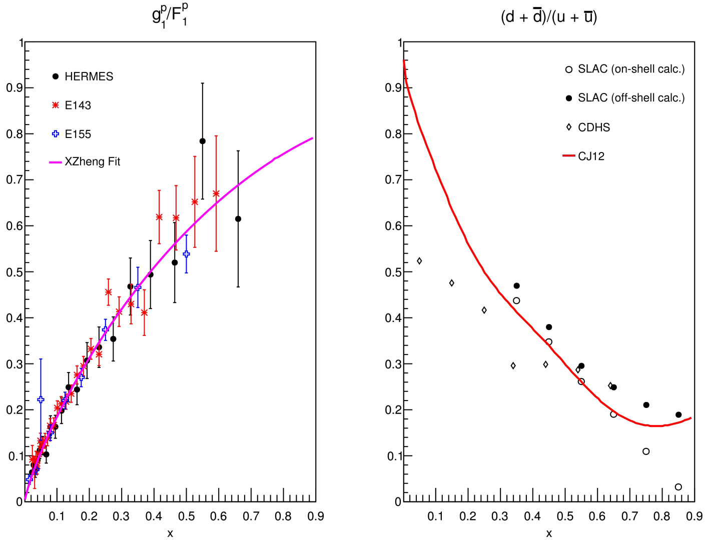
$$\frac{\Delta u + \Delta\bar{u}}{u+\bar{u}} = \frac{4}{15}\frac{g_1^p}{F_1^p}\left(4 + \frac{d+\bar{d}}{u+\bar{u}}\right) - \frac{1}{15}\frac{g_1^n}{F_1^n}\left(1 + 4\frac{d+\bar{d}}{u+\bar{u}}\right)$$

$$\frac{\Delta d + \Delta\bar{d}}{d+\bar{d}} = \frac{4}{15}\frac{g_1^n}{F_1^n}\left(4 + \frac{u+\bar{u}}{d+\bar{d}}\right) - \frac{1}{15}\frac{g_1^p}{F_1^p}\left(1 + 4\frac{u+\bar{u}}{d+\bar{d}}\right)$$

  - Note: This is for $s, \bar{s} = 0$ (these contributions are small, fold into systematic error)

Backup (8)

Flavor Decomposition: Fits



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