INFN/JLab Duality-05 Workshop, June 6-9, 2005.

Spin-Flavor Decomposition and Quark-Hadron Duality in Polarized Semi-Inclusive Deep-Inelastic Scattering

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Semi-inclusive deep-inelastic scattering (SIDIS) on polarized $\vec{p}$, $\vec{d}$ and ^{3}He ($\vec{n}$) targets at Jefferson Lab will provide precision data to improve our understanding of nucleon's spin-flavor structure.

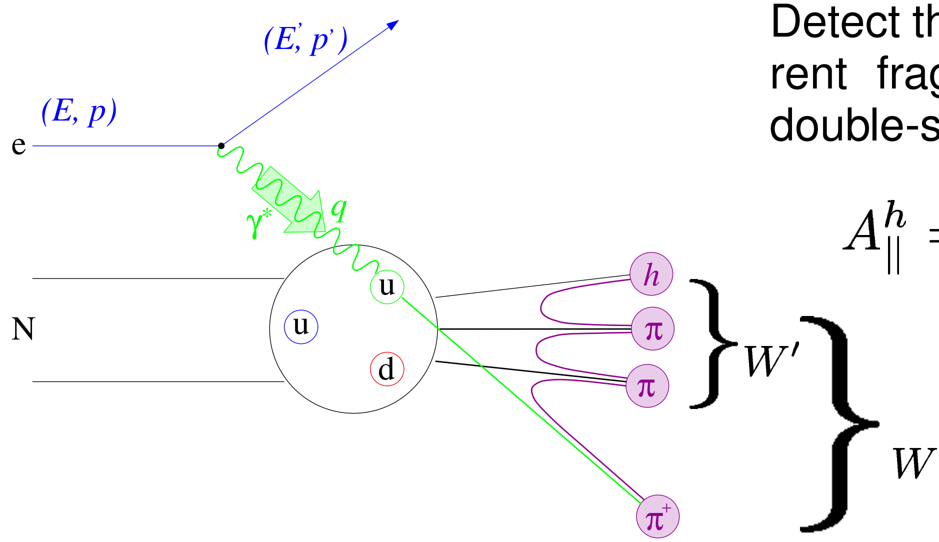
- Double-spin asymmetry A_{1N}^h and the combined asymmetry $A_{1N}^{\pi^+\pm\pi^-}$ on $\vec{p}$ and $\vec{d}$ targets: Semi-SANE experiment (E04-113) at Hall C.
- Extracting Δu_v, Δd_v from $A_{1N}^{\pi^+-\pi^-}$ at LO and NLO.
- Extracting the polarized sea asymmetry $\Delta\bar{u} - \Delta\bar{d}$.
- Next-to-leading order global QCD fit on both DIS and SIDIS data.

- Asymmetries on a polarized ^{3}He ($\vec{n}$) target are sensitive to Δd.
- With the polarized ^{3}He target in Hall A, precisions on A^h_{1n} can be improved by an order of magnitude.

Quark-hadron duality links polarized SIDIS with meson production:

- Two types of duality (hard scattering duality and fragmentation duality) corresponding to two energy scales (Q^2 and $z = E_h/\nu$) in SIDIS.
- Should we expect quark-hadron duality to work in spin-related observables ?

Flavor Tagging in Semi-Inclusive DIS



$z = E_\pi/\nu$

Detect the leading hadron from the current fragmentation and measure the double-spin asymmetry:

$$A_{\parallel}^{h} = f^{h} P_B P_T \cdot \mathcal{P}_{kin} \cdot A_{1N}^{h}$$

Two energy scales are involved. Assuming the leading order naive x-z factorization:

$$A_{1N}^{h}(x, Q^2, z) \equiv \frac{\Delta\sigma^{h}(x, Q^2, z)}{\sigma^{h}(x, Q^2, z)} = \frac{\sum_f e_f^2 \Delta q_f(x, Q^2) \cdot D_f^h(z, Q^2)}{\sum_f e_f^2 q_f(x, Q^2) \cdot D_f^h(z, Q^2)}.$$

Each asymmetry measurement provides an independent constrain on Δq_f.

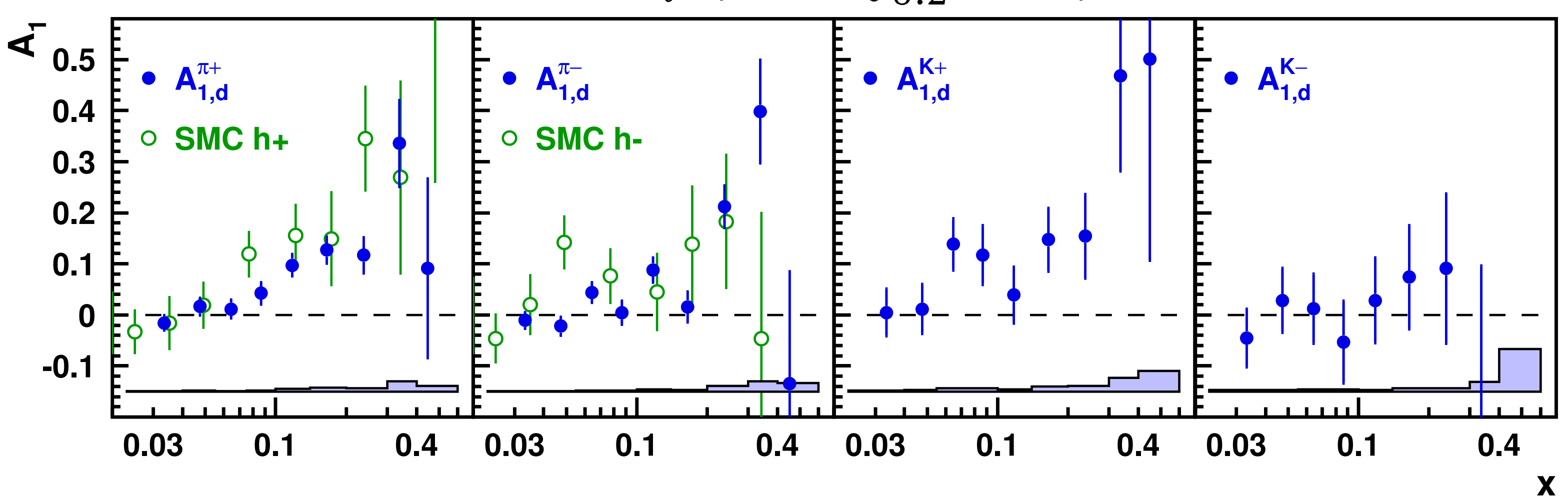
HERMES Flavor Decomposition: $\vec{A} = \mathcal{P}_f^h(x) \cdot \vec{Q}$

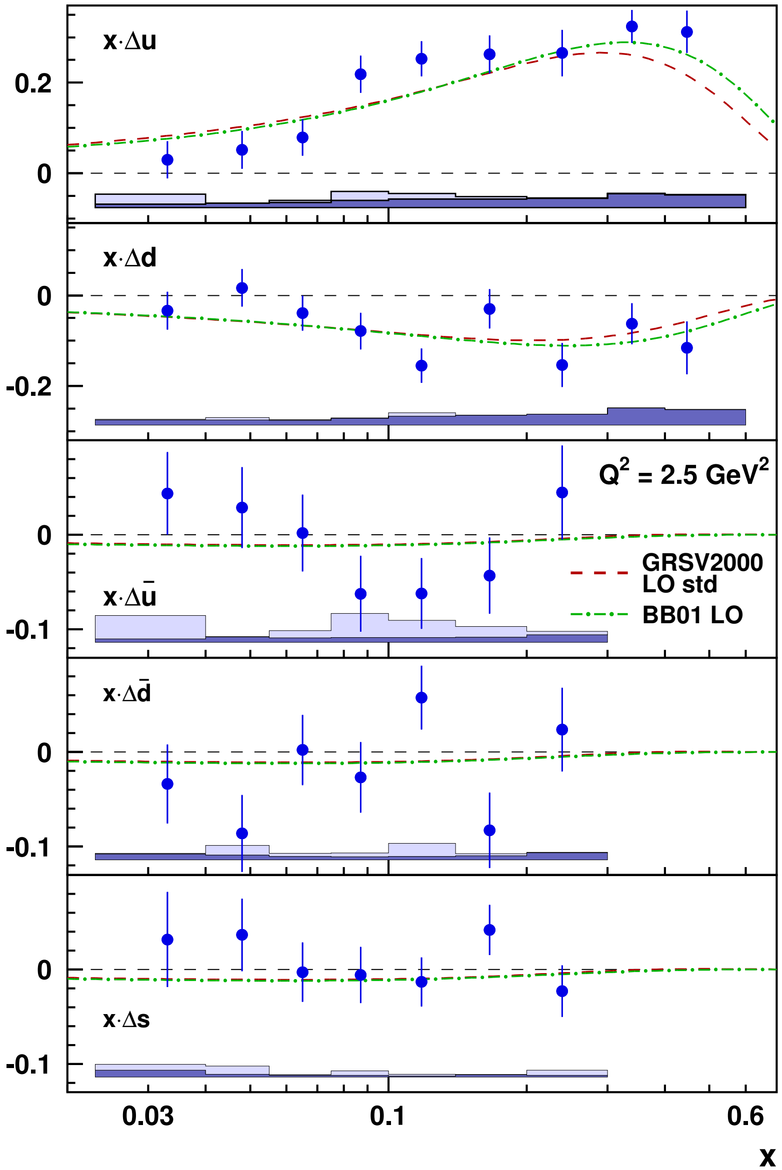
From measurements: $\vec{A} = \left(A_{1p}^{\pi^+}, A_{1p}^{\pi^-}, A_{1d}^{\pi^+}, A_{1d}^{\pi^-}, A_{1d}^{K^+}, A_{1d}^{K^-}, A_{1p}, A_{1d}\right)$

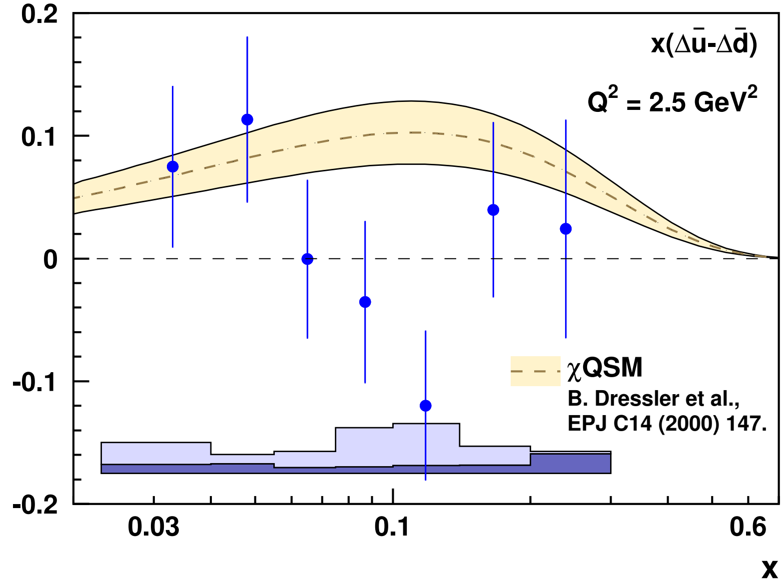
Solve for: $\vec{Q} = \left(x\Delta u, x\Delta d, x\Delta \bar{u}, x\Delta \bar{d}, x\Delta s\right)$.

Calculate "Purity" from a LUND based Monte Carlo:

$$\mathcal{P}_f^h(x) = \frac{e_f^2 q_f(x) \int_{0.2}^{0.8} dz D_f^h(z)}{\sum_i e_i^2 q_i(x) \int_{0.2}^{0.8} dz D_i^h(z)}$$







Assumes:

Leading order x-z factorization and current fragmentation.

Isospin symmetry and charge conjugation.

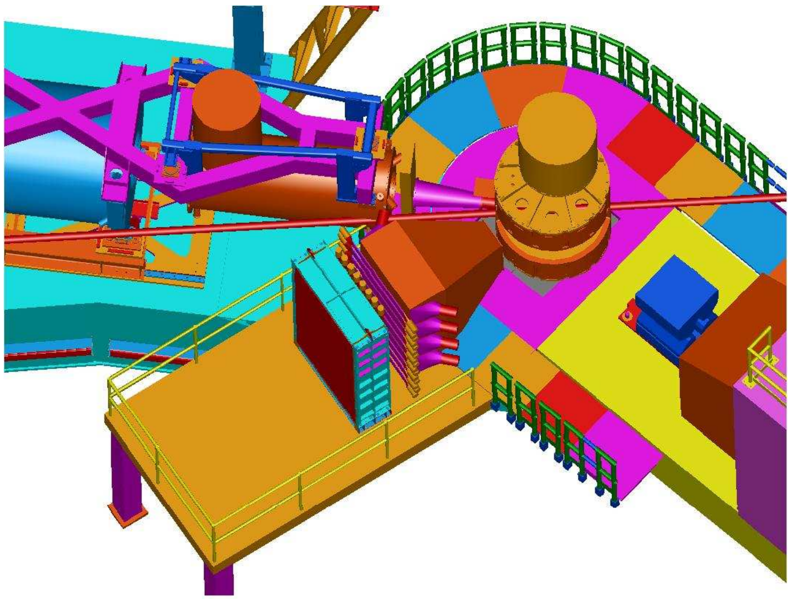
Purity from Monte Carlo.

The Semi-SANE Experiment at Jefferson Lab Hall C

E04-113: P. Bosted, D. Day, X. Jiang and M. Jones co-spokespersons

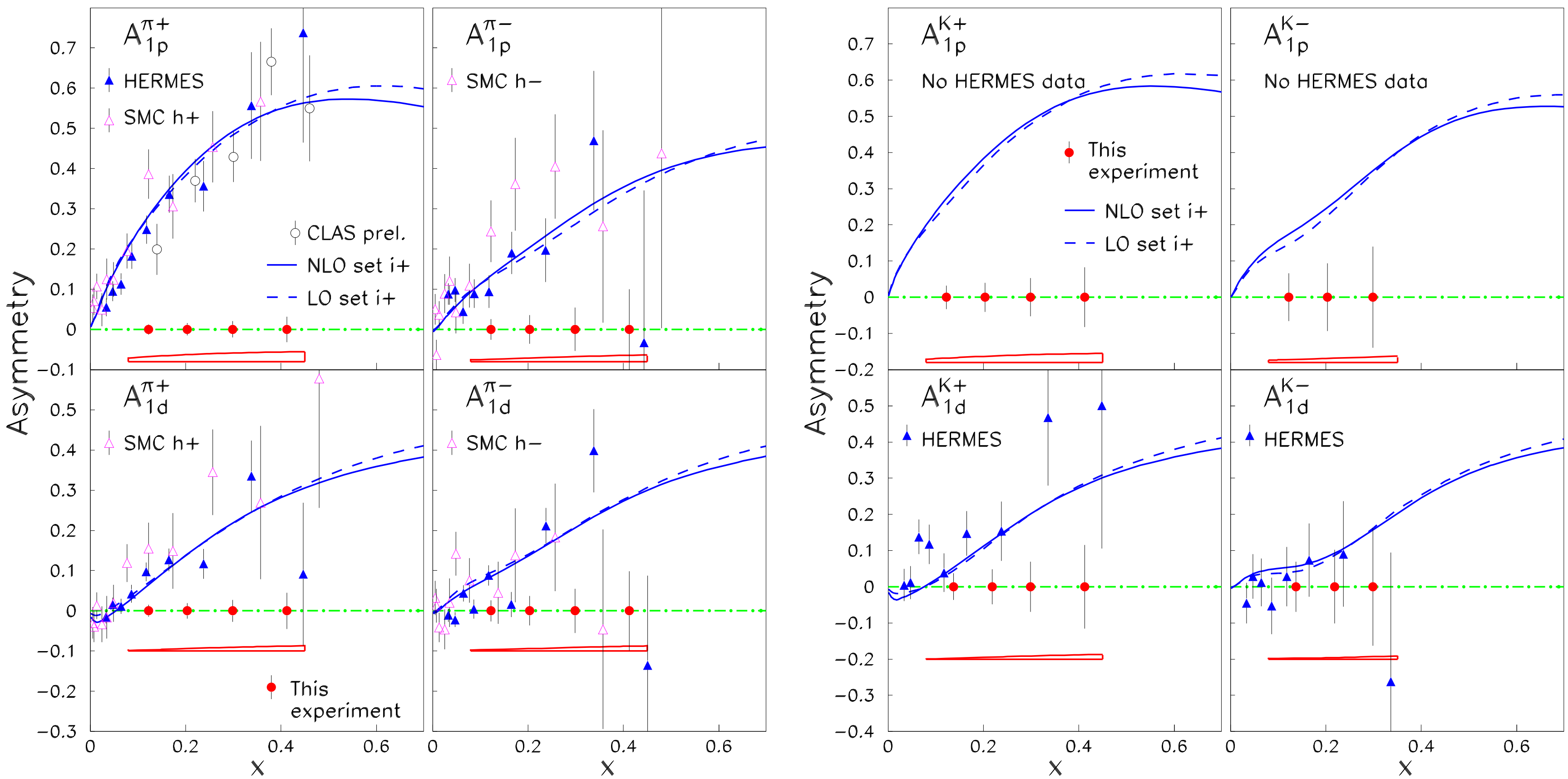
ANL, Duke, FIU, Hampton, JLab, Kentucky, UMass, Norfolk, ODU, RPI, Rutgers, Temple, UVa, W&M, Yerevan, Regina, IHEP-Protvino.

High precision asymmetry data in deep-inelastic $\vec{N}(\vec{e}, e'h)$ ($N = p, d, h = \pi^{\pm}, K^{\pm}$).



- $E_0 = 6$ GeV, $P_B = 0.80$.
- e-Arm: a calorimeter array $@30^{\circ}$.
- h-Arm: HMS spectrometer @10.8°, 2.71 GeV/c, $z \approx 0.5$. Particle ID detectors for π/K separation.
- Target: polarized NH_3 ($\vec{p}$) and LiD ($\vec{d} = \vec{p} + \vec{n}$).

The Expected Precision on A_{1p}^h and A_{1d}^h

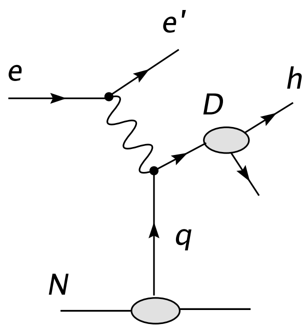


Approved for 25 days of beam time. Significant improvements on the statistical accuracy of $A_{1N}^{\pi^\pm}$. First data on $A_{1p}^{K^\pm}$.

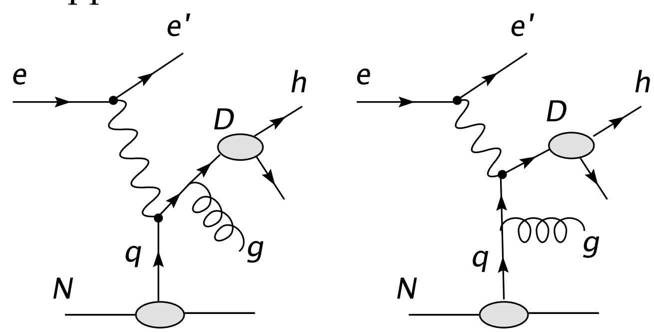
Interpretation of SIDIS Beyond the Leading Order

What if the naive LO x-z factorization doesn't hold exactly ? Extended the interpretation of SIDIS beyond LO (Christova and Leader, NPB 607 (2001) 369, de Florian, Navarro and Sassot hep-ex/0504155 and PRD.)

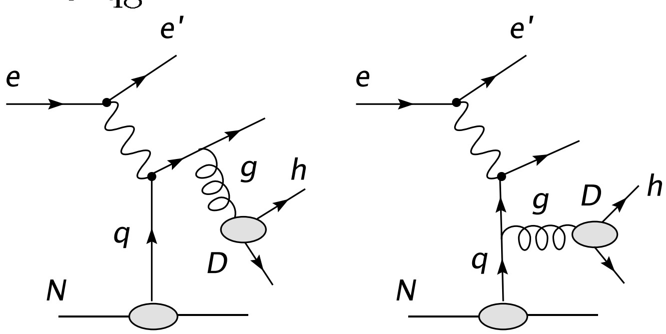
LO:



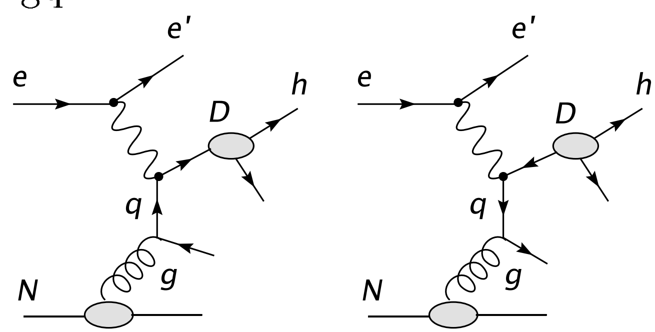
NLO-qq:



NLO-qg:



NLO-gq:



- At NLO the naive x-z factorization is violated in a calculable way.

SIDIS Cross Sections at the Next-to-Leading-Order

$$q(x,Q^2)\cdot D(z,Q^2) \Rightarrow \int \frac{dx'}{x'}\int \frac{dz'}{z'} q\left(\frac{x}{x'}\right) C(x',z') D\left(\frac{z}{z'}\right) = q \otimes C \otimes D$$

C are well-known Wilson coefficients (D. Graudenz, NPB432, 351(1994)).

$$\begin{aligned}\Delta\sigma^h &= \sum_i e_i^2 \Delta q_i \left[1 + \otimes \frac{\alpha_s}{2\pi}\Delta C_{qq}\otimes\right] D_{q_i}^h \\ &+ \left(\sum_i e_i^2 \Delta q_i\right) \otimes \frac{\alpha_s}{2\pi}\Delta C_{qg} \otimes D_G^h + \Delta G \otimes \frac{\alpha_s}{2\pi}\Delta C_{gq} \otimes \left(\sum_i e_i^2 D_{q_i}^h\right)\end{aligned}$$

Isospin symmetry and charge conjugation: $D_G^h = D_G^{\bar{h}}$, $\sum_i e_i^2 D_{q_i}^h = \sum_i e_i^2 D_{q_i}^{\bar{h}}$.

Higher order terms which have gluons involved vanish in $\pi^+ - \pi^-$ observables to all orders of QCD. $A_{1N}^{\pi^+-\pi^-}$ is theoretically clean.

From $A_{1N}^{\pi^+-\pi^-}(x)$ to $\Delta u_v(x)$ and $\Delta d_v(x)$

E. Christova and E. Leader, NPB607,369 (2001):

$$\frac{\Delta\sigma_p^{\pi^+} - \Delta\sigma_p^{\pi^-}}{\sigma_p^{\pi^+} - \sigma_p^{\pi^-}} = \frac{(4\Delta u_v - \Delta d_v)\,[1 + \otimes(\alpha_s/2\pi)\Delta C_{qq}\otimes]\,D_u^{\pi^+-\pi^-}}{(4u_v - d_v)\,[1 + \otimes(\alpha_s/2\pi)C_{qq}\otimes]\,D_u^{\pi^+-\pi^-}}$$

$$\frac{\Delta\sigma_d^{\pi^+} - \Delta\sigma_d^{\pi^-}}{\sigma_d^{\pi^+} - \sigma_d^{\pi^-}} = \frac{(\Delta u_v + \Delta d_v)\,[1 + \otimes(\alpha_s/2\pi)\Delta C_{qq}\otimes]\,D_u^{\pi^+-\pi^-}}{(u_v + d_v)\,[1 + \otimes(\alpha_s/2\pi)C_{qq}\otimes]\,D_u^{\pi^+-\pi^-}}$$

$$\frac{\Delta\sigma_{He}^{\pi^+} - \Delta\sigma_{He}^{\pi^-}}{\sigma_{He}^{\pi^+} - \sigma_{He}^{\pi^-}} = \frac{(4\Delta d_v - \Delta u_v)\,[1 + \otimes(\alpha_s/2\pi)\Delta C_{qq}\otimes]\,D_u^{\pi^+-\pi^-}}{(7u_v + 2d_v)\,[1 + \otimes(\alpha_s/2\pi)C_{qq}\otimes]\,D_u^{\pi^+-\pi^-}}$$

- Δu_v and Δd_v are non-singlets which do not mix with gluon and sea densities.
- Data from two targets are needed to extract Δu_v and Δd_v. Measurements on the third target provide extra constrains.
- Proton data are mostly sensitive to Δu_v, neutron data (^{3}He) are mostly sensitive to Δd_v.

From $\Delta u_v(x)$ and $\Delta d_v(x)$ to $\Delta\bar{u}(x) - \Delta\bar{d}(x)$:

Once we obtain $\Delta u_v(x)$ and $\Delta d_v(x)$ at any QCD-order, $\Delta\bar{u}(x) - \Delta\bar{d}(x)$ can be extracted to the same order by combining with the inclusive data.

$$\Delta\bar{u}(x) - \Delta\bar{d}(x) = \frac{1}{2}(\Delta u + \Delta\bar{u} - \Delta d - \Delta\bar{d} + \Delta d_v - \Delta u_v)$$

where $\Delta q_{NS}(x) = \Delta u + \Delta\bar{u} - \Delta d - \Delta\bar{d}$ can be extracted from inclusive data.

At LO: $\Delta q_{NS}(x) = 6(g_1^p(x) - g_1^n(x))$.

“Bjorken Sum Rule” links the moments at all orders of QCD (Sissakian *et al.* PRD68, 031502 (2003)).

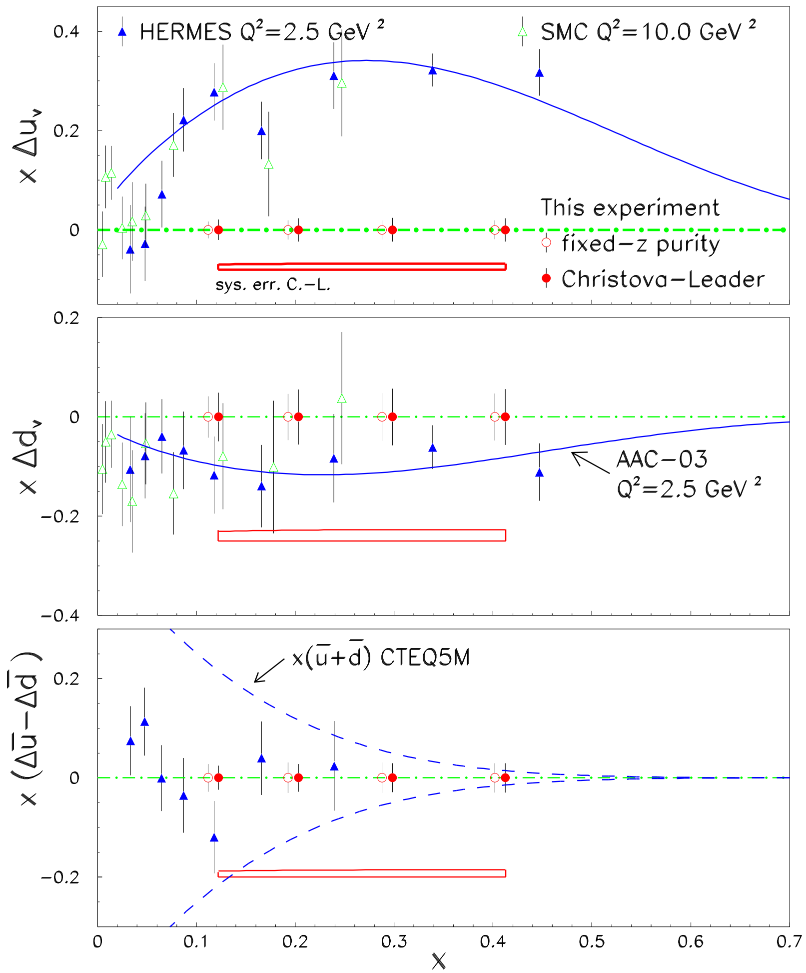
$$2\int_0^1 (\Delta\bar{u} - \Delta\bar{d})dx + \int_0^1 (\Delta u_v - \Delta d_v)dx = |\frac{g_A}{g_V}| = 1.2670 \pm 0.0035$$

To obtain $A_{1N}^{\pi^+-\pi^-}$ we need:

Well-controlled phase space and hadron PID

$$A_{1N}^{\pi^+-\pi^-} = \frac{\Delta\sigma_N^{\pi^+} - \Delta\sigma_N^{\pi^-}}{\sigma_N^{\pi^+} - \sigma_N^{\pi^-}} = \frac{A_{1N}^{\pi^+} - A_{1N}^{\pi^-} \cdot r}{1-r}, \quad r = \frac{\sigma^{\pi^-}}{\sigma^{\pi^+}}.$$

Jefferson Lab E04-113: Expected Results on Δq



$E_0 = 6$ GeV, $\langle Q^2 \rangle = 2.2$ GeV^2.

$$\Delta u_v = \Delta u - \Delta \bar{u}$$
$$\Delta d_v = \Delta d - \Delta \bar{d}$$

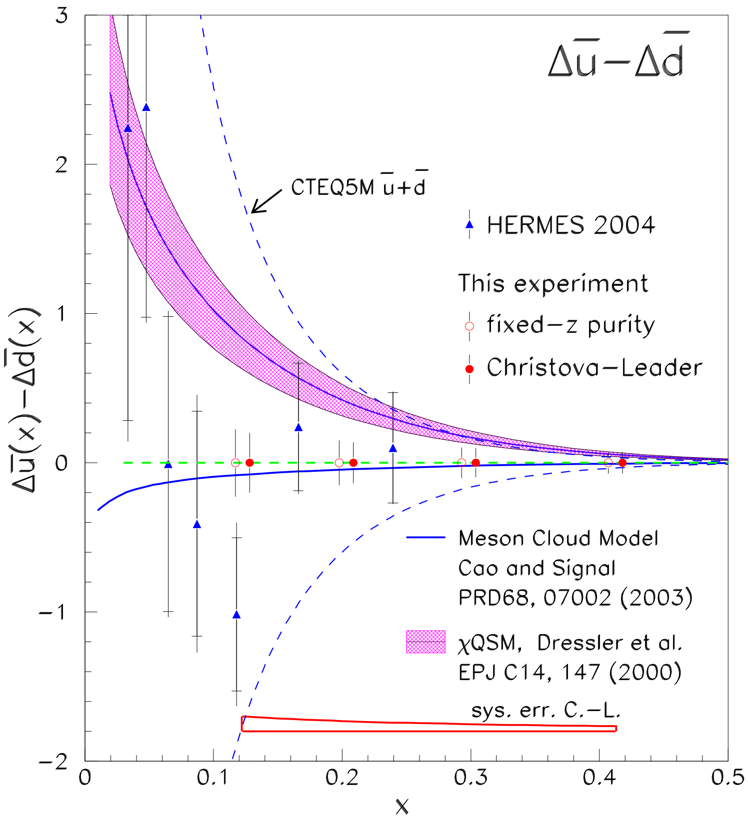
Tow independent methods of flavor decomposition:

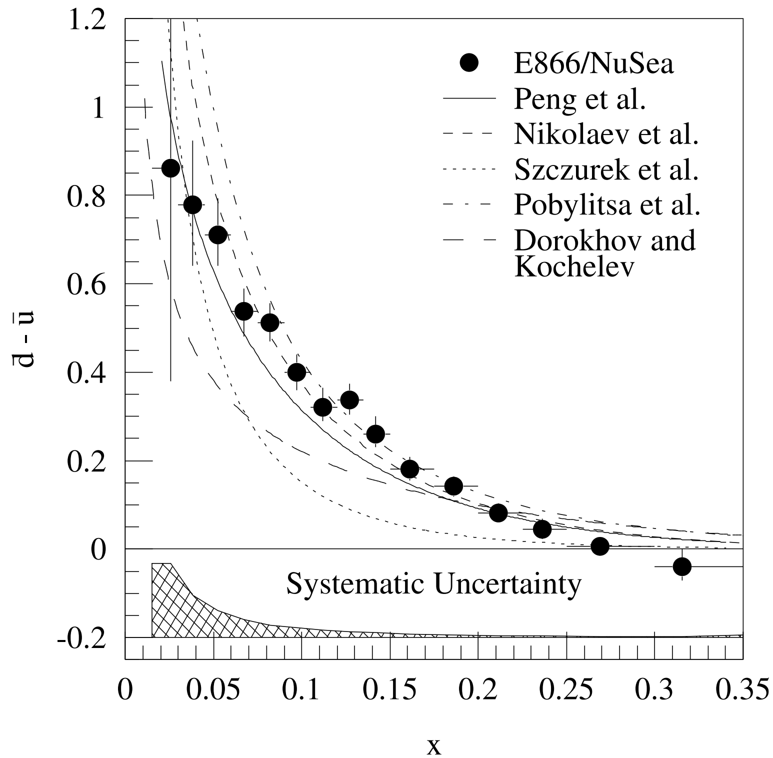
i, Christova-Leader method.

ii, “Purity” at a fixed-z.

Statistical uncertainties dominate.

Flavor Asymmetry in the Nucleon Sea





Many other model predicted large $\Delta\bar{u} - \Delta\bar{d}$. In Chiral-quark soliton model, $\Delta\bar{u} - \Delta\bar{d}$ appears in LO (N_c^2) while $\bar{d} - \bar{u}$ appears in NLO (N_c).

Fermilab $pp, pd \rightarrow \mu^+\mu^-$ data. Many models explain $\bar{d} - \bar{u}$, including the meson-cloud model (π) which predicts $\Delta\bar{u} = \Delta\bar{d} = 0$.

Pauli-blocking model: $\int_0^1 [\Delta\bar{u}(x) - \Delta\bar{d}(x)]dx = \frac{5}{3} \cdot \int_0^1 [\bar{d}(x) - \bar{u}(x)]dx \approx 0.2$.

A New Tool: NLO Global Fit to DIS and SIDIS Data

(hep-ph/0504155 and PRD, de Florian, Navarro, Sassot.)

- Fit inclusive and semi-inclusive DIS data at the same time.
- To the next-to-leading order in PDFs and fragmentation functions.
- Different parameterization of FF (KRE and KKP).
- Gives error bands on polarized PDF and translate into error bands on asymmetry observables.
- Translate error bars from any new data set to overall constrains on moments of polarized PDFs.
- Preliminary CLAS EG1b data agrees with the NLO prediction.

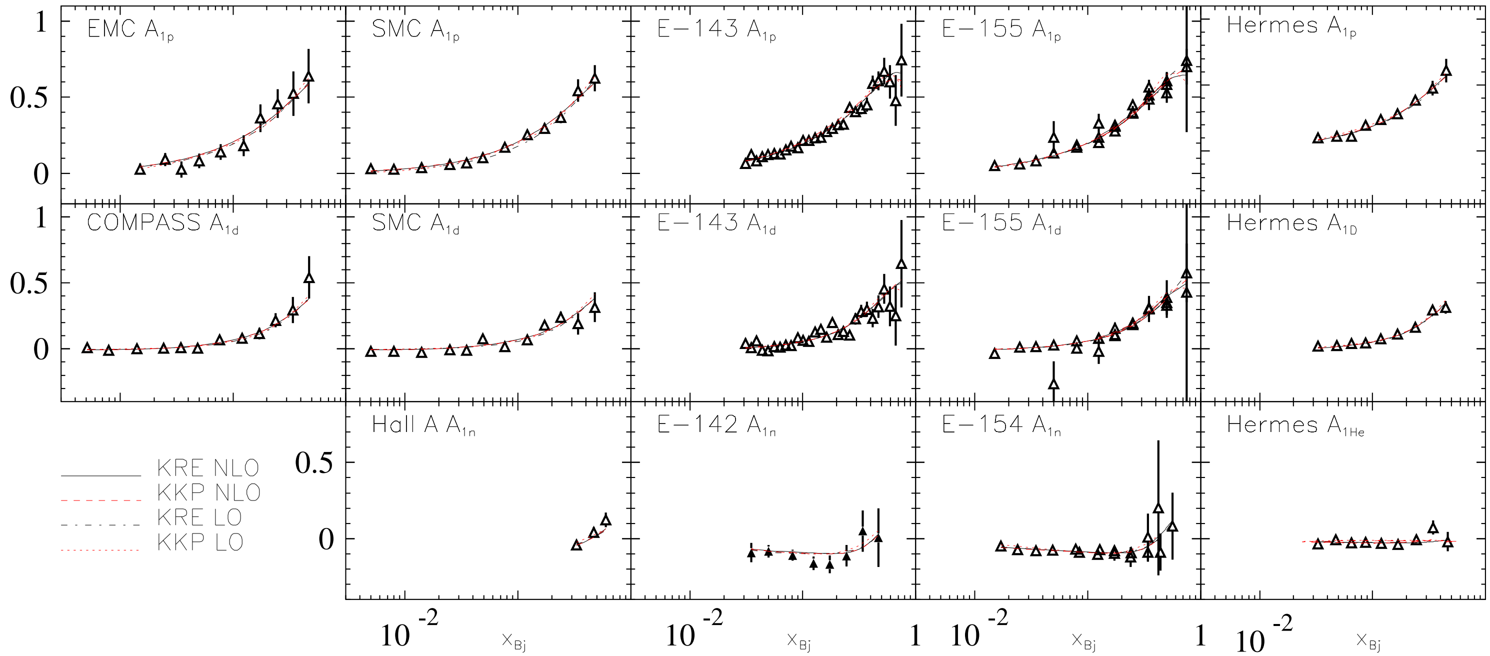
Fit to inclusive $g_1^p(x)$, $g_1^n(x)$ and $g_1^d(x)$:

$$
\begin{aligned}
g_1^N(x,Q^2) &= \frac{1}{2}\sum_{q,\bar{q}} e_q^2 \Bigg[\Delta q(x,Q^2) \\
&+ \frac{\alpha_s(Q^2)}{2\pi} \int_x^1 \frac{dz}{z} \left\{ \Delta C_q(z) \Delta q(\frac{x}{z},Q^2) + \Delta C_g(z) \Delta g(\frac{x}{z},Q^2) \right\} \Bigg].
\end{aligned}
$$

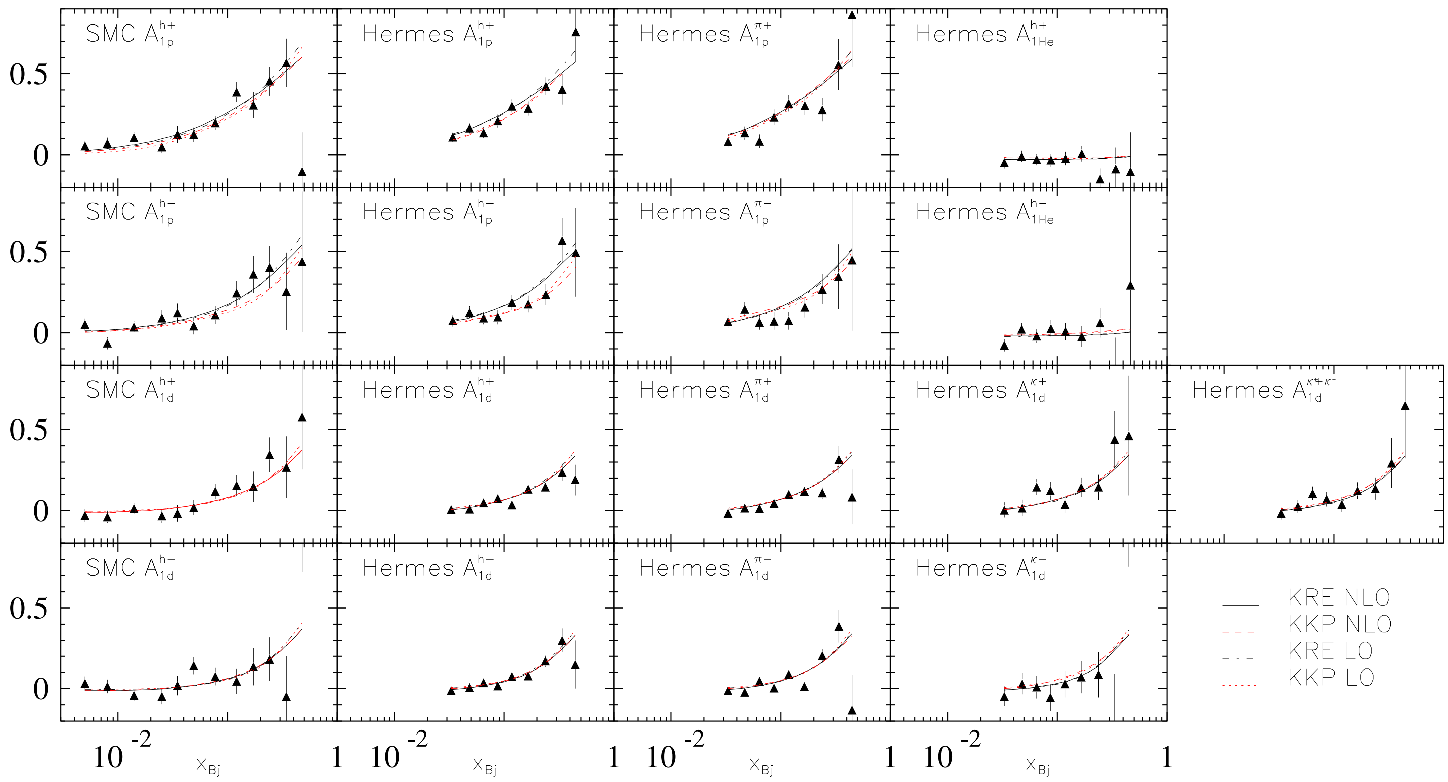
Fit to semi-inclusive $A_{1p}^{h}(x)$, $A_{1He}^{h}(x)$ and $A_{1d}^{h}(x)$:

$$
\begin{aligned}
\Delta\sigma_N^h(x,z,Q^2) &= A_{1N}^h(x,z,Q)\cdot\sigma_N^h(x,z,Q) \\
&= \frac{1}{2}\sum_{q,\bar{q}} e_q^2 \Bigg[\Delta q\left(x,Q^2\right) D_q^H\left(z,Q^2\right) \\
&+ \frac{\alpha_s(Q^2)}{2\pi}\int_x^1 \frac{d\hat{x}}{\hat{x}}\int_z^1 \frac{d\hat{z}}{\hat{z}}\Bigg\{\Delta q\left(\frac{x}{\hat{x}},Q^2\right)\Delta C_{qq}^{(1)}(\hat{x},\hat{z},Q^2) D_q^H\left(\frac{z}{\hat{z}},Q^2\right) \\
&+ \Delta q\left(\frac{x}{\hat{x}},Q^2\right)\Delta C_{gq}^{(1)}(\hat{x},\hat{z},Q^2) D_g^H\left(\frac{z}{\hat{z}},Q^2\right) \\
&+ \Delta g\left(\frac{x}{\hat{x}},Q^2\right)\Delta C_{qg}^{(1)}(\hat{x},\hat{z},Q^2) D_q^H\left(\frac{z}{\hat{z}},Q^2\right)\Bigg\}\Bigg]
\end{aligned}
$$

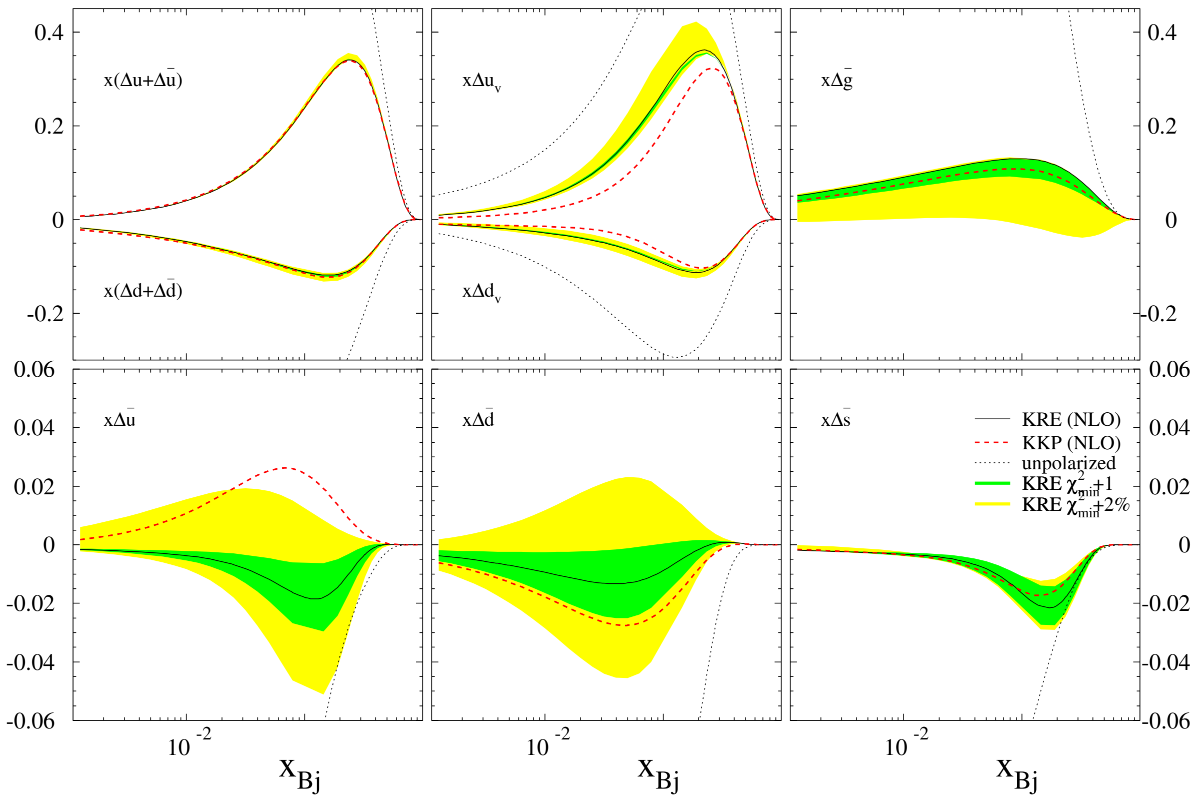
The Best Fit Compare with Inclusive Data:



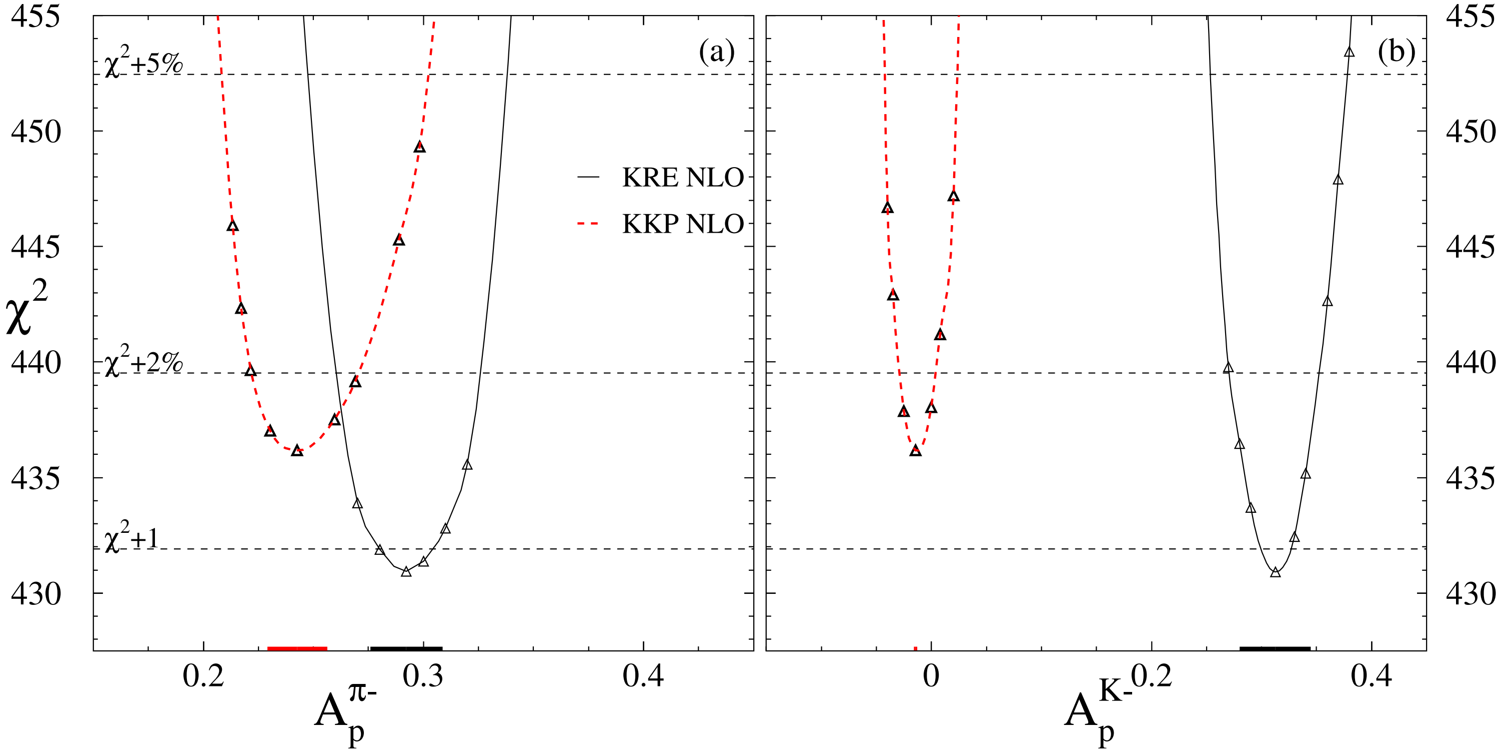
The Best Fit Compare with Semi-Inclusive DIS Data:



Error bands of NLO polarized PDF

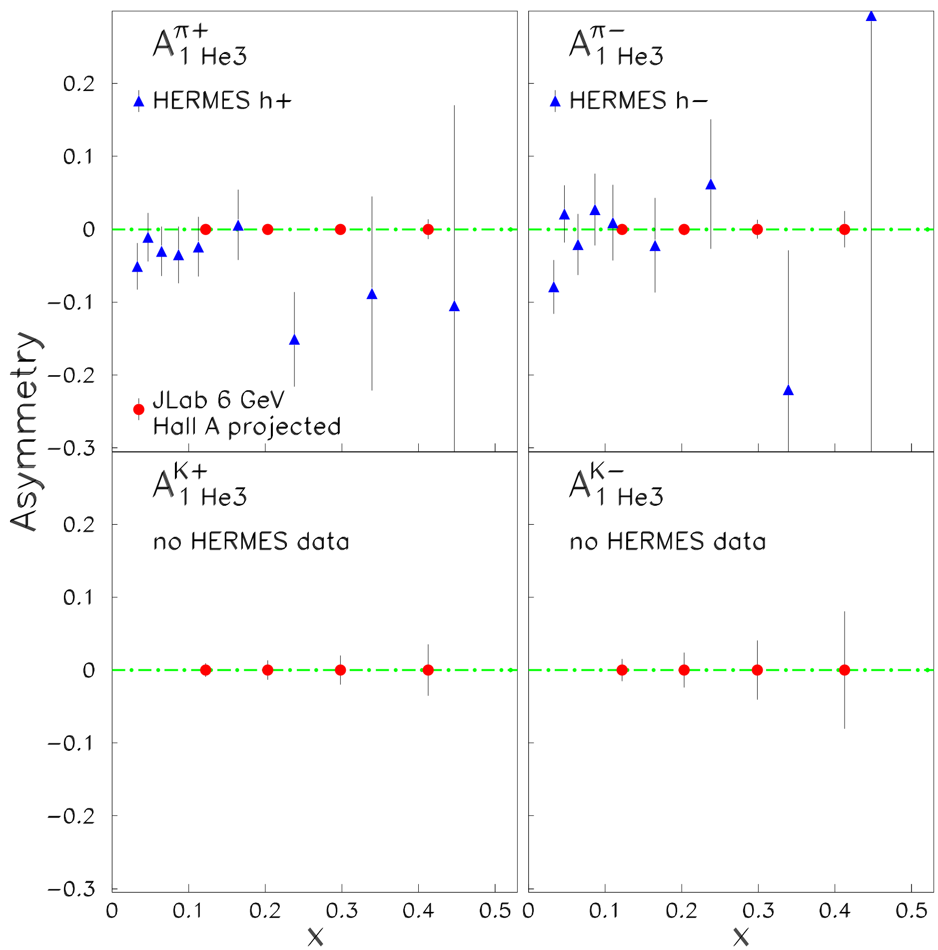


Impacts of Semi-SANE Data to NLO Fit



Experiment error bar on $A_{1p}^{\pi^-}$ and $A_{1p}^{K^-}$ for $x = 0.2$ bin. Kaon production data will put strong constrains on the fragmentation functions (Kretzer vs. KKP)

The Δd Experiment: SIDIS with Polarized ^{3}He



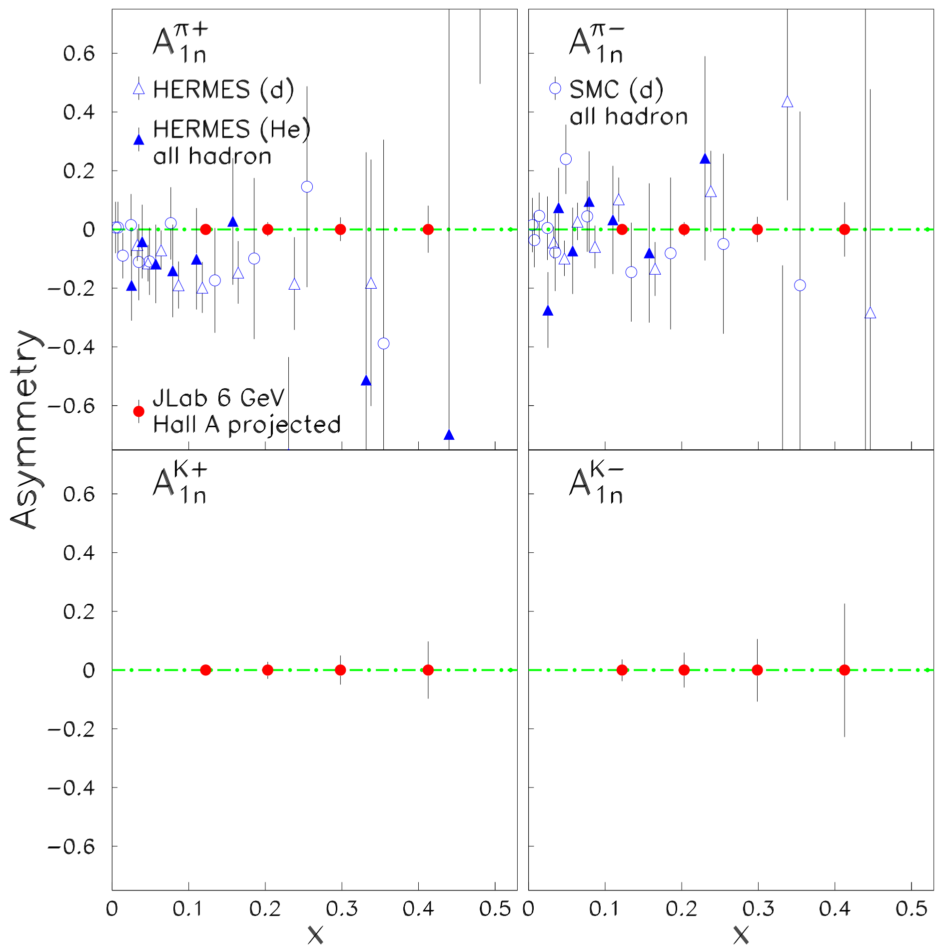
A new proposal to PAC28.

A^h_{LL} on polarized ^{3}He in Hall A.

- A^h_{1He} are sensitive to Δd.
- Extract Δd_v (and Δu_v) from $A^{\pi^+ - \pi^-}_{1He}$.
- High precision constrains to the global NLO fit.
- First data on $A^{K^+}_{1He}$ and $A^{K^-}_{1He}$

- BigBite at 30° as e-arm. HRS+septum at 6° as h-arm, standard Hall A polarized ^{3}He target.
- All equipments exist in Hall A.
- Request for 28 days of total beam time.

The Δd Experiment: Projected Uncertainties on A_{1n}^{h}



The high luminosity Hall A polarized ^{3}He target allows significant improvements over HERMES data.

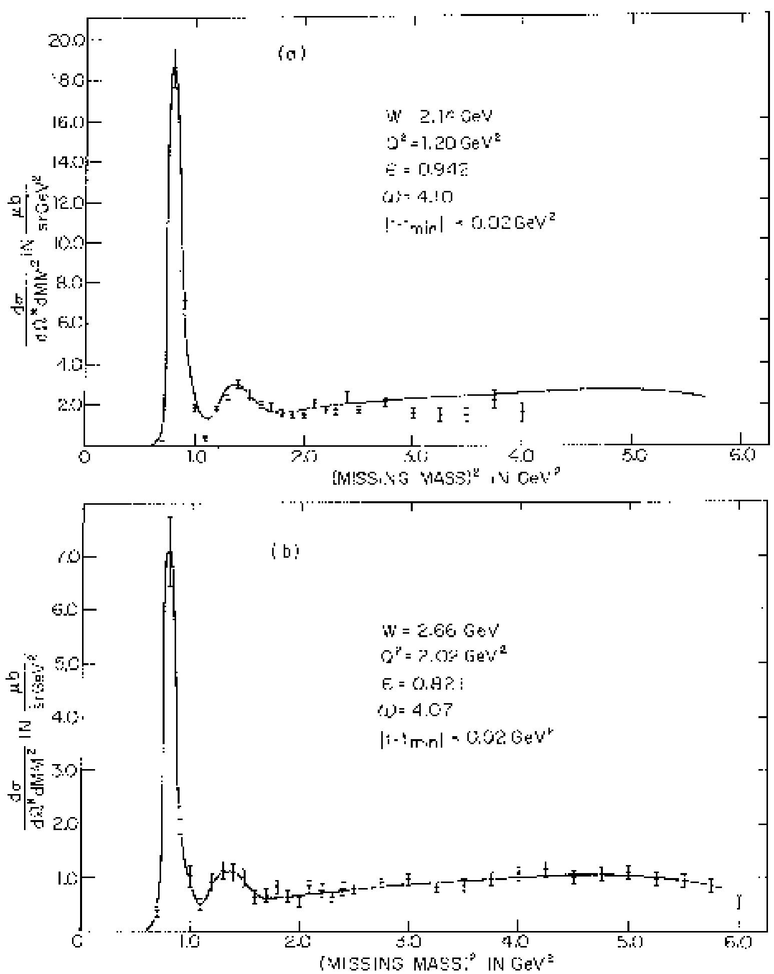
- Hall A with a 6 GeV beam.
- $\langle Q^2 \rangle = 2.2$ GeV^2.
- 28 days of beam time.

Duality in SIDIS: Two-Types of Duality ?

“Fragmentation Duality”: at high-z (low-W', keep Q^2 and W high) when the number of final hadron becomes very limited, semi-inclusive meson production looks similar to semi-inclusive DIS reaction. No resonance structure above $W' > m_\Delta$.

“DIS Duality”: at low Q^2 and W, semi-inclusive meson production looks similar to semi-inclusive deep-inelastic scattering reaction.

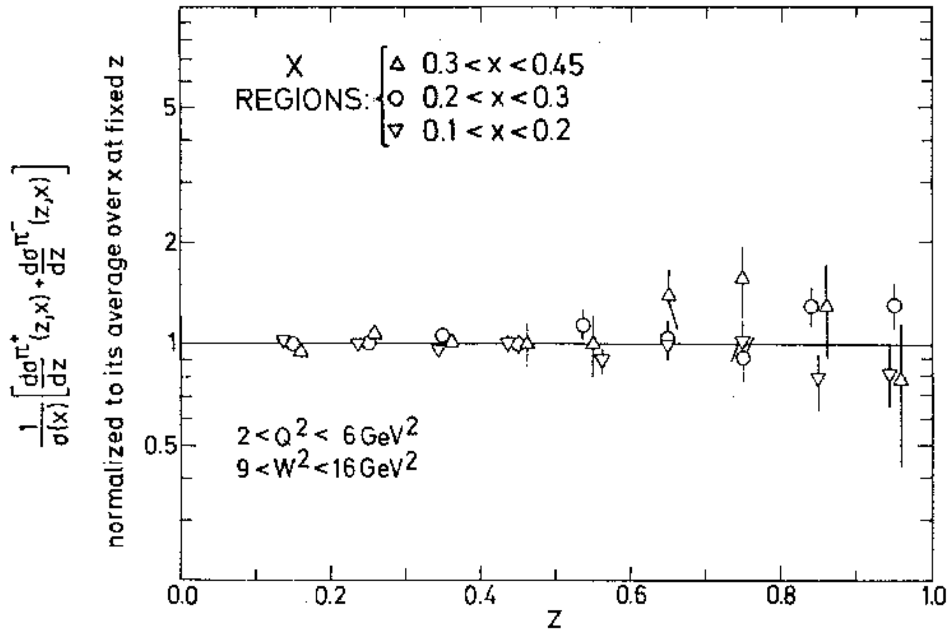
Duality in SIDIS: Cross Section vs. W'



Cornell $p(e, e'\pi^+)X$ data 1971.

- $E_0 = 11$ GeV. $Q^2 = 1.2, 2.0$ GeV^2.
- Smooth cross sections at $W' > 1.3$ GeV.

Cornell Data: $\sigma_p^{\pi^+} + \sigma_p^{\pi^-}$



Drews *et al.* PRL 41, 1433 (1978).

- $E_0 = 11.5$ GeV. $\langle Q^2 \rangle = 2.8$ GeV^2
- Cross section ratios have no x-dependence for $z < 0.6$.
- At large z, resonance production dominates.
- At $z > 0.6$ exclusive ρ^0 production start ruining the SIDIS interpretation ?

$$\frac{1}{\sigma_{DIS}(x)} \left(\frac{d\sigma}{dz}^{\pi^+}(x,z) + \frac{d\sigma}{dz}^{\pi^-}(x,z) \right) \cong D^+(z) + D^-(z)$$

Recall that in $\pi^+ - \pi^-$ gluons don't contribute. We can construct clean observables in which exclusive ρ^0 contribution vanishes:

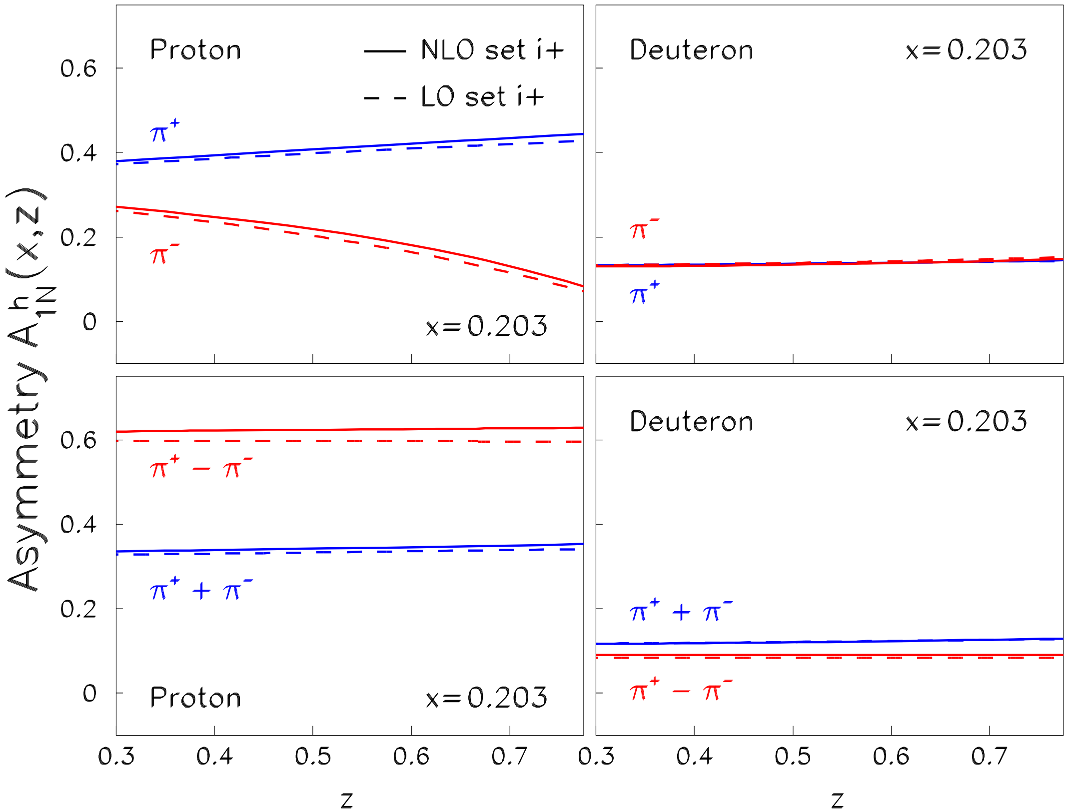
$$\frac{1}{\sigma_{DIS}(x)}\left(\frac{d\sigma}{dz}^{\pi^+}(x,z) - \frac{d\sigma}{dz}^{\pi^-}(x,z)\right) \cong D^+(z) - D^-(z)$$

"Fragmentation duality" will work better for $\pi^+ - \pi^-$ at high-z.

In the case of polarized semi-inclusive meson production, which observable will show duality behavior ?

Let's look at NLO predictions on the z-dependency of SIDIS asymmetries:

LO and NLO Predictions of $A_{1N}^{h}(x,z)$ in SIDIS



$A_{1p}^{\pi^+}$ and $A_{1p}^{\pi^-}$ depend on z.

A_{1d}^{h} and $A_{1N}^{\pi^+\pm\pi^-}$ are z-independent.

Expect duality to appear in:
$A_{1N}^{\pi^+-\pi^-}(x,z)$. No gluon, no ρ^0 to start with.
$A_{1d}^{h}(x,z)$. Flat in SIDIS.

G. Navarro and R. Sassot private communications, D. de Florian and R. Sassot, PRD 62, 094025(2000)

Summary

Double-spin asymmetry measurements in SIDIS at Jefferson Lab:

- Spin-flavor decomposition with $\vec{p}$ and $\vec{d}$ (E04-113 in Hall C).
- Constrain Δd through SIDIS with polarized ^{3}He (new proposal in Hall A).

Duality in SIDIS:

- I expect two types of duality: "fragmentation duality" at large-z while keeping the hard scattering part deep-inelastic. "hard-scattering duality" at lower Q^2 and W, merge the resonance production picture with the picture of quark scattering followed by fragmentation.
- Experimentally, I expect duality to appear in two types of observables: $A_{1N}^{\pi^+-\pi^-}$ and A_{1d}^h.

Plan ahead for JLab experiments at 6 and 12 GeV:

- Polarized target SIDIS experiments at high-z.
- Polarized target meson production experiments at lower-Q^2 and W.