A Planned Jefferson Lab Experiment on Spin-Flavor Decomposition

Semi-Inclusive Spin Asymmetries on the Nucleon Experiment

(E04-113, Semi-SANE)

Xiaodong Jiang, Rutgers University. Oct. 15, 2004 @ SPIN2004

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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 $\vec{N}(\vec{e}, e'h)$ $(N = p, d, h = \pi^{\pm}, K^{\pm})$.

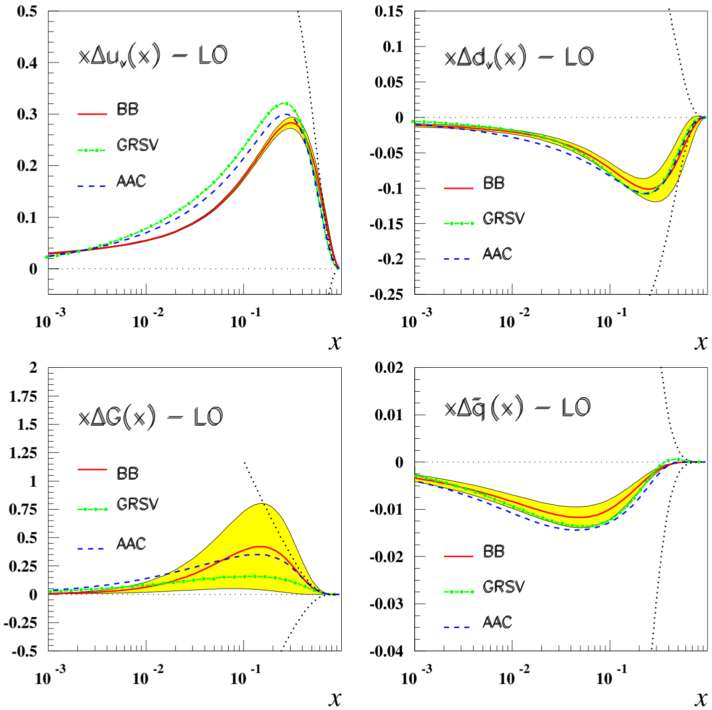
- Double-spin asymmetry A_{1N}^{h} and the combined asymmetry $A_{1N}^{h\pm\bar{h}}$.
- $\Delta u_v, \Delta d_v$ from $A_{1N}^{\pi^+-\pi^-}$ at LO and NLO (Christova-Leader method). Sensitive to $\Delta\bar{u} - \Delta\bar{d}$ when combined with inclusive data $g_1^p - g_1^n$.

Built-in measures of systematic uncertainties:

- Measure the violation of LO x-z factorization using $A_{1N}^{\pi^++\pi^-} - A_{1N}$.

Approved for 25 days of 6 GeV beam in Jefferson Lab Hall C.

Motivation: the Nucleon Spin Structure

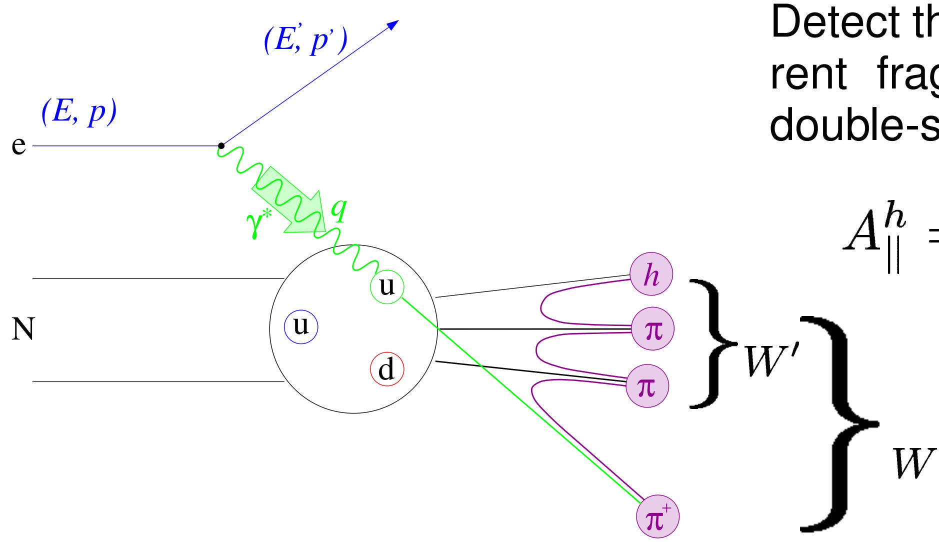


Global QCD fits to the inclusive DIS data.

- Have to assume the sea behavior. As in BB: $\Delta\bar{q} = \Delta\bar{u} = \Delta\bar{d} = \Delta\bar{s}$.
- Inclusive data can not distinguish between q and $\bar{q}$ since $\sigma = \sum_f e_f^2 q_f$.
- Only one flavor non-singlet accessible: $\Delta q_3 = (\Delta u + \Delta\bar{u}) - (\Delta d + \Delta\bar{d})$.
- Can not access $\Delta\bar{u} - \Delta\bar{d}$.

Semi-inclusive deep inelastic scattering (SIDIS) offers extra handle of q vs $\bar{q}$ due to flavor tagging. Provide access to the valence and the sea structure of the nucleon spin.

Flavor Tagging in Semi-Inclusive DIS



$$z = E_\pi / \nu$$

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

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

Assume leading order naive x-z factorization (HERMES):

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

Each asymmetry measurement provides an independent constrain on Δq_f.

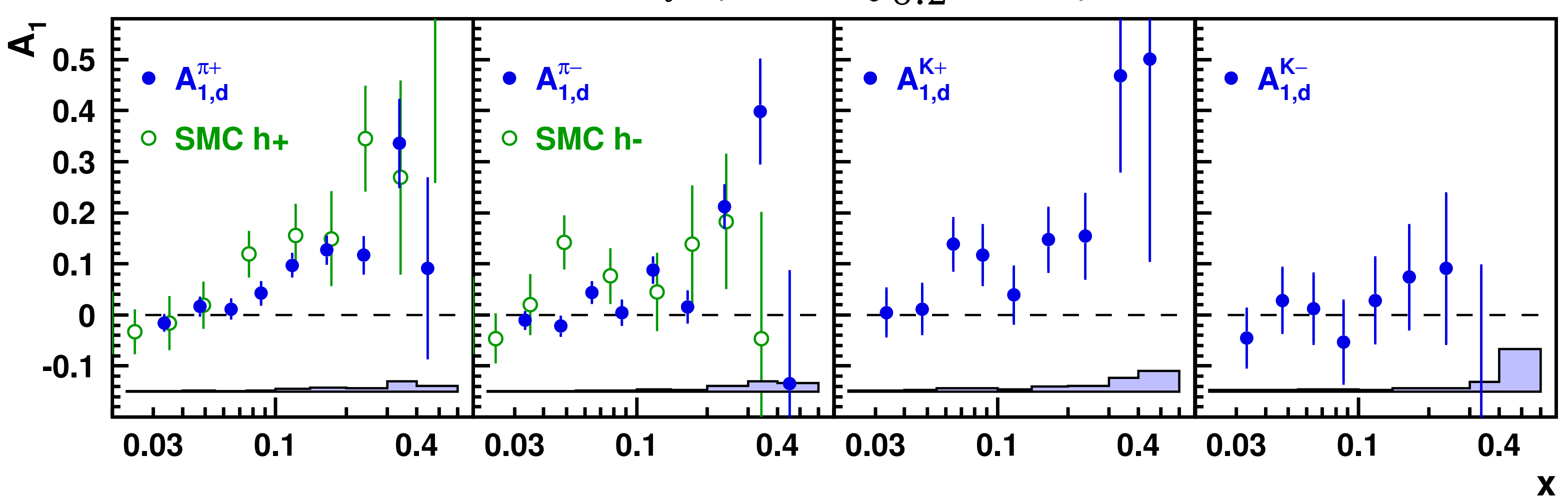
HERMES Flavor Decomposition: $\vec{A} = \mathcal{P}_f^h(x) \cdot \vec{Q}$

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

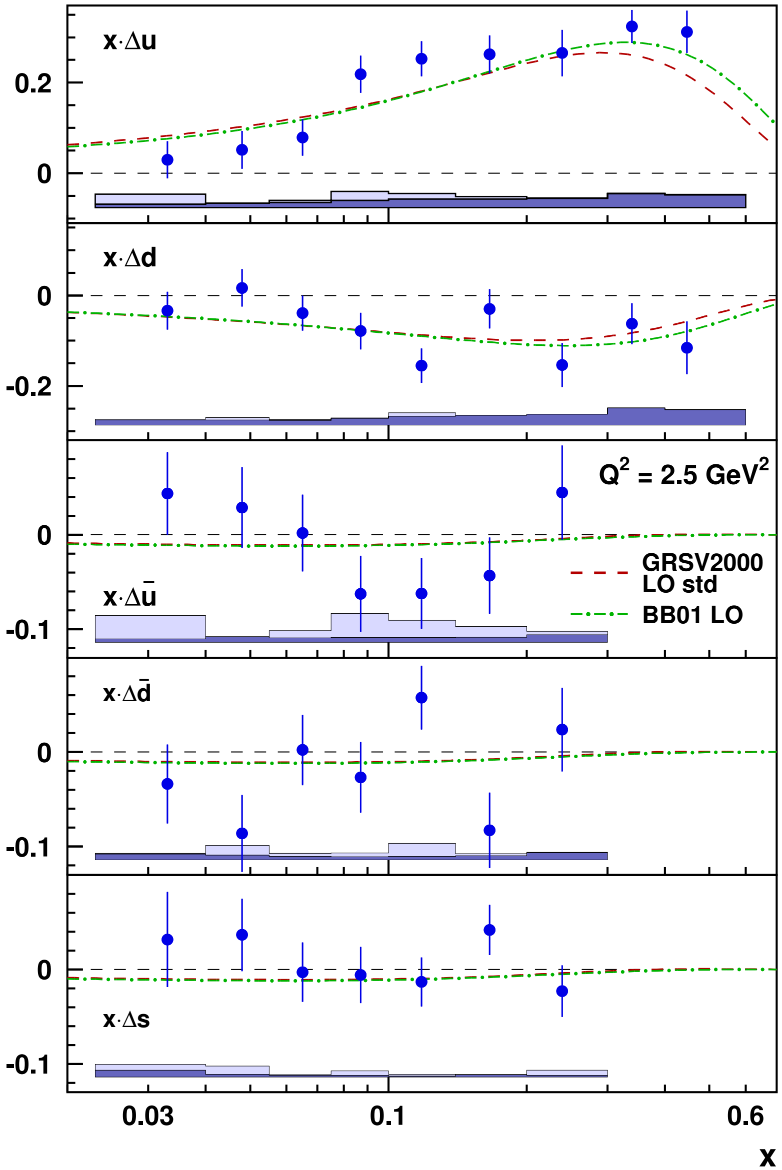
Solve for: $\vec{Q} = \left(x\Delta u, x\Delta d, x\Delta \bar{u}, x\Delta \bar{d}, x\Delta s\right)$.

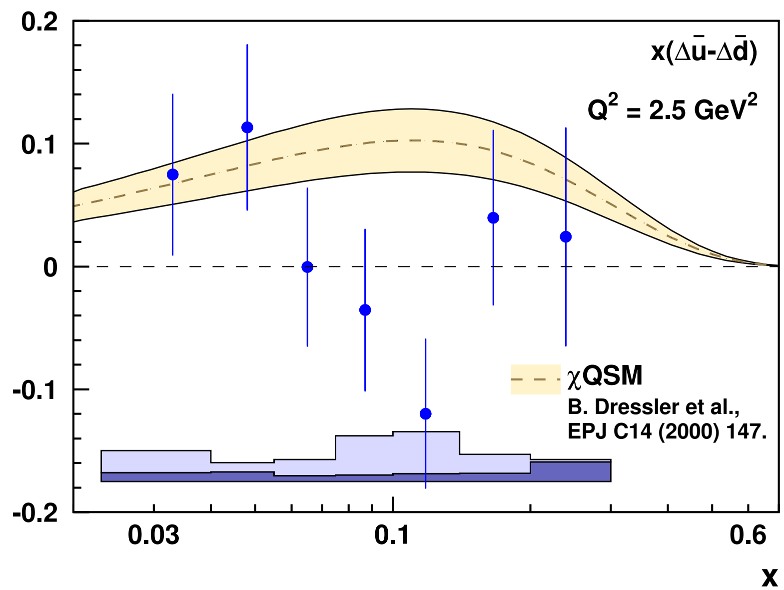
Calculate "Purity" from a LUND based Monte Carlo:

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



HERMES 2004





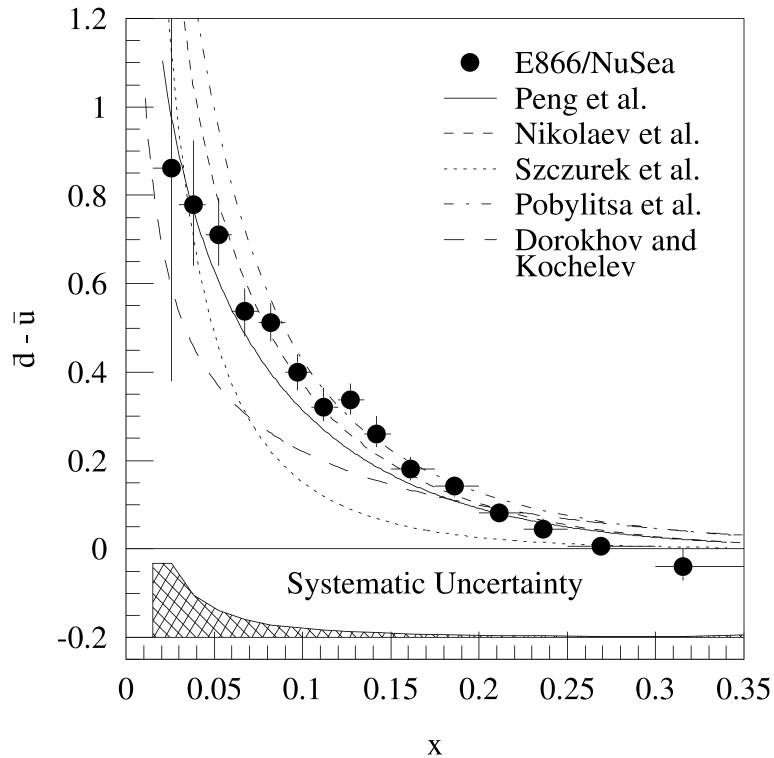
Assumes:

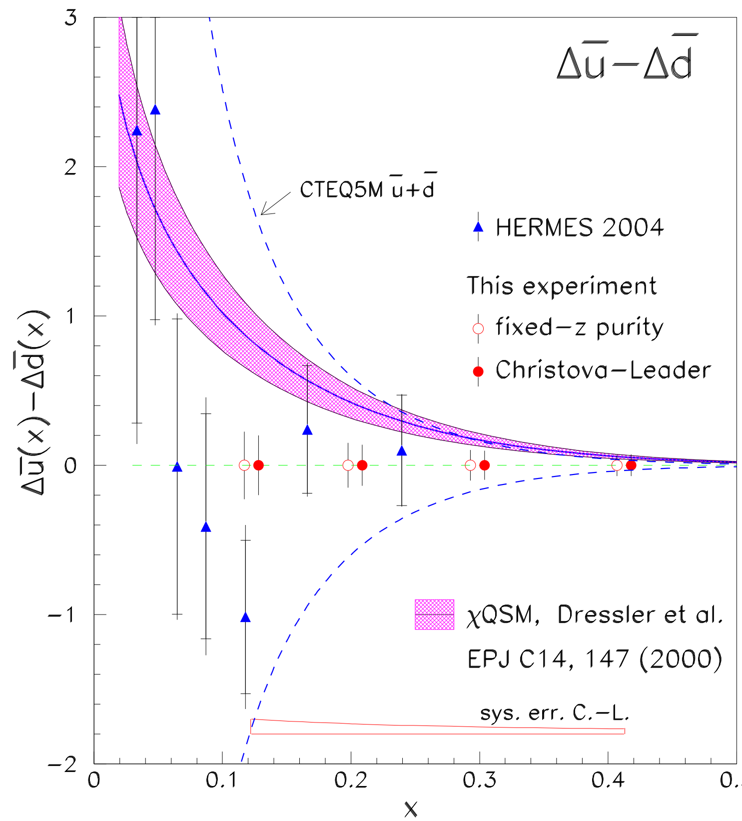
Leading order x-z factorization and current fragmentation.

Isospin symmetry and charge conjugation.

"Purity" calculated from Monte Carlo.

Flavor Asymmetry in the Nucleon Sea





$\int_0^1 (\bar{d} - \bar{u}) dx \;=\; 0.118 \pm 0.012.$

Many models explain $\bar{d} - \bar{u}$, including the meson-cloud model (π) which predicts $\Delta\bar{u} = \Delta\bar{d} = 0$.

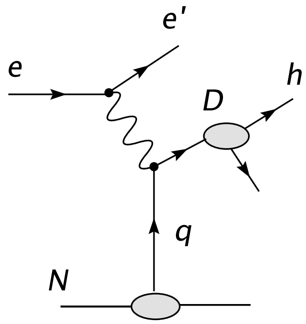
Many other model predicted large $\Delta\bar{u} - \Delta\bar{d}$. In Chiral-quark soliton model, $\Delta\bar{u} - \Delta\bar{d}$ appears in LO (N_c^2) while $\bar{d} - \bar{u}$ appears in NLO (N_c).

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

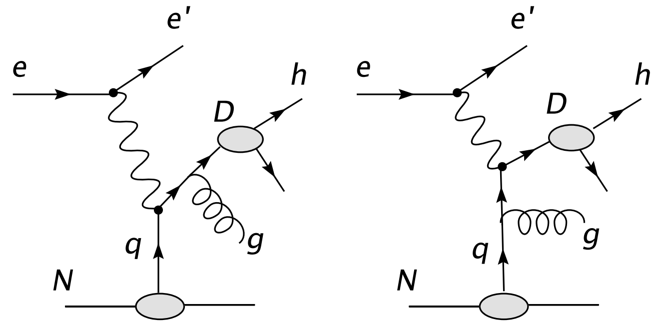
Interpretation of SIDIS Beyond the Leading Order

What if the naive LO x-z factorization doesn't hold exactly ? Are the NLO terms large enough to ruin the parton density interpretation ? Recent theoretical developments have extended the interpretation of SIDIS data beyond LO.

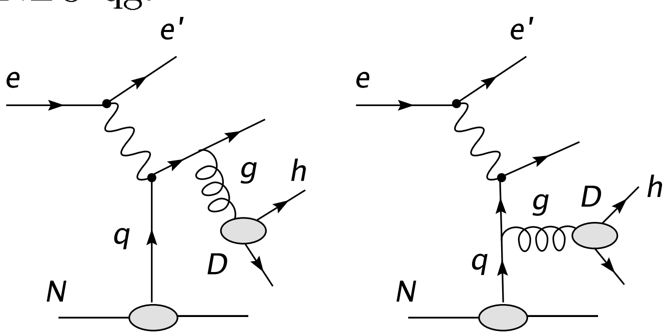
LO:



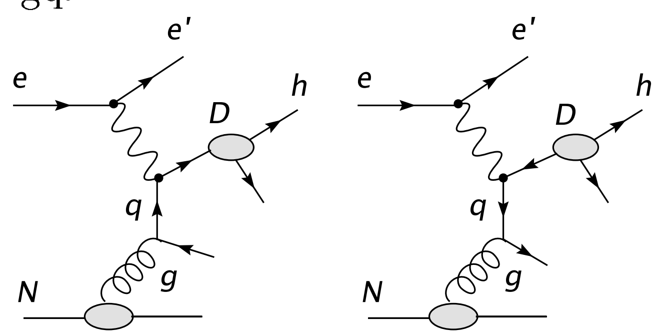
NLO-qq:



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: $D_G^h = D_G^{\bar{h}}$, $\sum_i e_i^2 D_{q_i}^h = \sum_i e_i^2 D_{q_i}^{\bar{h}}$.

The last two terms vanish in $\pi^+ - \pi^-$. $A_{1N}^{\pi^+-\pi^-}$ is theoretically clean.

From $A_{1N}^{\pi^+-\pi^-}$ to Δu_v, Δd_v and $\Delta\bar{u} - \Delta\bar{d}$

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

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

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

Δu_v and Δd_v are non-singlets do not mix with the other quark and gluon densities.

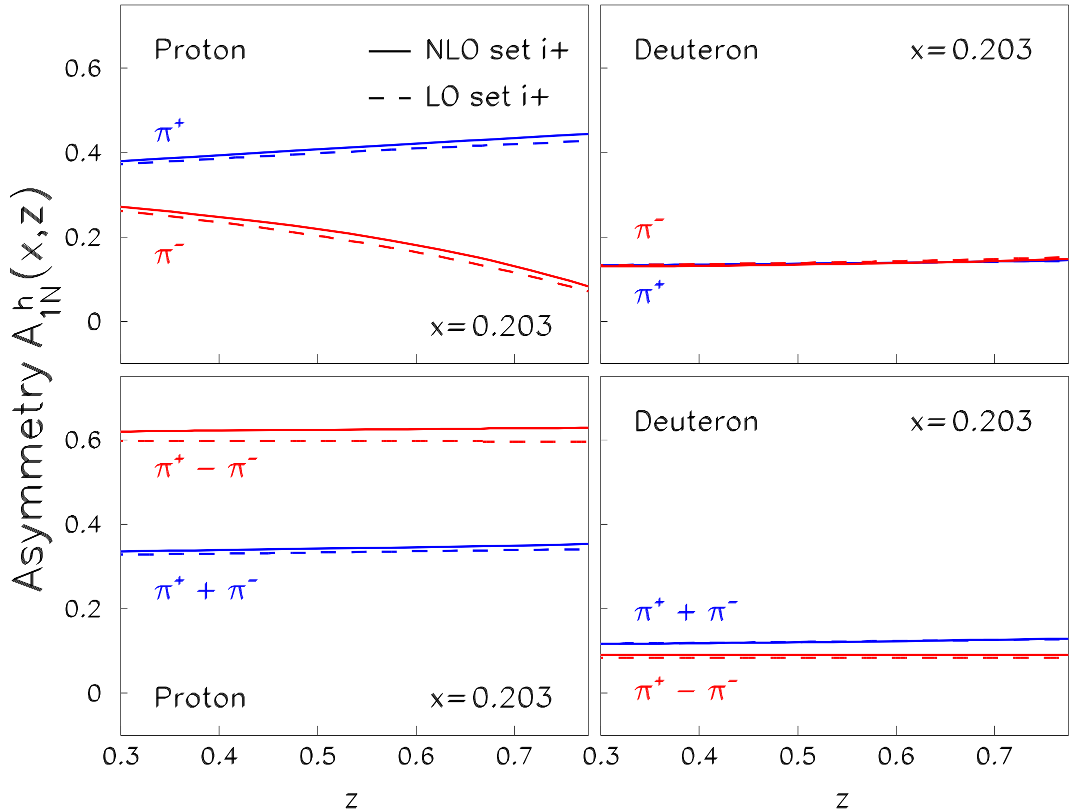
$$(\Delta\bar{u} - \Delta\bar{d})|_{LO} = \frac{1}{2}(\Delta q_3 + \Delta d_v - \Delta u_v)|_{LO}$$

where $\Delta q_3 = \Delta u + \Delta\bar{u} - \Delta d - \Delta\bar{d} = 6(g_1^p - g_1^n)$ from inclusive data.

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

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

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



LO and NLO curves are close:
At $z = 0.5$:
$(A_{NLO} - A_{LO})/A_{LO} = 2.3\%(A_{1p}^{\pi^+})$, 7.6% $(A_{1p}^{\pi^-})$.

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

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

$A_{1N}^{\pi^+ + \pi^-}(x,z) \approx A_{1N}(x)$.

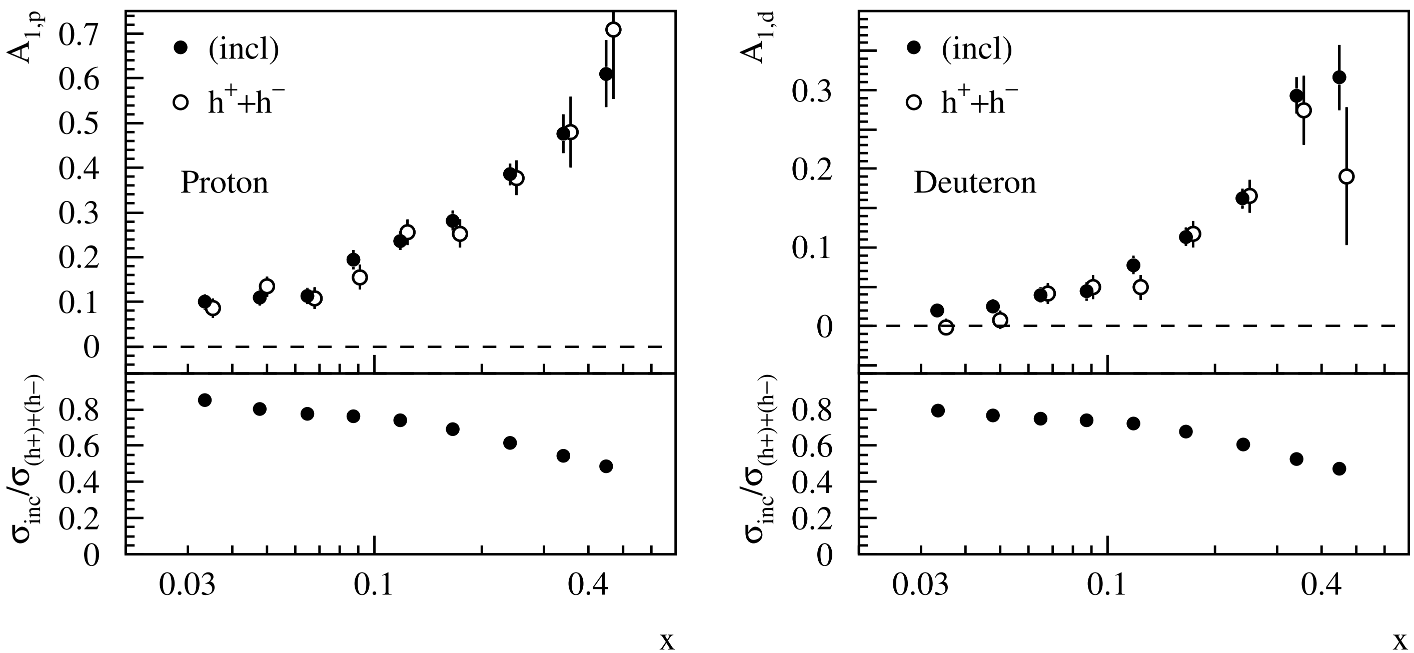
G. Navarro and R. Sassot private communications, D. de Florian and R. Sassot, PRD 62, 094025(2000)

Tests of LO x-z Factorization: $A_{1N}^{\pi^+ + \pi^-} \stackrel{?}{=} A_{1N}$

$$A_{1p}^{\pi^+ + \pi^-}(x,z) = \frac{\Delta\sigma_p^{\pi^+} + \Delta\sigma_p^{\pi^-}}{\sigma_p^{\pi^+} + \sigma_p^{\pi^-}} = \frac{4(\Delta u + \Delta\bar{u}) + \Delta d + \Delta\bar{d}}{4(u+\bar{u}) + d + \bar{d}} \equiv A_{1p}(x)$$

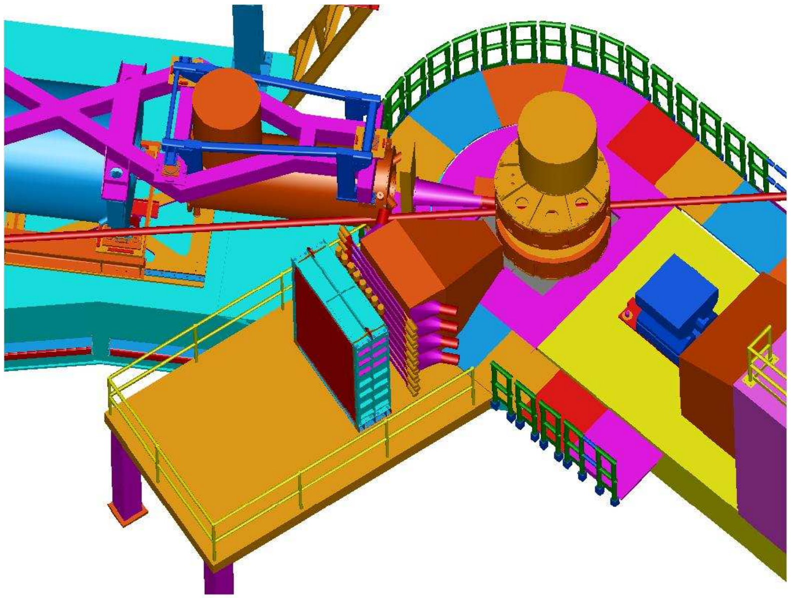
$$A_{1d}^{\pi^+ + \pi^-}(x,z) = \frac{\Delta\sigma_d^{\pi^+} + \Delta\sigma_d^{\pi^-}}{\sigma_d^{\pi^+} + \sigma_d^{\pi^-}} = \frac{\Delta u + \Delta d + \Delta\bar{u} + \Delta\bar{d}}{u + d + \bar{u} + \bar{d}} \equiv A_{1d}(x)$$

As shown in HERMES data ($0.2 < z < 0.8$, J. Wendland, Ph.D. thesis 2003).



What will happen at a well-localized point of $z = 0.5$?

The Semi-SANE Experiment: $\vec{N}(\vec{e}, e'h)$



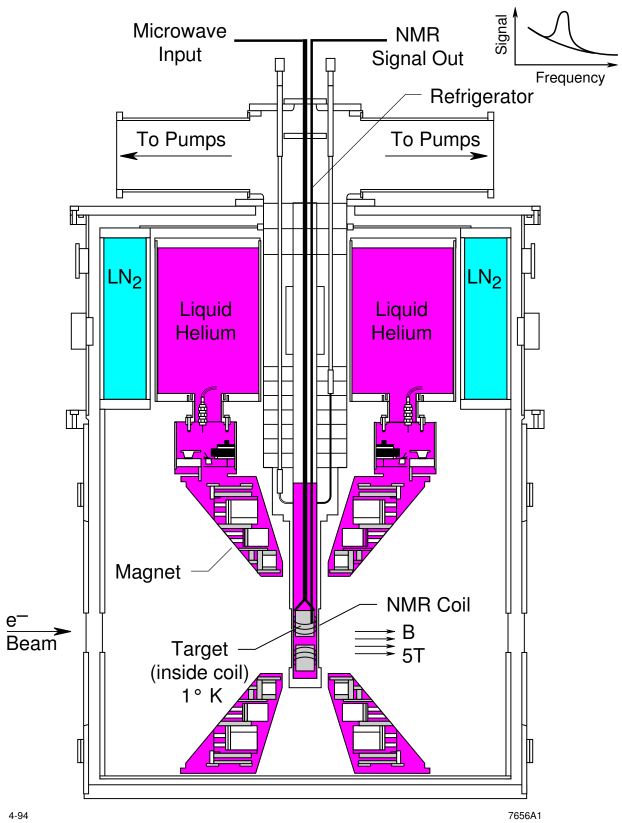
- $E_0 = 6$ GeV, I=80 nA $P_B = 0.80$.
- e-Arm: a large calorimeter+gas Č, $\Delta\Omega \approx 200$ msr, @30°.
- h-Arm: HMS@10.8°, 2.71 GeV/c, $z \approx 0.5$. Gas Č + aerogel for π/K identification
- Target: longitudinal polarized NH_3 and LiD (SLAC and Hall C).

Well-controlled phase space and hadron PID

$$A_{1N}^{\pi^+ \pm \pi^-} = \frac{\Delta\sigma_N^{\pi^+} \pm \Delta\sigma_N^{\pi^-}}{\sigma_N^{\pi^+} \pm \sigma_N^{\pi^-}} = \frac{A_{1N}^{\pi^+} \pm A_{1N}^{\pi^-} \cdot r}{1 \pm r}, \quad r = \frac{\sigma^{\pi^-}}{\sigma^{\pi^+}} = 0.27 \sim 0.64.$$

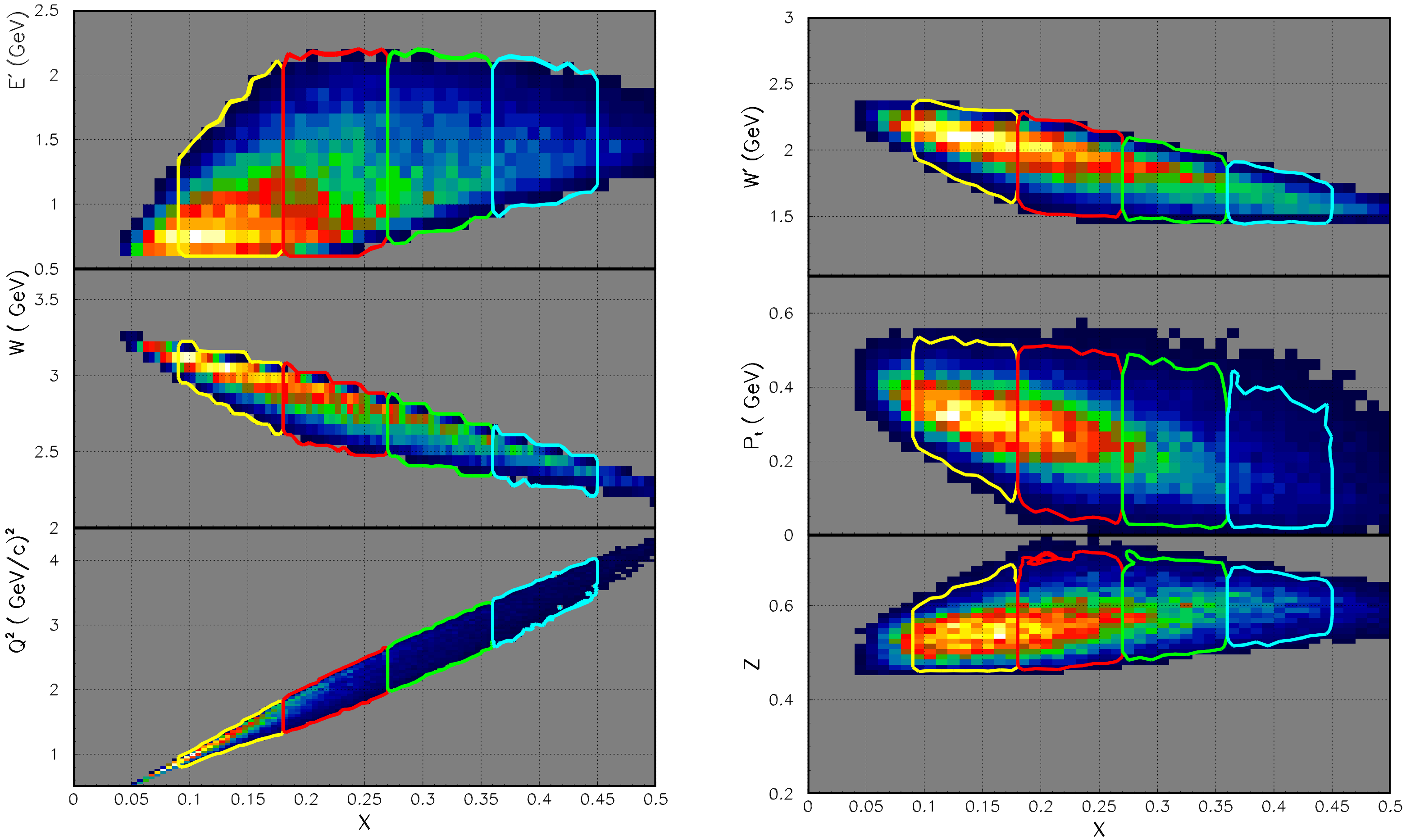
(Method not applies for low-z experiments where $\sigma^{\pi^-}/\sigma^{\pi^+} \sim 1.0$)

The Standard Hall C Polarized Target



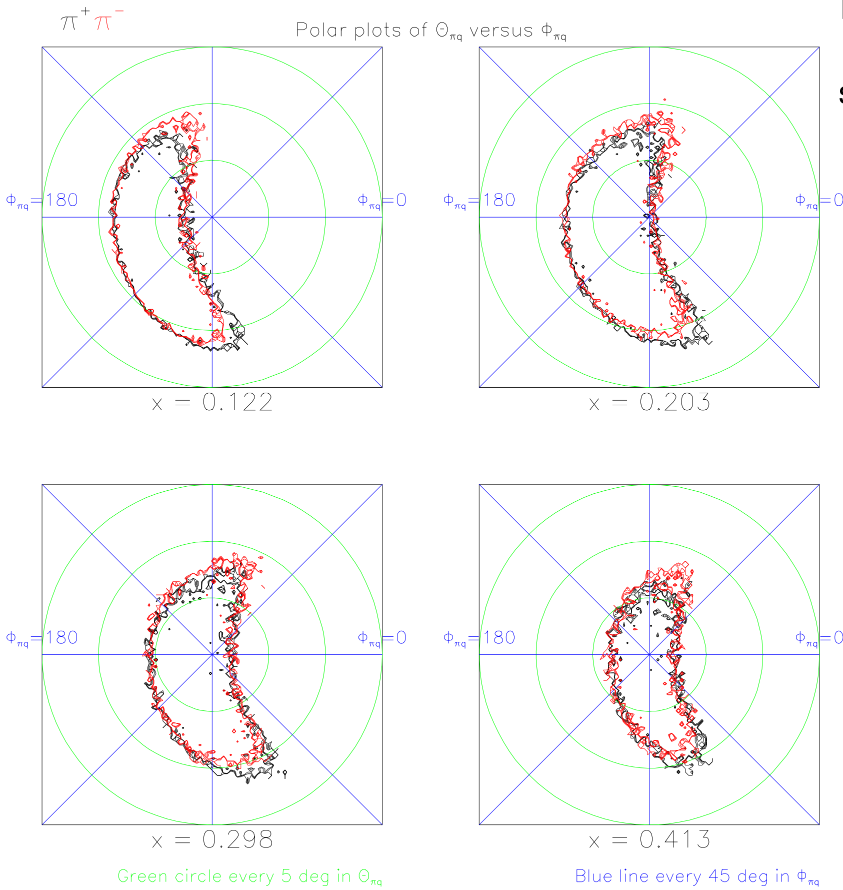
- Use longitudinal spin only.
- P_T(NH$_3$)=80%, P_T(LiD) $\geq 20\%$, $\delta P_T / P_T = \pm 2.5\%$
- Dilution factor: $f^h = 0.17 \sim 0.22$(NH$_3$), $0.40 \sim 0.45$ (LiD). $\delta f^h / f^h = \pm 2.5\%$.

Kinematics and Phase Space Coverage



$0.122 < x < 0.413$, $\langle Q^2 \rangle = 2.2$ GeV^2. $z > 0.5$. Only shown $W' > 1.5$ GeV.

Angular Coverage in (θ_{qh}, ϕ_l^h)



We cover at least 180° in ϕ_l^h.

Related terms in ϕ_l^h:

see Boer and Mulders, PRD57, 5780 (1998)

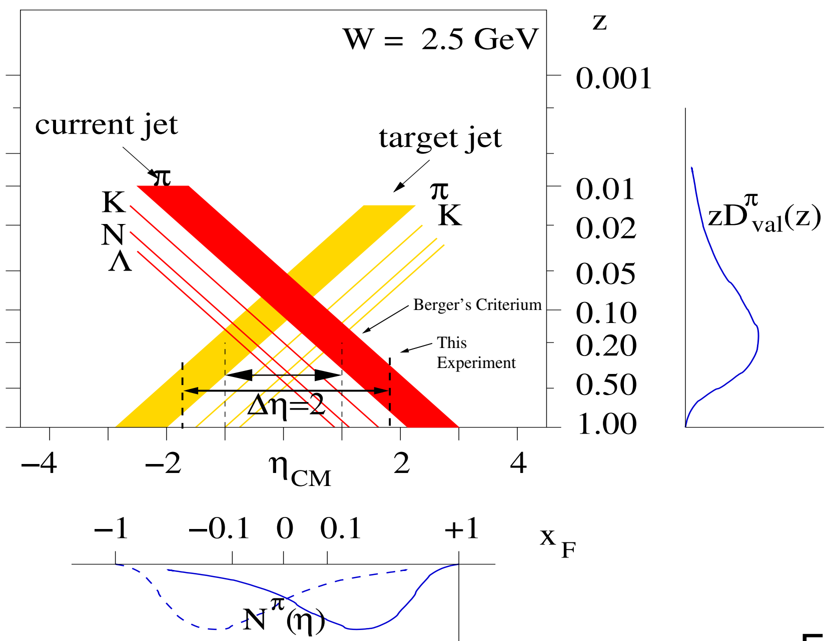
- $\cos(2\phi_l^h)$ term in $d\sigma^h$ averaged out.
- $\cos(\phi_l^h)$ term in A_{LL} is small ($\propto S_T$), reverse sign when target spin is reversed.
- Unexpected $\sin(\phi_l^h)$ term in A_{LL} can be checked with data.
- Extra free physics: large enough coverage in ϕ_l^h even allow extraction of single-spin asymmetry A_{UL} for $\sin\phi_l^h$ and $\sin(2\phi_l^h)$ moments.

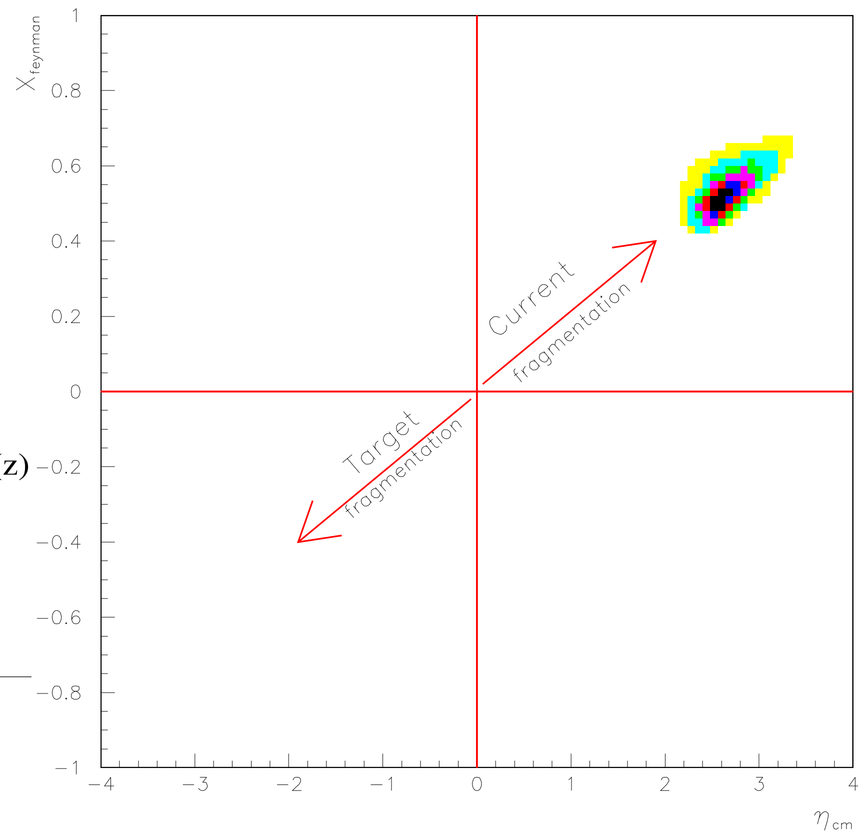
Kinematics Strongly Favor Current Fragmentation

Center of Mass rapidity

$$\eta_{CM} = \frac{1}{2} ln \frac{E^{\star} + P_L^{\star}}{E^{\star} - P_L^{\star}}$$

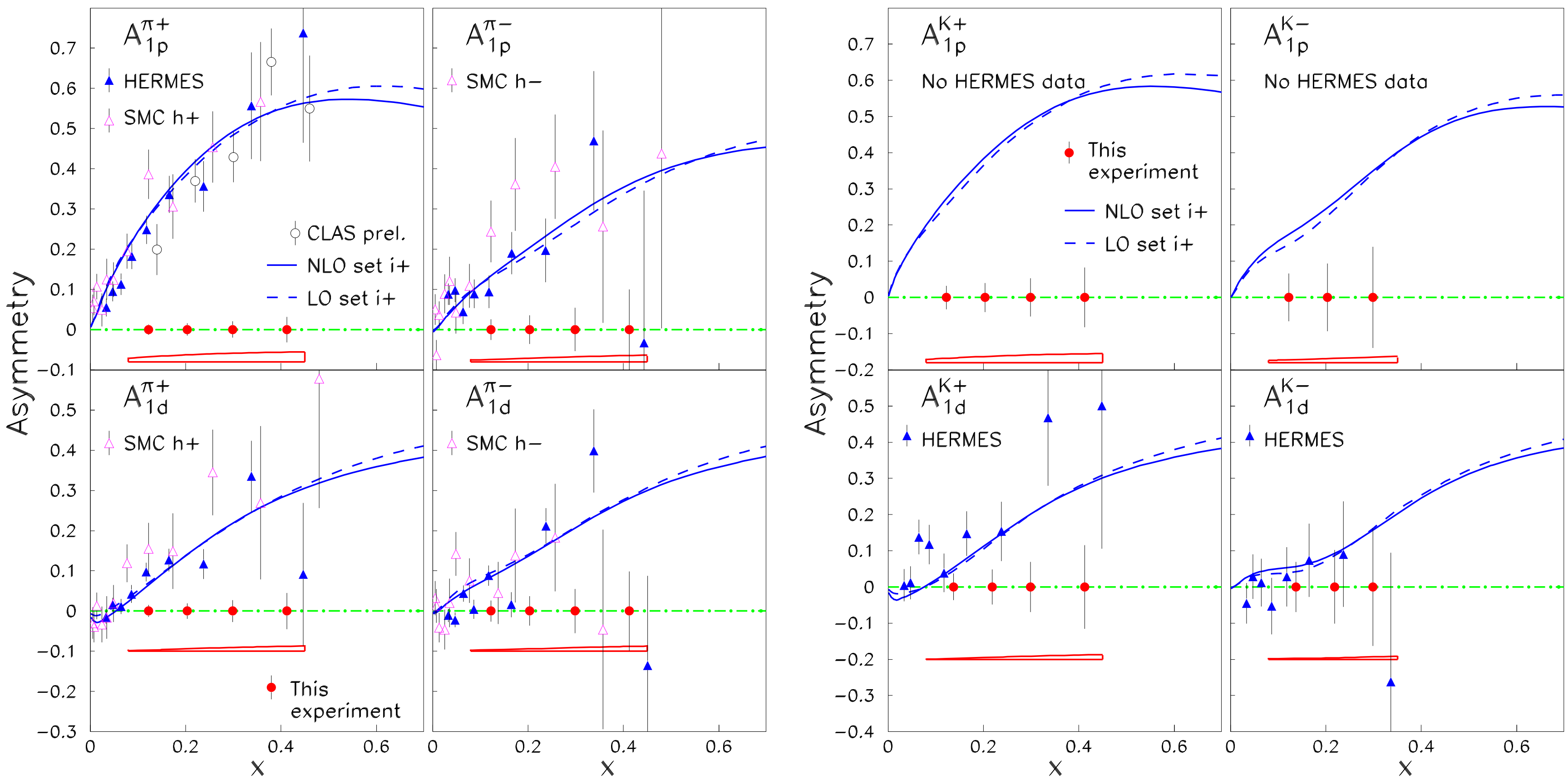
and $x_F = \frac{P_L^{\star}}{P_{Lmax}^{\star}}$ (P. Mulders, hep-ph/0010199.)





For $\pi^{\pm}$, $\eta_{CM} \sim 2.8$ ($\Delta\eta_{CM} \approx 5.6$), $x_F \sim 0.5$.

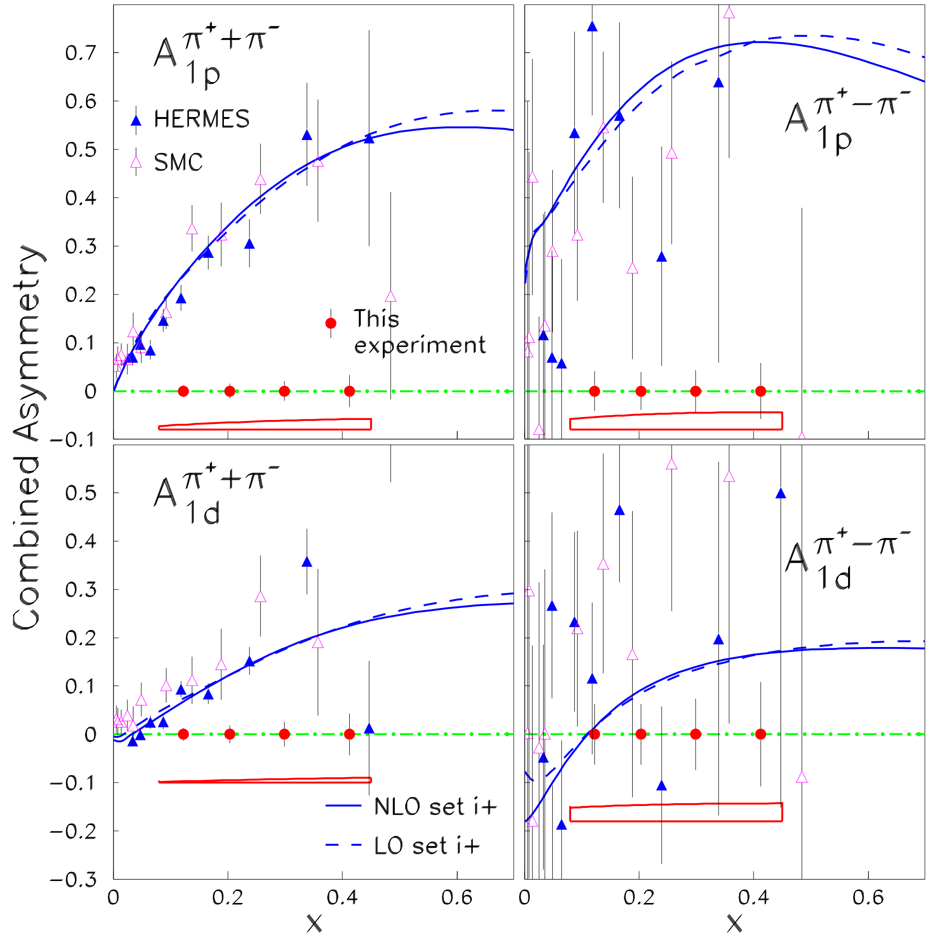
The Expected Results: Double-Spin Asymmetries A_{1N}^h



Significant improvements on the statistical accuracy of $A_{1N}^{\pi^\pm}$. First data on $A_{1p}^{K^\pm}$.

Systematic of A_{1N}^h: $\pm 4.3\%$ relative ($\delta P_T/P_T = \pm 2.5\%$, $\delta P_B/P_B = \pm 2.0\%$, dilution factor $\delta f^h/f^h = \pm 2.5\%$, rad. cor. and smearing $\pm 1.5\%$).

The Combined Asymmetries: $A_{1N}^{\pi^+ + \pi^-}$ and $A_{1N}^{\pi^+ - \pi^-}$



This Experiment: Methods of Spin-Flavor Decomposition

Four leading-order methods:

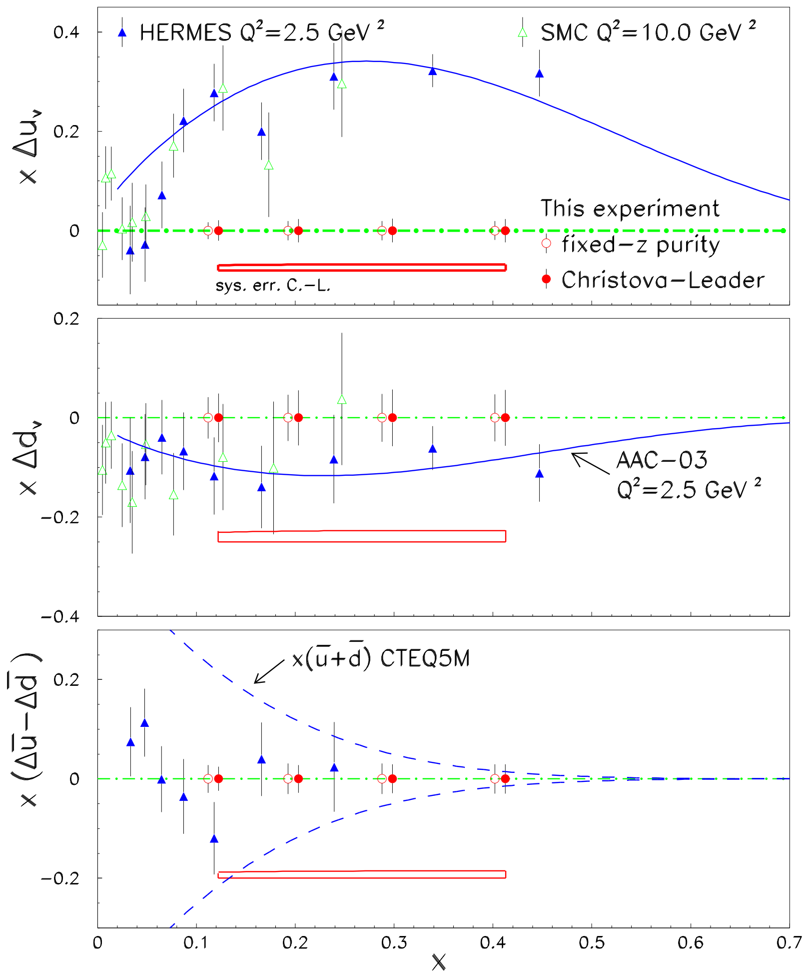
- The LO Christova-Leader method: $A_{1p}^{\pi^+-\pi^-}$, $A_{1d}^{\pi^+-\pi^-}$ $\Rightarrow$ $\Delta u_v, \Delta d_v$. Use $g_1^p(x) - g_1^n(x)$ as inputs to obtain $\Delta\bar{u} - \Delta\bar{d}$.
- "Fixed-z purity" method: calculate purity (inputs: PDFs and ratio of $D^-(z)/D^+(z)$) for well-localized z-bins. Solve linear equations $\vec{A}(x,z) = \mathcal{P}(x,z)\vec{Q}(x)$.
- Monte Carlo purity method (HERMES). Purity from LUND Monte Carlo.
- LO global fit method (supports from: D. de Florian, G. Navarro and R. Sassot).

Two next-to-leading order methods:

- The NLO Christova-Leader method (inputs: PDFs and $D^+(z) - D^-(z)$).
- NLO global fit method (D. de Florian, G. Navarro and R. Sassot).

Consistency checks between different methods provide clear measures of systematic uncertainty associated with the flavor decomposition methods.

The Expected Results on Δq: Two LO Methods



Statistical uncertainties dominate.

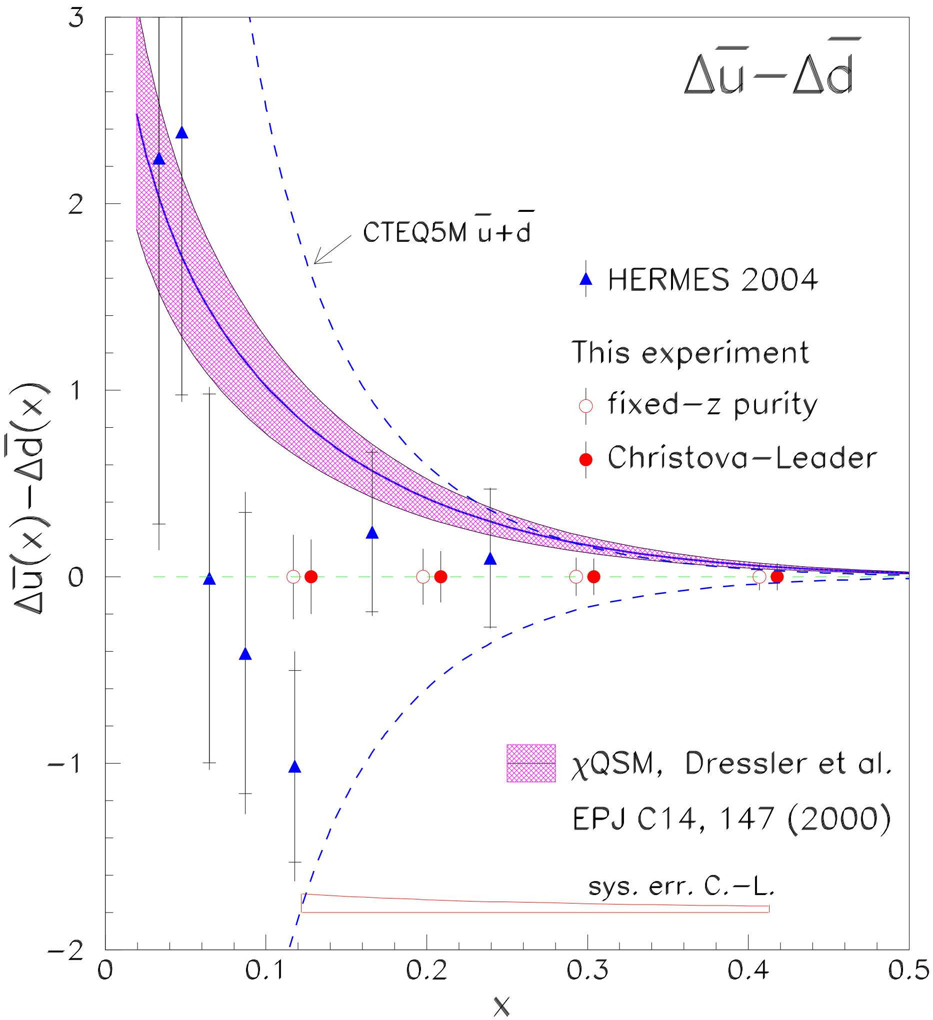
Also included in the statistical uncertainties of $x(\Delta\bar{u} - \Delta\bar{d})$: $\delta g_1^p = 0.0059$ (projected SANE and this experiment), $\delta g_1^n = 0.0057$ (Hall A polarized ^{3}He data).

Systematics in Christova-Leader method, $\sim 70\%$ each from:

- $\delta A_{1p}^{\pi^+-\pi^-}$ and $\delta A_{1d}^{\pi^+-\pi^-}$
- Uncertainties in unpolarized PDFs (CTEQ6).

$$[\delta(x\Delta u_v)]_{sys} \approx 0.012,$$
$$[\delta(x\Delta d_v)]_{sys} \approx 0.026,$$
$$[\delta(x(\Delta\bar{u} - \Delta\bar{d})]_{sys} \approx 0.015.$$

Is the Polarized Sea Asymmetric ?



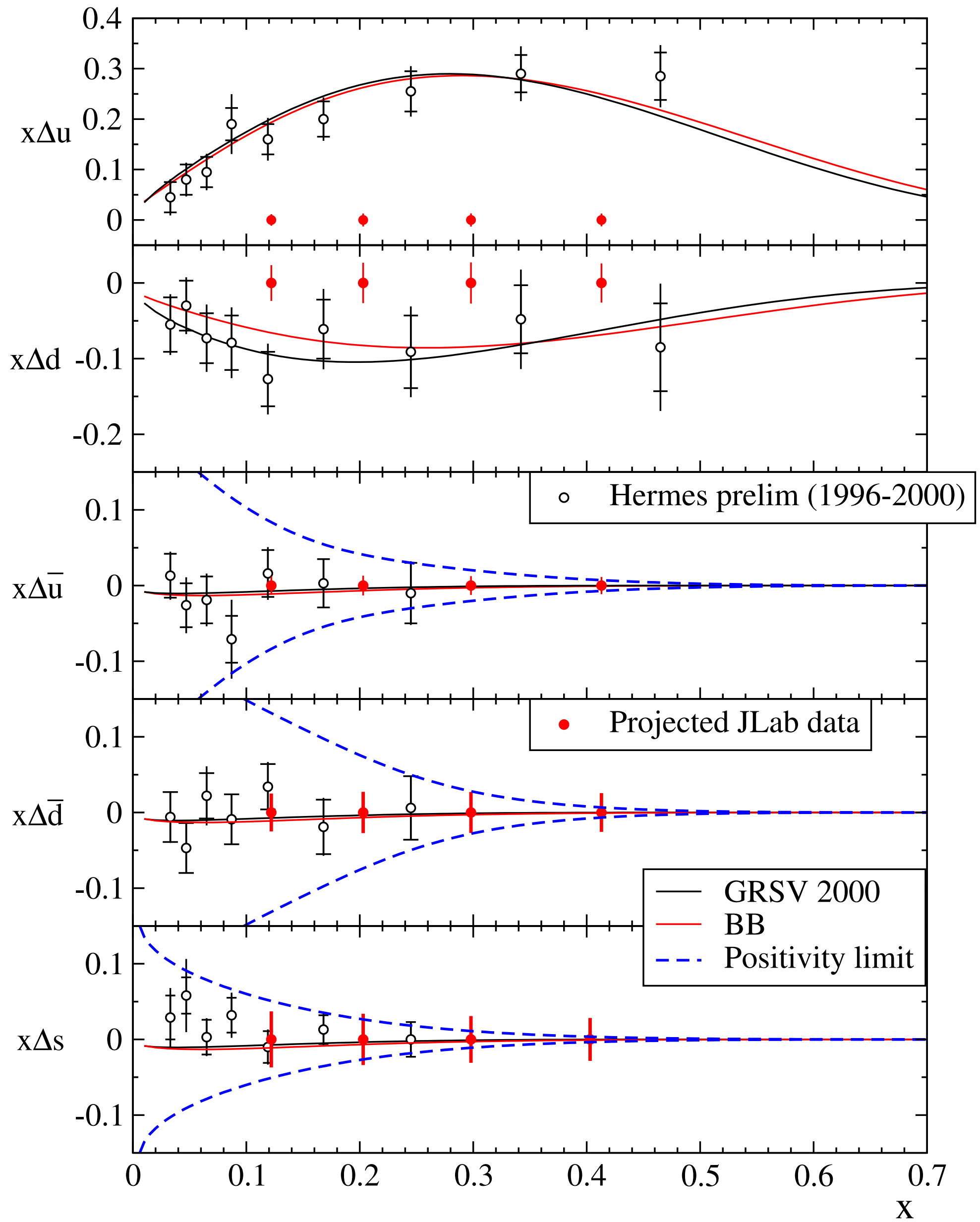
- Much improved statistical accuracy.
- Could be the first clear observation.

Test a wide range of model predictions of $\int_0^1(\Delta\bar{u}-\Delta\bar{d})dx$:

- Meson cloud (π): 0.
- Chiral-quark soliton: 0.31.
- Pauli-blocking: $0.2 \sim 0.3$.
- Instanton: 0.2
- Statistical: 0.12

$\int_0^1(\bar{d}-\bar{u})dx = 0.118 \pm 0.012$ (E866)

One expects at least $\Delta\bar{u}-\Delta\bar{d} > (\bar{d}-\bar{u})$!!!

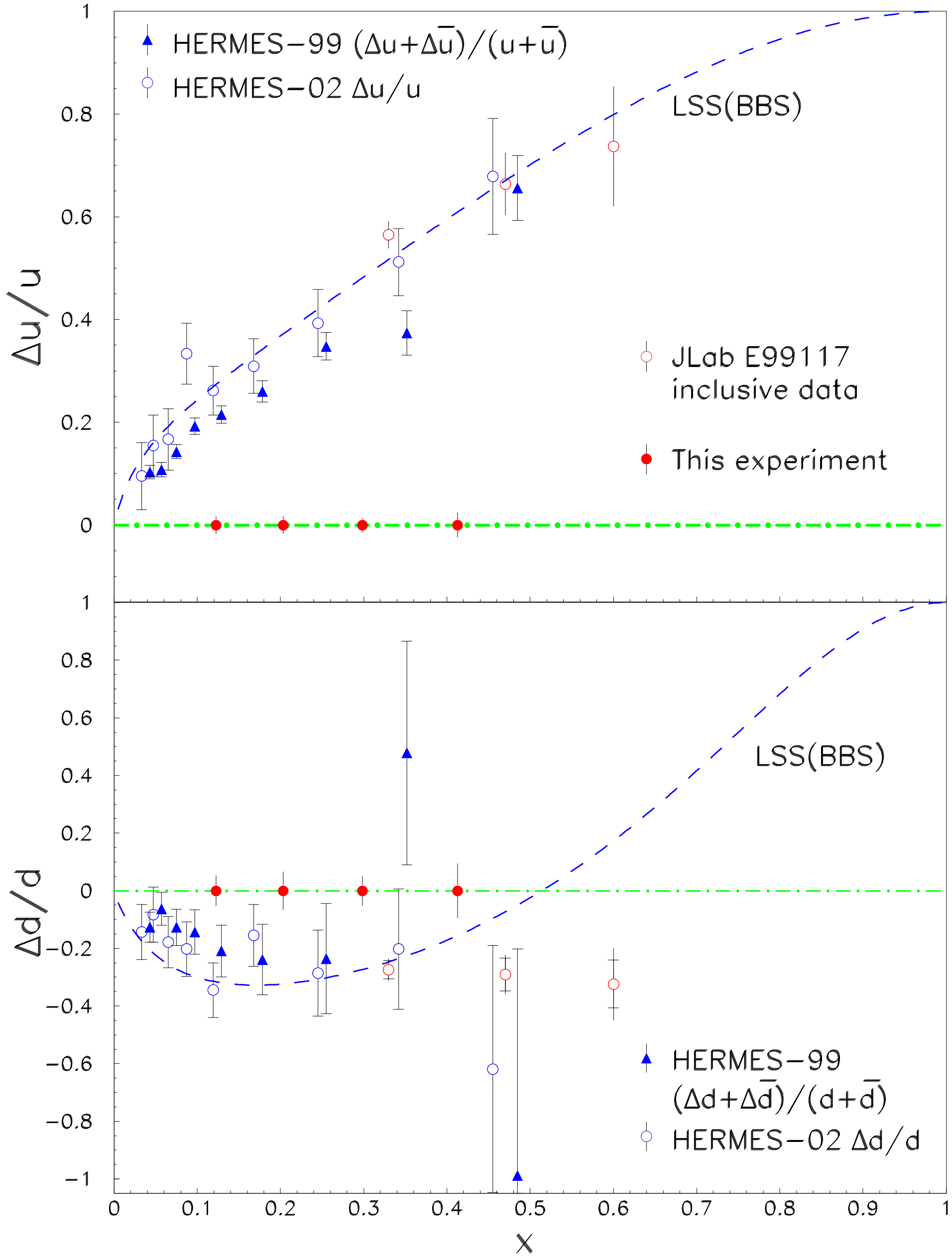


Five-Flavor Δq: the Fixed-z Method

Systematic uncertainties are expected to be similar to that of HERMES.

Except that:

- Only the ratios of fragmentation functions are involved in the purity at fixed-z.



An Extra Cross Check:

Will $\Delta u/u$ and $\Delta d/d$ agree with the inclusive data at large-x ?

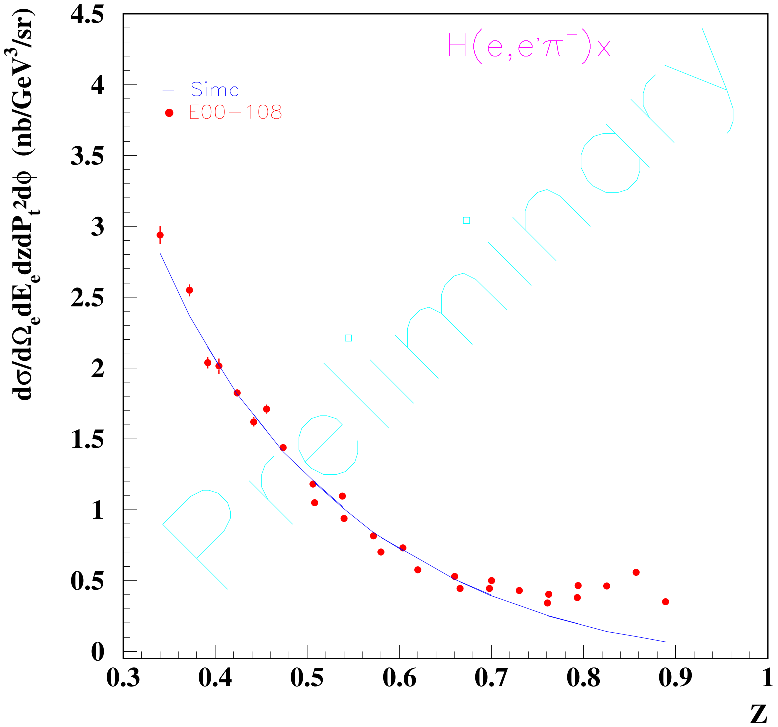
A clear demonstration of the validity of the SIDIS method.

Summary

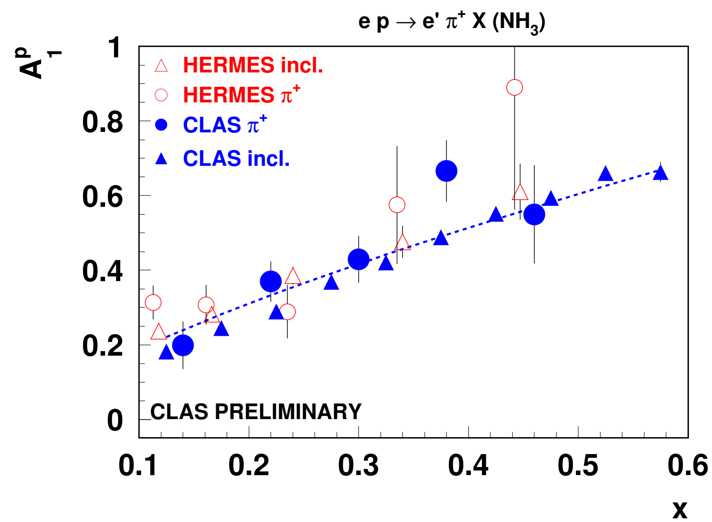
Experiment E04-113 will start a new generation of spin experiments at Jefferson Lab:

- High precision asymmetry data are interesting by themselves. First data on $A_{1N}^{\pi^+-\pi^-}$.
- Could be the first experiment to observe $\Delta\bar{u} - \Delta\bar{d} \neq 0$.
- Provide strong constrains on polarized PDFs in $0.12 < x < 0.41$. Feed into a global QCD fit that provides moments of polarized PDFs to confront with Lattice.
- Complimentary to other high-energy spin physics experiments.
- Lead to new physics with the planned 12 GeV upgrade at Jefferson Lab.

Leading-Order x-z Factorization at JLab 6 GeV ?



Hall C E00-108 preliminary. Cross section reproduced by Monte Carlo based on LO x-z factorization.



CLAS Eg1b: semi-inclusive asymmetry $A_{1p}^{\pi^+}$ agree with HERMES, SMC, fall on the same curve of inclusive A_{1p}. No clear z-dependence observed for $z > 0.5$.

LO x-z factorization is not violated much at 6 GeV.