Flavor Decomposition of Nucleon Spin Structure

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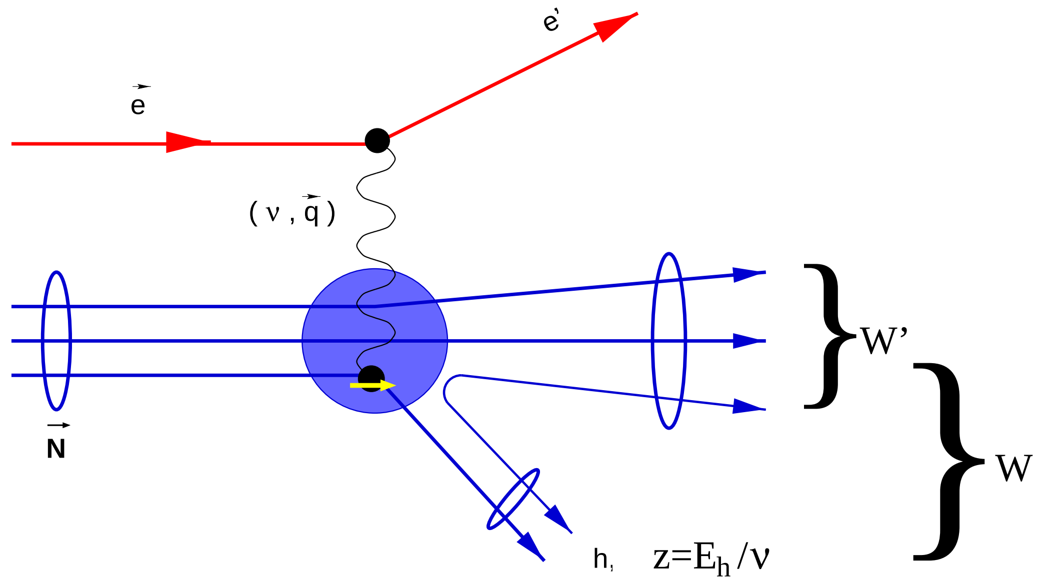
ODU, RPI, Rutgers, Temple, UVa, W&M, Yerevan-Armenia, Regina-Canada

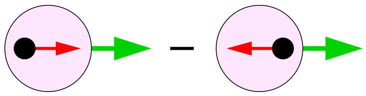
$$A_1^h \propto A_\parallel^h = \frac{\sigma^{\uparrow\downarrow} - \sigma^{\uparrow\uparrow}}{\sigma^{\uparrow\downarrow} + \sigma^{\uparrow\uparrow}}$$



Semi-inclusive asymmetry A_1^h in $\vec{p}(\vec{e}, e'h)X$ and $\vec{d}(\vec{e}, e'h)X$ $(h = \pi^+, \pi^-, K^+, K^-)$.

- Flavor tagging in SIDIS ➡ flavor decomposition: Δu, Δd, $\Delta\bar{u}$, $\Delta\bar{d}$, $\Delta s = \Delta\bar{s}$.
- Well-controlled phase space and efficiency ➡ combined yield ratio $A_1^{\pi^+ + \pi^-}$.
  Build-in tests of factorization: z-independence of $A_1^{\pi^+ + \pi^-}$.
- Access the sea polarization $\Delta\bar{u} - \Delta\bar{d}$ and Δs.

Accessing quark spin Δq_f



$$\Delta q_f(x) \equiv q_f^{\uparrow\uparrow}(x) - q_f^{\uparrow\downarrow}(x)$$

Inclusive DIS $\vec{N}(\vec{e}, e') \Rightarrow$ access only $\Delta q + \Delta\bar{q}$.
Introduce the assumption of SU$(3)_f$ flavor symmetry, link with hyperon β-decay:

- Quarks contribute only a small part of nucleon spin.
- $\Delta s < 0$.

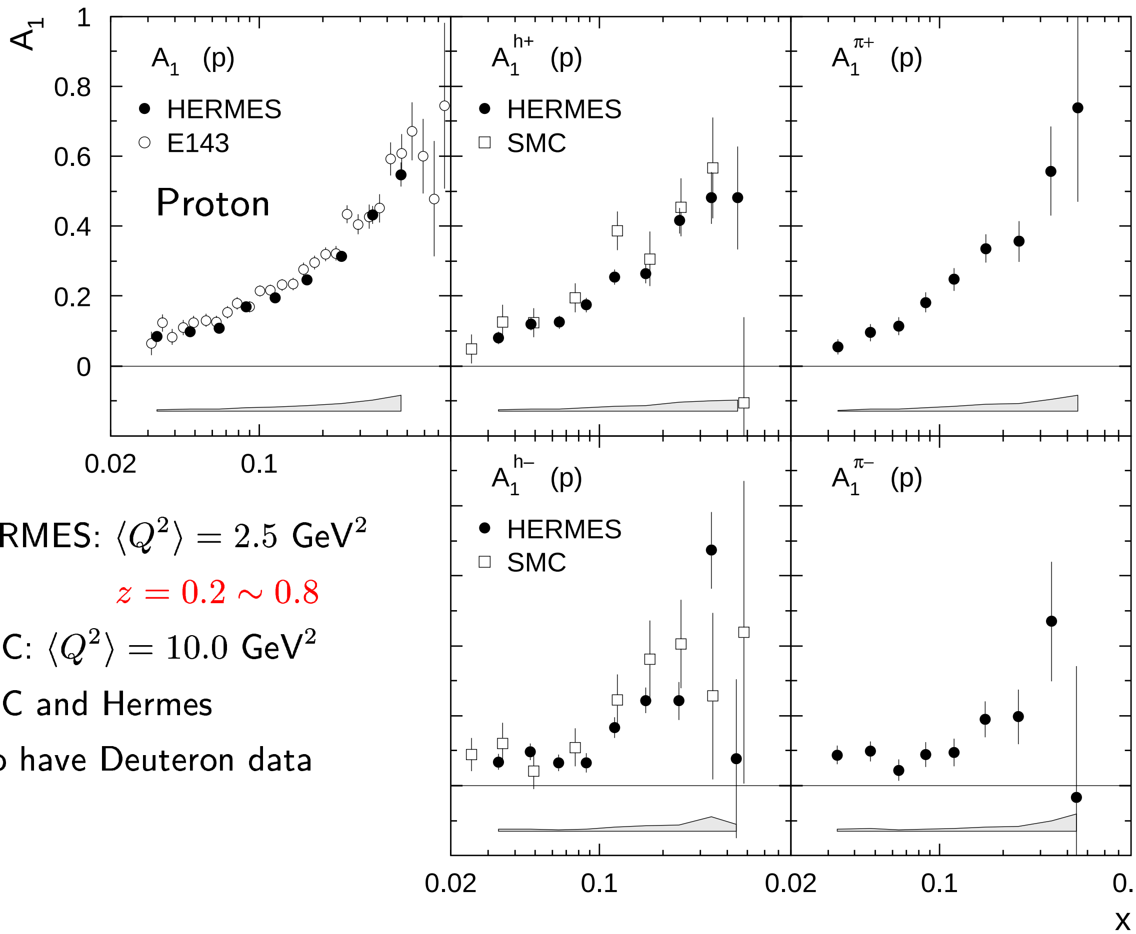
Measure spin asymmetries A_{1N}^h in semi-inclusive DIS $\vec{N}(\vec{e}, e'h)$ which tags the quark flavor and allows clean access to Δq and $\Delta\bar{q}$ separately

In leading order

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

Data from SMC ($\langle Q^2 \rangle = 10$ GeV^2) and HERMES ($\langle Q^2 \rangle = 2.5$ GeV^2).

Precocious Scaling $A_1^h(\nu, Q^2) \to A_1^h(x)$?



HERMES: $\langle Q^2 \rangle = 2.5$ GeV^2

$z = 0.2 \sim 0.8$

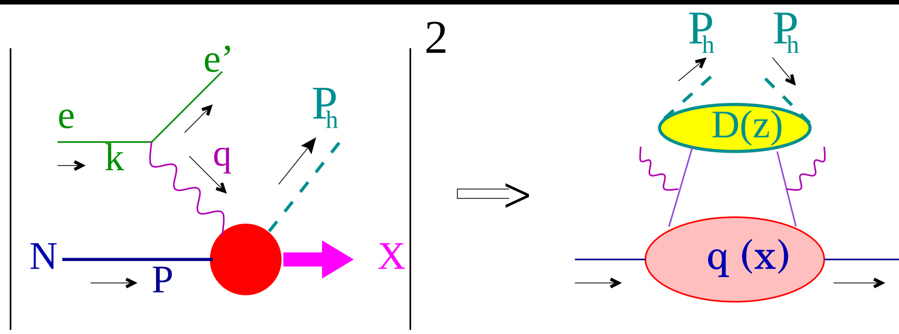
SMC: $\langle Q^2 \rangle = 10.0$ GeV^2

SMC and Hermes

also have Deuteron data

- Will A_1^h still scale at lower Q^2?
- What about the z-dependency of $A_1^h(x, z)$?
- Will pion and kaon asymmetries also scale with Q^2 ?

Flavor Decomposition: the HERMES method



At the leading order:

$$\sigma^h(x,z) = \sum_f e_f^2 \cdot q_f(x) \cdot D_{q_f}^h(z)$$

$$\Delta\sigma^h(x,z) = \sigma^h_{++} - \sigma^h_{+-} = \sum_f e_f^2 \cdot \Delta q_f(x) \cdot D_{q_f}^h(z)$$

$$A_1^h(x) \equiv \sum_f \mathcal{P}_f^h(x) \cdot \frac{\Delta q_f(x)}{q_f(x)},$$

the "purity matrix" is integrated over $0.2 < z < 0.8$:

$$\mathcal{P}_f^h(x) = \frac{e_f^2 q_f(x) \int dz D_f^h(z)}{\sum_{f'} e_{f'}^2 q_{f'}(x) \int dz D_{f'}^h(z)},$$

Need inputs of:

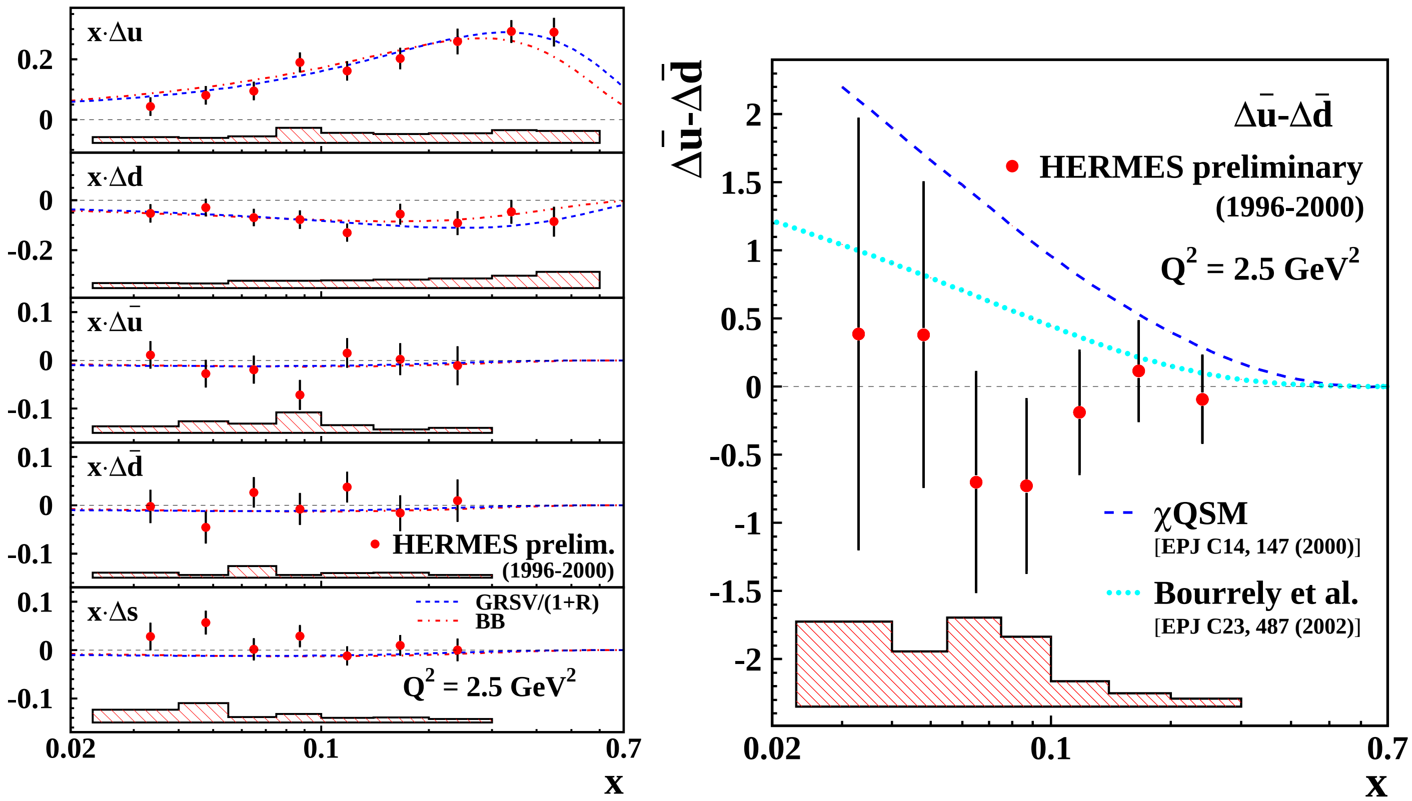
- Unpolarized parton distributions: CTEQ5M.
- Monte Carlo model of spectrometer and detectors.
- Fragmentation functions: LUND Monte Carlo model.

solve for:

$$\vec{A}(x) = \sum_f \mathcal{P}_f^h(x) \cdot \vec{Q}(x)$$

$$\vec{A}(x) = \left(A_{1p}, A_{1d}, A_{1p}^{\pi^\pm}, A_{1d}^{\pi^\pm}, A_{1d}^{K^\pm}\right), \qquad \vec{Q}(x) = \left(\frac{\Delta u}{u}, \frac{\Delta d}{d}, \frac{\Delta \bar{u}}{\bar{u}}, \frac{\Delta \bar{d}}{\bar{d}}, \frac{\Delta s + \Delta \bar{s}}{s + \bar{s}}\right)$$

HERMES Preliminary Results



- $\Delta u > 0$, $\Delta d < 0$ as expected.
- $\Delta\bar{u}$ and $\Delta\bar{d}$ are small, $\Delta\bar{u} - \Delta\bar{d} \approx 0$? Not enough statistics to tell.
- Δs is not negative ? ➡ A total breakdown of SU(3)$_f$ symmetry.

  "Almost impossible !" E. Leader and D. B. Stamenov, PRD **67**, 037503 (2003).

Flavor Decomposition: This Experiment

Measure asymmetries $\vec{A}(x,z) = (A_{1p}^{\pi^\pm}, A_{1d}^{\pi^\pm}, A_{1p}^{K^\pm}, A_{1d}^{K^\pm})$ as functions of z.

Solve for $\vec{Q}(x)$ through a maximum likelihood fit of:

$$\vec{A}(x,z) = \sum_f \mathcal{P}_f^h(x,z) \cdot \vec{Q}(x)$$

where $\vec{Q}(x) = (\Delta u, \Delta d, \Delta \bar{u}, \Delta \bar{d}, \Delta s = \Delta \bar{s})$

the new "purity matrix" $\mathcal{P}_f^h(x,z)$ is NOT integrated over z:

$$\mathcal{P}_f^h(x,z) = \frac{e_f^2 q_f(x)}{\sum_{f'} e_{f'}^2 q_{f'}(x) \frac{D_{f'}^h(z)}{D_f^h(z)}},$$

➡ $\mathcal{P}_f^h(x,z)$ need inputs from:

- Unpolarized parton distributions: CTEQ5M.
- Ratios of fragmentation functions.
  R. D. Field and R. P. Feynman, NPB **136**, 1 (1978).
  S. Kretzer, E. Leader and E. Christova, EPJC **22**, 269 (2001).
  J. Binnewies, B. A. Kniehl and G. Kramer, PRD **52**, 4947 (1995).

➡ At each x-bin, solve for 5 Δq_f from:

- 24 equations for $x = 0.12$, 0.17, 0.23, 0.29 bins.
- 16 equations for $x = 0.35$ bin.
- 12 equations for $x = 0.43$ bin.

Plus

the better-known inclusive asymmetries (A_{1p}, A_{1d}) add two extra constraints.

SIDIS Asymmetries at the Leading Order

Charge pion asymmetries:

$$A_{1p}^{\pi^+}(x,z) = \frac{4\Delta u + \Delta\bar{d} + (4\Delta\bar{u} + \Delta d)\,\lambda_\pi + 2\Delta s \xi_\pi}{4u + \bar{d} + (4\bar{u} + d)\,\lambda_\pi + 2s\;\xi_\pi},$$

$$A_{1p}^{\pi^-}(x,z) = \frac{(4\Delta u + \Delta\bar{d})\lambda_\pi + 4\Delta\bar{u} + \Delta d + 2\Delta s \xi_\pi}{(4u + \bar{d})\lambda_\pi + 4\bar{u} + d\; + 2s\xi_\pi},$$

$$A_{1d}^{\pi^+}(x,z) = \frac{4(\Delta u + \Delta d) + \Delta\bar{u} + \Delta\bar{d} + \left(\Delta u + \Delta d + 4(\Delta\bar{u} + \Delta\bar{d})\right)\lambda_\pi + 4\Delta s\xi_\pi}{4(u+d) + \bar{u} + \bar{d} + \left(u + d + 4(\bar{u} + \bar{d})\right)\lambda_\pi + 4s\xi_\pi},$$

$$A_{1d}^{\pi^-}(x,z) = \frac{\left(4(\Delta u + \Delta d) + \Delta\bar{u} + \Delta\bar{d}\right)\lambda_\pi + \Delta u + \Delta d + 4(\Delta\bar{u} + \Delta\bar{d}) + 4\Delta s\xi_\pi}{\left(4(u+d) + \bar{u} + \bar{d}\right)\lambda_\pi + u + d + 4(\bar{u} + \bar{d}) + 4s\xi_\pi}.$$

Charge kaon asymmetries:

$$A_{1p}^{K^+}(x,z) = \frac{4\Delta u + \Delta s + (4\Delta\bar{u} + \Delta s)\,\lambda_K + (\Delta d + \Delta\bar{d})\xi_K}{4u + s + (4\bar{u} + s)\,\lambda_K + (d + \bar{d})\xi_K},$$

$$A_{1p}^{K^-}(x,z) = \frac{(4\Delta u + \Delta s)\,\lambda_K + 4\Delta\bar{u} + \Delta s + (\Delta d + \Delta\bar{d})\xi_K}{4u + s + (4\bar{u} + s)\,\lambda_K + (d + \bar{d})\xi_K},$$

$$A_{1d}^{K^+}(x,z) = \frac{4(\Delta u + \Delta d) + 2\Delta s + \left(4(\Delta\bar{u} + \Delta\bar{d}) + 2\Delta s\right)\lambda_K + (\Delta u + \Delta\bar{u} + \Delta d + \Delta\bar{d})\xi_K}{4(u+d) + 2s + \left(4(\bar{u} + \bar{d}) + 2s\right)\lambda_K + (u + \bar{u} + d + \bar{d})\xi_K},$$

$$A_{1d}^{K^-}(x,z) = \frac{(4(\Delta u + \Delta d) + 2\Delta s)\,\lambda_K + 4(\Delta\bar{u} + \Delta\bar{d}) + 2\Delta s + (\Delta u + \Delta\bar{u} + \Delta d + \Delta\bar{d})\xi_K}{(4(u+d) + 2s)\,\lambda_K + 4(\bar{u} + \bar{d}) + 2s + (u + \bar{u} + d + \bar{d})\xi_K}.$$

The fragmentation function ratios are:

$$\lambda_\pi(z) = D_\pi^-(z)/D_\pi^+(z), \qquad \xi_\pi(z) = D_s^\pi(z)/D_\pi^+(z),$$
$$\lambda_K(z) = D_K^-(z)/D_K^+(z), \qquad \xi_K(z) = D_d^K(z)/D_K^+(z).$$

How Much is Factorization Violated ?

Tests have been suggested:

L. L. Frankfurt, M. I. Strikman *et al.*, PLB **230**, 141 (1989).
F. E. Close and R. G. Milner, PRD **44**, 3691 (1991).
E. Christova and E. Leader PLB **468**, 299 (1999) and NPB **607** 369 (2001).

Assuming isospin symmetry and charge conjugation
the fragmentation functions simplify to

favored:

$$D^+(z) \equiv D_u^{\pi^+} = D_d^{\pi^-} = D_{\bar{u}}^{\pi^-} = D_{\bar{d}}^{\pi^+}$$

and unfavored :

$$D^-(z) \equiv D_u^{\pi^-} = D_d^{\pi^+} = D_{\bar{u}}^{\pi^+} = D_{\bar{d}}^{\pi^-}$$

$$9\sigma_p^{\pi^+}(x,z) = (4u(x) + \bar{d}(x)) \cdot D^+(z) + (4\bar{u}(x) + d(x)) \cdot D^-(z)$$
$$9\sigma_p^{\pi^-}(x,z) = (4u(x) + \bar{d}(x)) \cdot D^-(z) + (4\bar{u}(x) + d(x)) \cdot D^+(z)$$

$$\Rightarrow \quad 9\sigma_p^{\pi^+ + \pi^-}(x,z) = (4[u(x) + \bar{u}(x)] + d(x) + \bar{d}(x)) \cdot [D^+(z) + D^-(z)]$$

The combined spin-dependent yield ratio:

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

$$A_{1p}^{\pi^+ + \pi^-}(x,z) \equiv A_{1p}(x)$$

Factorization in SIDIS $\Rightarrow$ $A_{1N}^{\pi^+ + \pi^-}(x,z)$ is z-independent!

$\Rightarrow$ Need well-controlled phase space and detector efficiency.

This Experiment

The Goal of This Experiment

- High statistics data as functions of z: $\vec{A}(x, z) = (A_{1p}^{\pi^\pm}, A_{1d}^{\pi^\pm}, A_{1p}^{K^\pm}, A_{1d}^{K^\pm})$.
- Flavor decomposition of nucleon spin structure: $\Delta u, \Delta d, \Delta \bar{u}, \Delta \bar{d}, \Delta s = \Delta \bar{s}$.
- Build-in measures of facorization violation in SIDIS:

  z-dependency of $A_{1p}^{\pi^+ + \pi^-}$ and $A_{1d}^{\pi^+ + \pi^-}$.

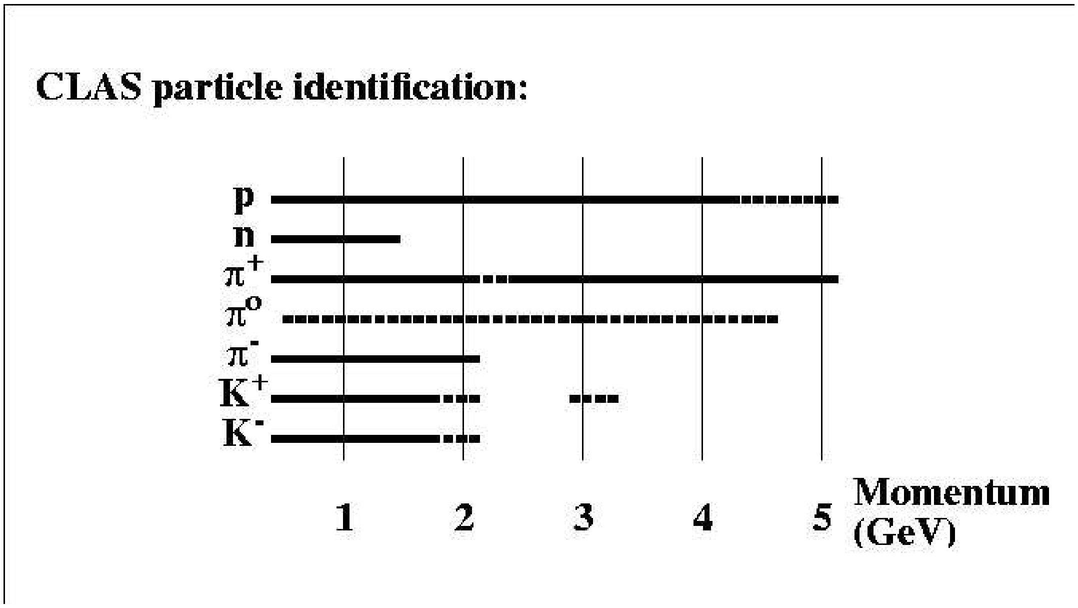
  (as well as: $A_{1(2p-d)}^{\pi^+ + \pi^-}$, $A_{1p}^{\pi^+ - \pi^-}$, $A_{1d}^{\pi^+ - \pi^-}$, $A_{1p}^{K^+ - K^-}$ and $A_{1d}^{K^+ - K^-}$.)
- Consistency check of SIDIS vs inclusive DIS analysis:

  at the high-x bins, $\Delta u/u$, $\Delta d/d$ agree with the Hall-A data ?
- Access the sea polarization: $\Delta \bar{u} - \Delta \bar{d}$ and Δs.

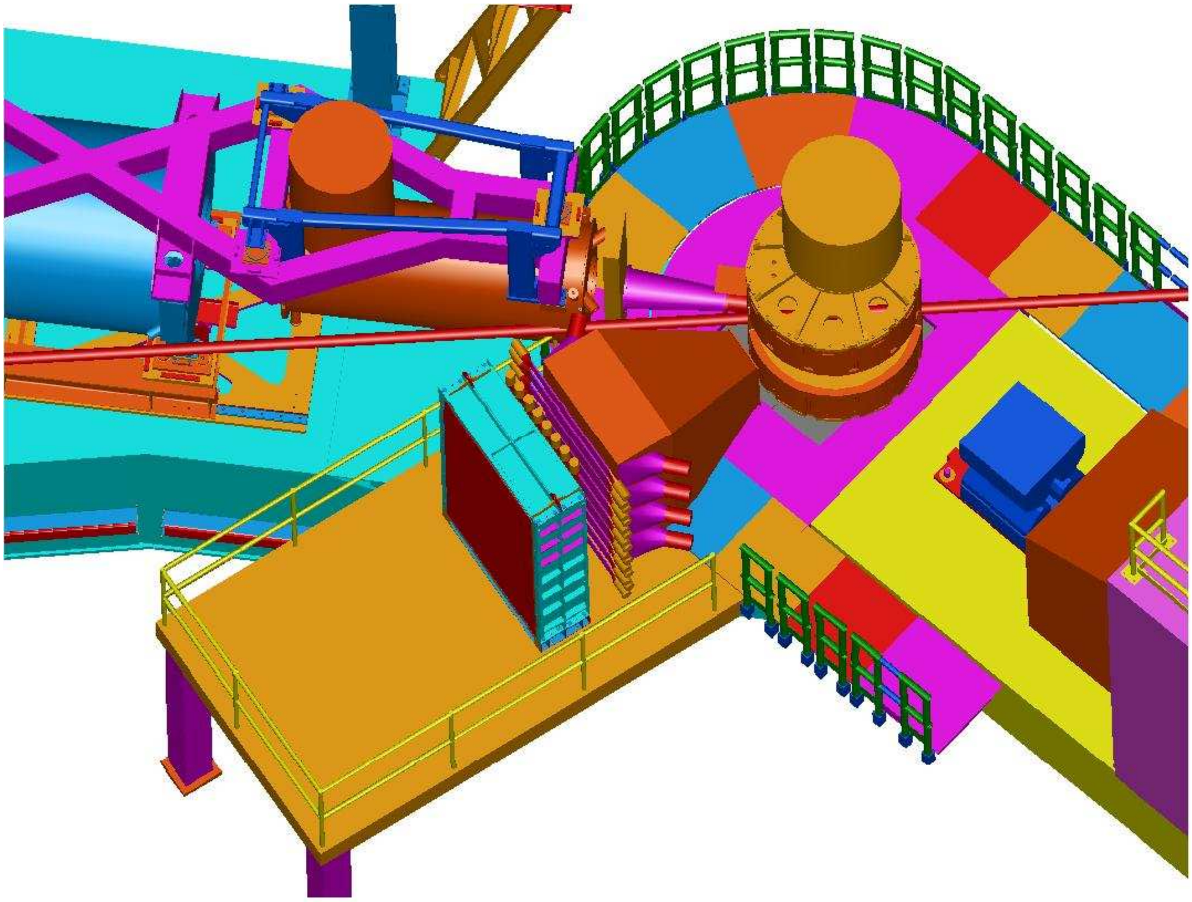
SIDIS at JLab

- Experimental requirements
  - Clear e/π/K/p PID in hadron arm needed for flavour decomposition and factorization test.
  - Detect electrons at relatively large angle to have $1 < Q^2 < 4$, $2.3 < W < 3.5$ and $0.1 < x < .45$
  - Detect hadrons with momentum above 2 GeV/c and near $\vec{q}$ to access $0.3 < Z = \frac{E_h}{\nu} < 0.8$
- This conditions are not matched by the existing data taken in Hall B $\vec{p}(\vec{e}, e')X$ and $\vec{d}(\vec{e}, e')X$
  - For momentum above 2 GeV/c PID becomes problematic.

From W. Brooks proposal P-02-104 and Hall B NIM article



The Proposed Experiment



- e-arm:
  a large calorimeter array (being built for E01-109)
  augmented by a threshold gas Č located at 30°
- h-arm:
  HMS at $10.8°$, $\Delta\Omega$ =6 msr, $\Delta p/p = \pm 10\%$,
  cover $p_h = 1.8 \sim 3.5$ GeV/c in 3 momentum settings
  add two aerogel Č to existong one for clean PID
- Polarized NH$_3$ ($p_t \approx 80\%$) and LiD ($p_t \approx 20\%$) targets.
  Used in previous Hall C experiments (G_{En} and RSS)

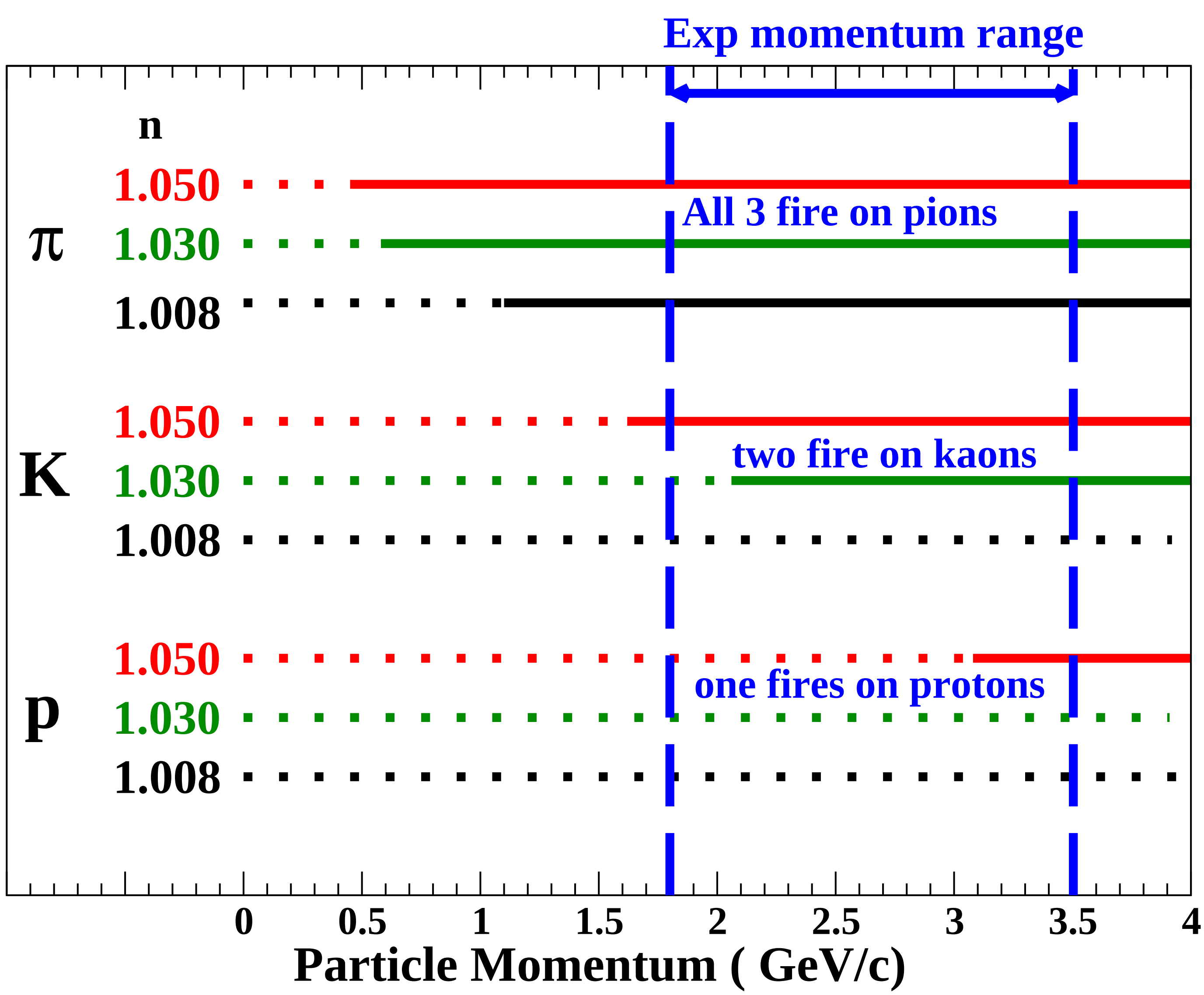
$\mathcal{L}(\vec{p},\vec{d}) = 10^{35} cm^{-2}s^{-1}$ (HERMES: $\mathcal{L}(\vec{p}) = 2 \sim 8 \times 10^{30} cm^{-2}s^{-1}$).

Electron Arm

- Glen Warren has done extensive Geant MC.
- Calorimeter (presently being built for e01-109)
  - Highly segmented: 1744 lead glass blocks.
    Each $\sim$4x4x40cm ⇨ Pileup no problem
  - Large size: 128cm width by 218cm tall and front face 325cm from target.
  - Energy resolution: 5%/$\sqrt{E}$.
  - Time resolution: $3\sigma \approx$ 3-5ns.
    Good for coincidence time cut.
- Gas Cerenkov
  - Use N_2 occupying length of 125cm.
    Expected number of photo-electrons 17-20.
  - Segmented into eight mirrors.
  - Hardware 100:1 π rejection factor (1 p.e. cut)
  - Software 1000:1 π rejection factor
  - 20:1 rejection factor with coincidence timing.

Hadron in the HMS

- e/π separation using cut on ratio of energy deposited in calorimeter to particle momentum. Electrons will peak at E/p = 1. $\epsilon > 99\%$.
- π/K/p separation by combining existing n=1.030 aerogel with two more n = 1.008 and 1.050 aerogel Cerenkov.



Parallel Spin Asymmetry

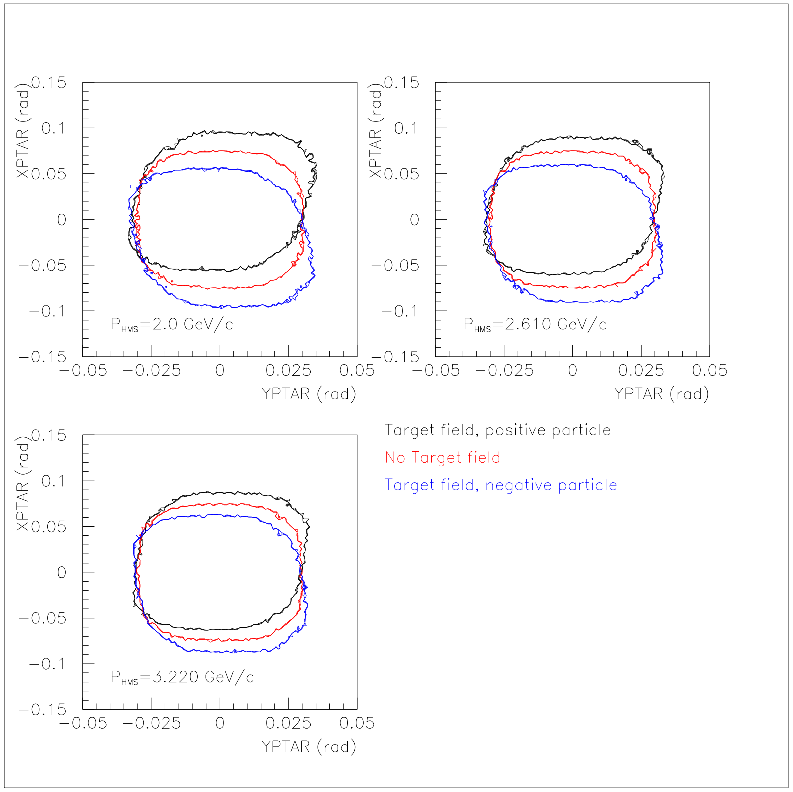
$$A_2^h \approx 0 \text{ so } A_1^h \propto A_\parallel^h = \frac{\sigma^{\uparrow\downarrow} - \sigma^{\uparrow\uparrow}}{\sigma^{\uparrow\downarrow} + \sigma^{\uparrow\uparrow}}$$

$$A_\parallel^h = f \cdot P_B \cdot P_T \cdot \mathcal{D} \cdot \mathcal{K} \cdot A_1^h$$

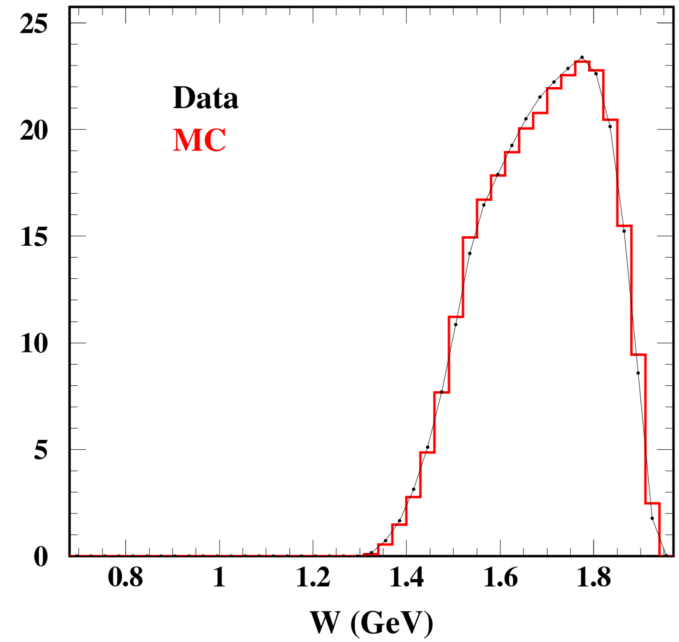
- Beam polarization, P_B = 80%
- Target polarization
  P_T = 80% for NH_3 and P_T = 20% for LiD.
- Dilution factor,
  f = 18% for NH_3 and f = 40% for LiD
- Kinematic factors $\mathcal{K} \approx 1.2$ and $\mathcal{D} \approx 0.8$
- Use R $= \sigma_L/\sigma_T$ from SLAC global fit.

Effects of target field on acceptance

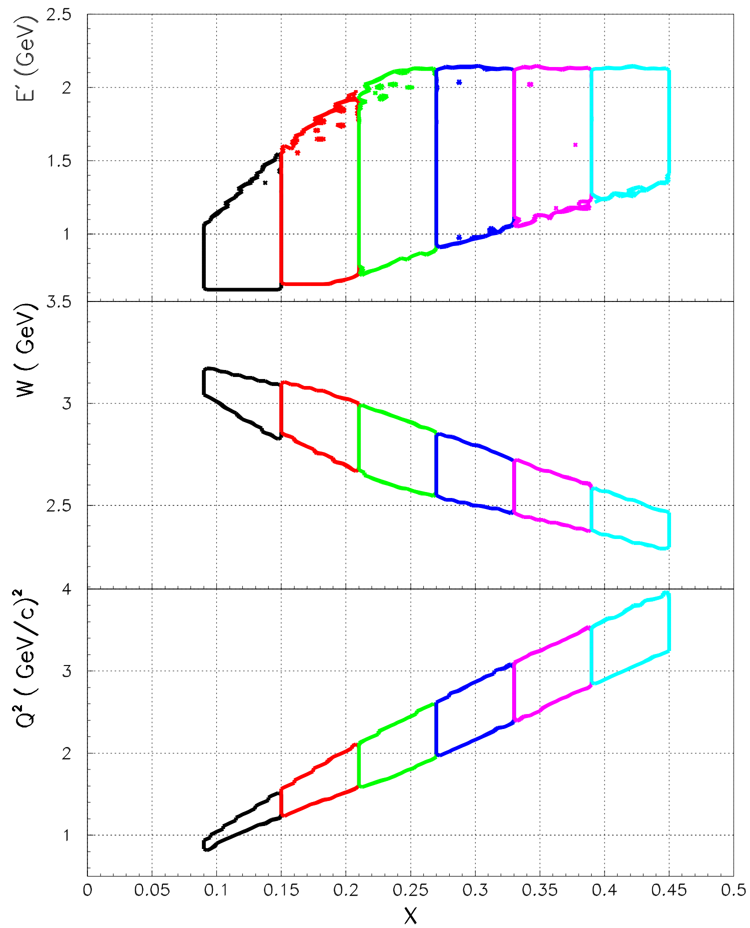
The target field for parallel spin mainly effects the out-of-plane component of the particles trajectory.

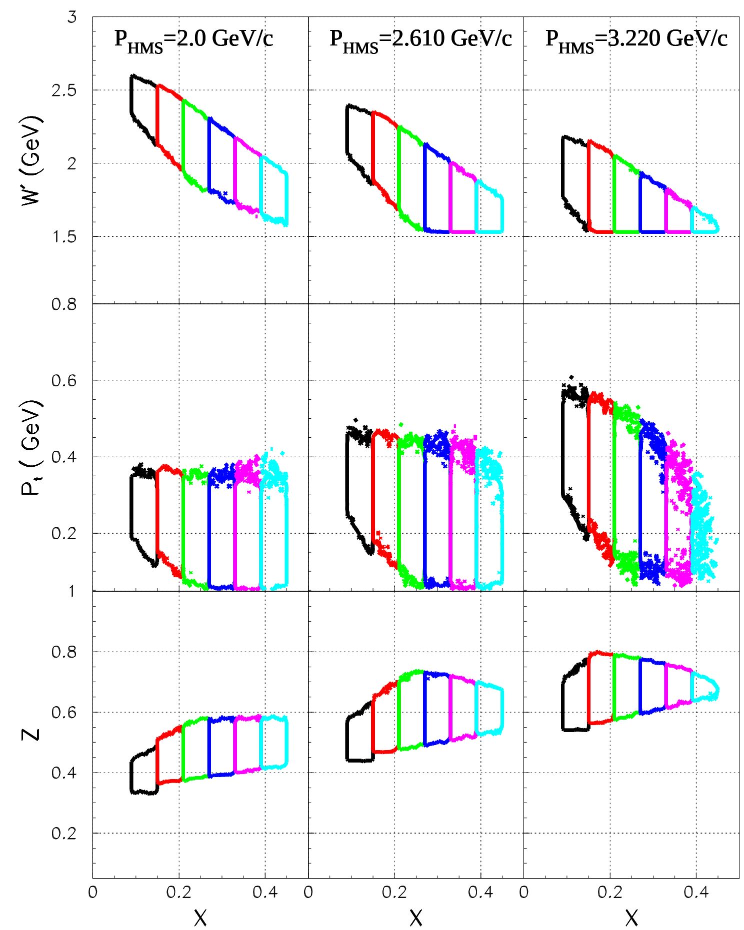


HMS acceptance well understood. Example from $^{12}C(e,e')$ with E_{beam} = 5.7 GeV and θ_e = 13° with parallel target field.



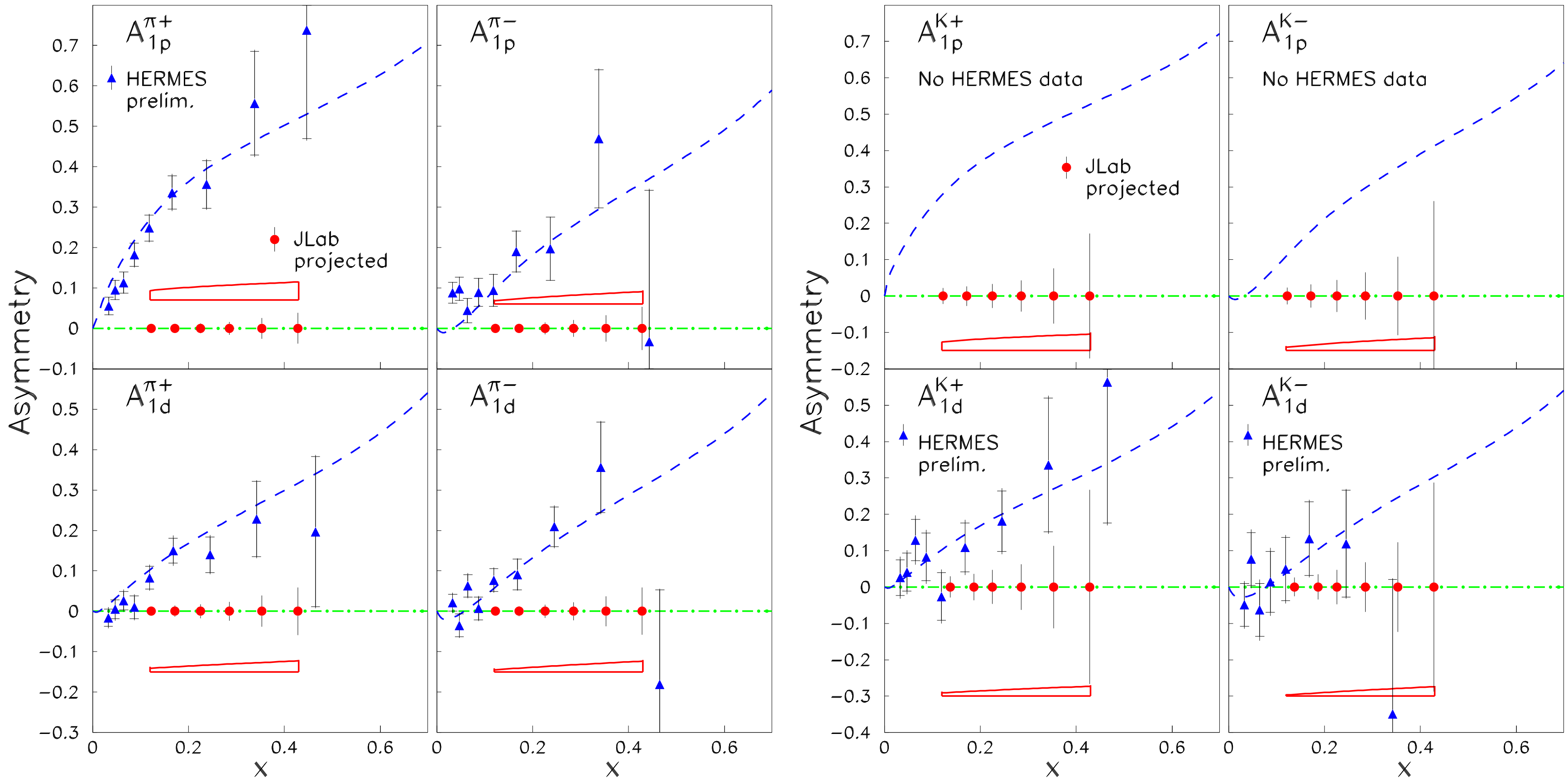
Phase space coverage





Compare with the HERMES Asymmetries

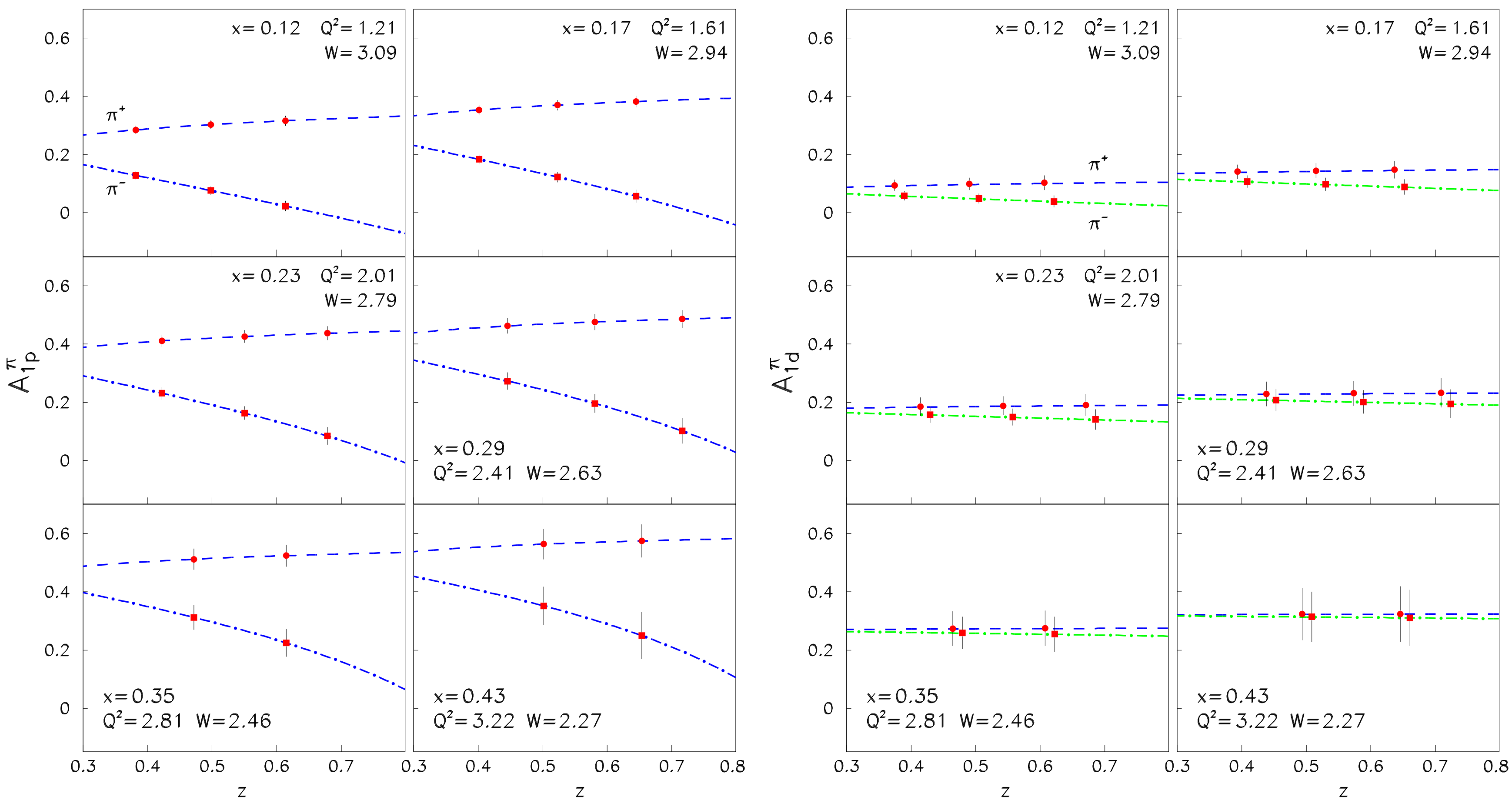
Sum over all z-bins to compare with the HERMES asymmetries:



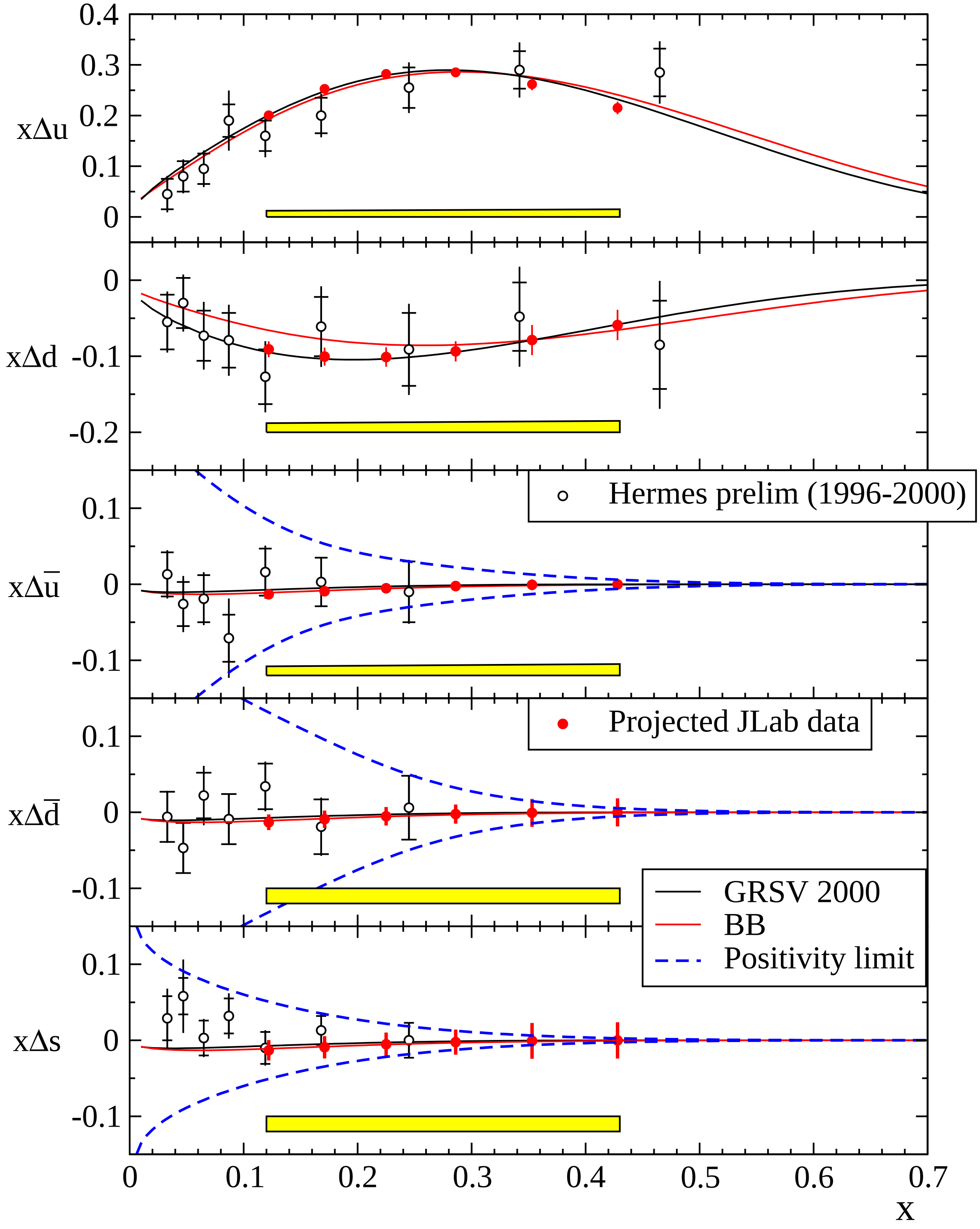
$(\delta A_1^h)_{sys} \approx \pm 0.043 \times A_1^h$.

Main sources of systematics: $\delta P_T/P_T \approx \pm 0.025$, $\delta P_B/P_B \approx \pm 0.020$, $\delta f/f \approx \pm 0.025$, radiative corrections: $\pm 1.5\%$.

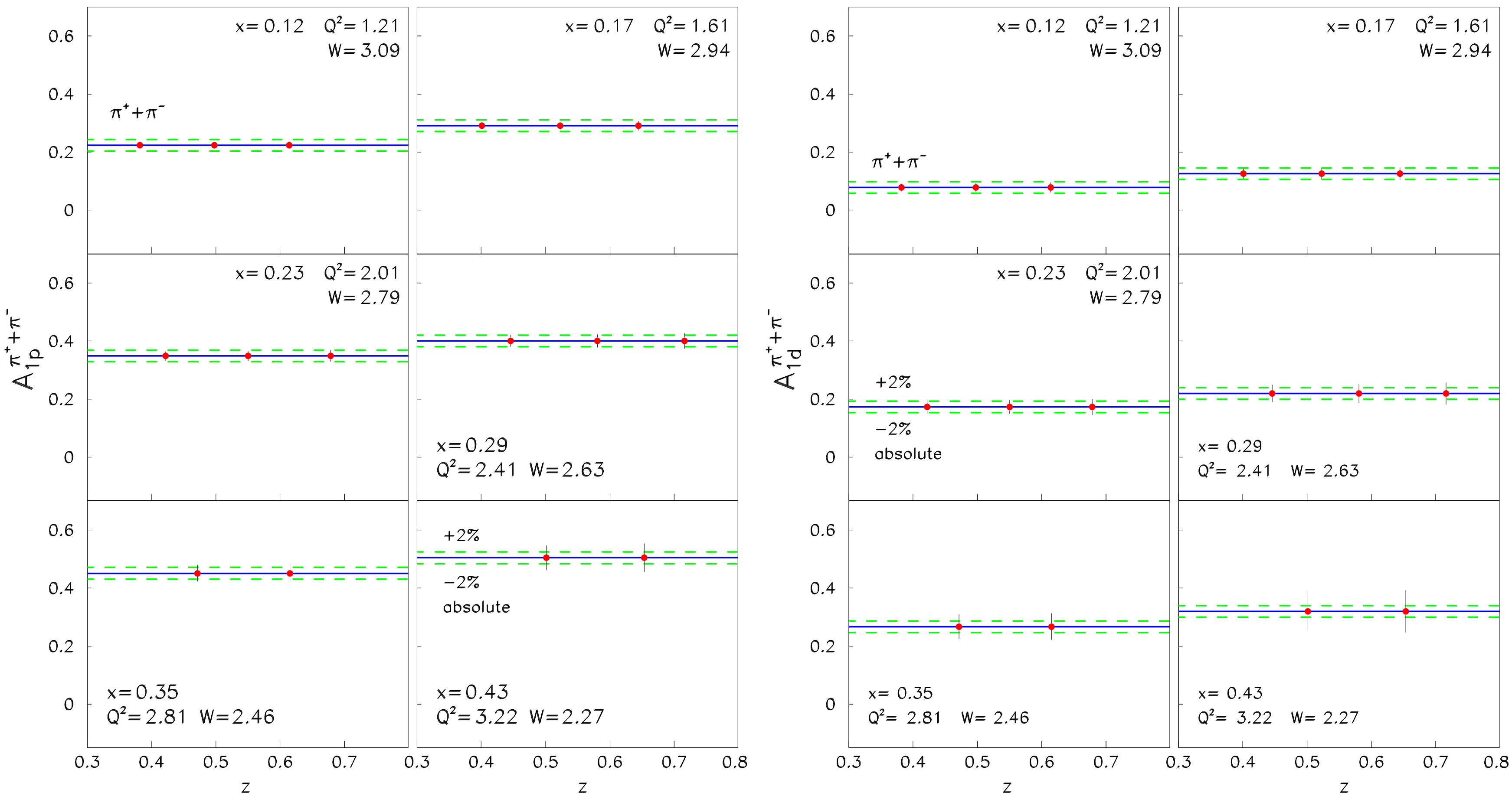
Spin Asymmetries A_1^π



Flavor Decomposition of Nucleon Spin

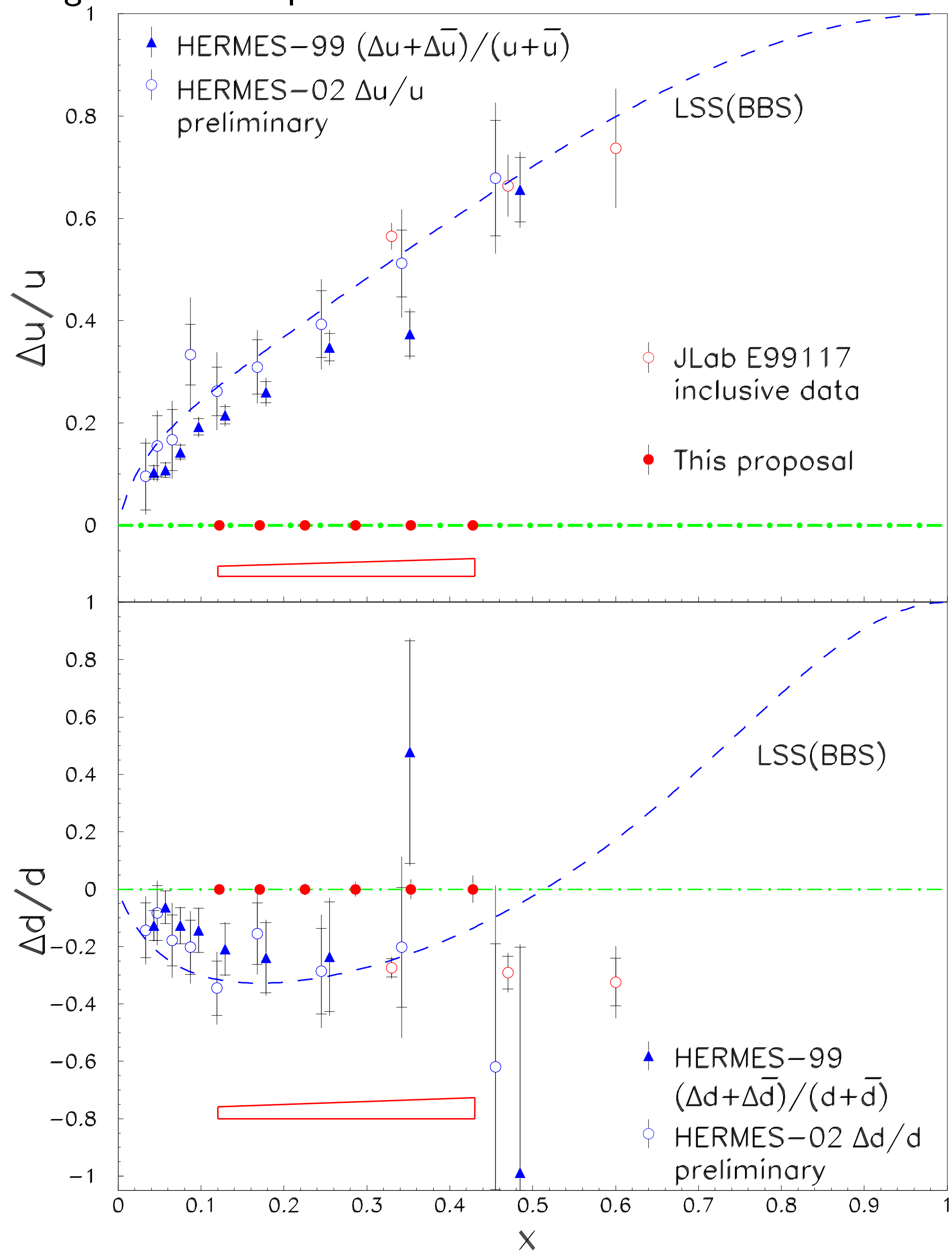


Yield Ratio $A_1^{\pi^+ + \pi^-}$



Consistency Check with the Inclusive Data

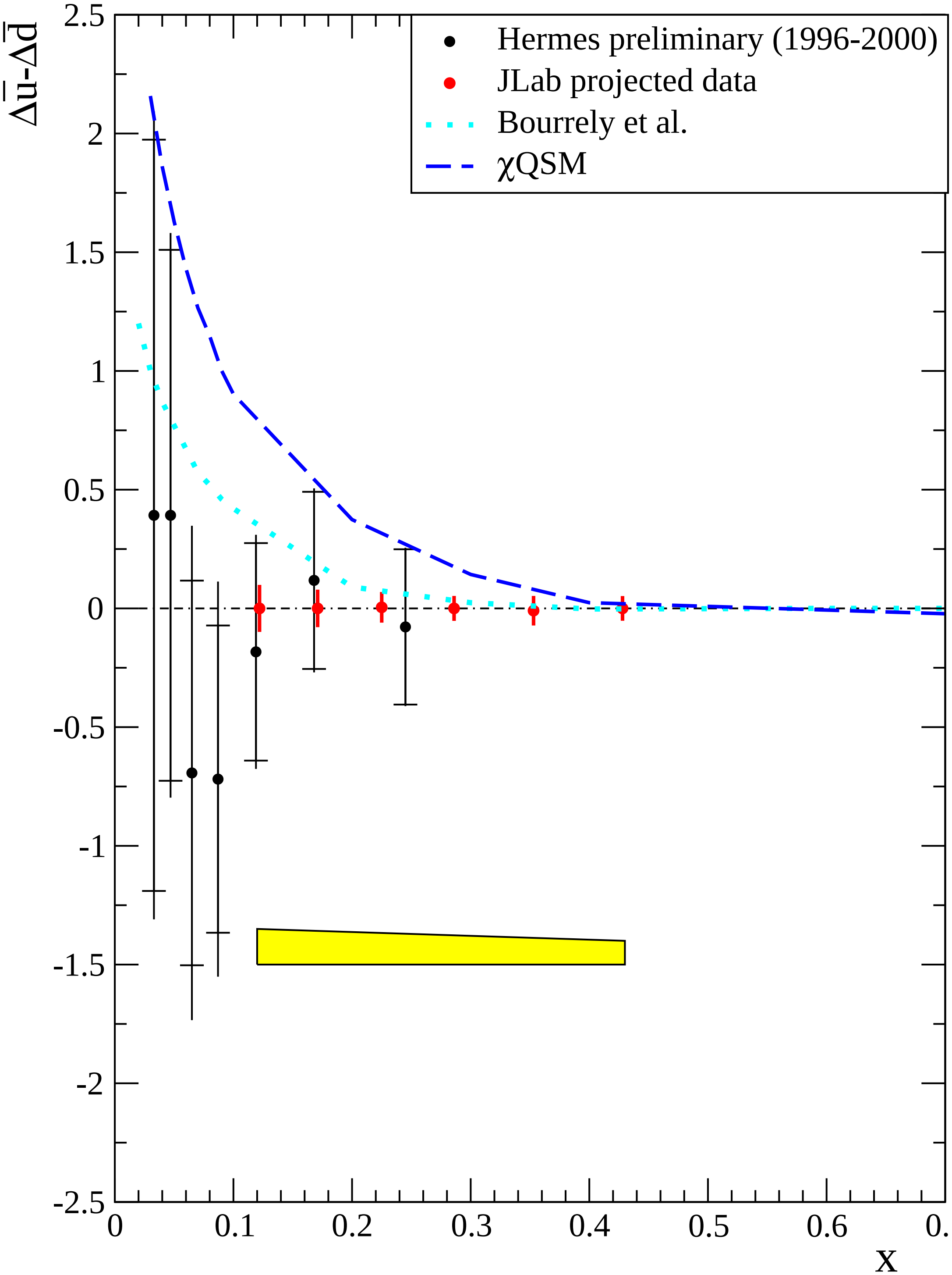
At the high x-bins compare with the recent Hall-A results:



$\delta(\Delta u/u)_{sys} \approx 0.020 \sim 0.035$, $\delta(\Delta d/d)_{sys} \approx 0.042 \sim 0.073$.

Main sources of systematics: kinematic smearing (1/3), uncertainties in fragmentation functions (1/3).

$$\Delta\bar{u} - \Delta\bar{d}$$



Summary

This experiment measures $A_1^h(x, z)$ $(h = \pi^+, \pi^-, K^+, K^-)$ with high statistics.

- Spin-flavor decomposition at $x = 0.12 \sim 0.43$, $Q^2 = 1.21 \sim 3.22$ GeV^2.
- Compare $\Delta u/u$ and $\Delta d/d$ with inclusive data at high-x.
- Access $\Delta\bar{u} - \Delta\bar{d}$ and Δs.

First measurement of $A_{1p}^{\pi^+ + \pi^-}(x, z)$ and $A_{1d}^{\pi^+ + \pi^-}(x, z)$:

- Build-in tests of factorization, a crucial step in SIDIS experiments.

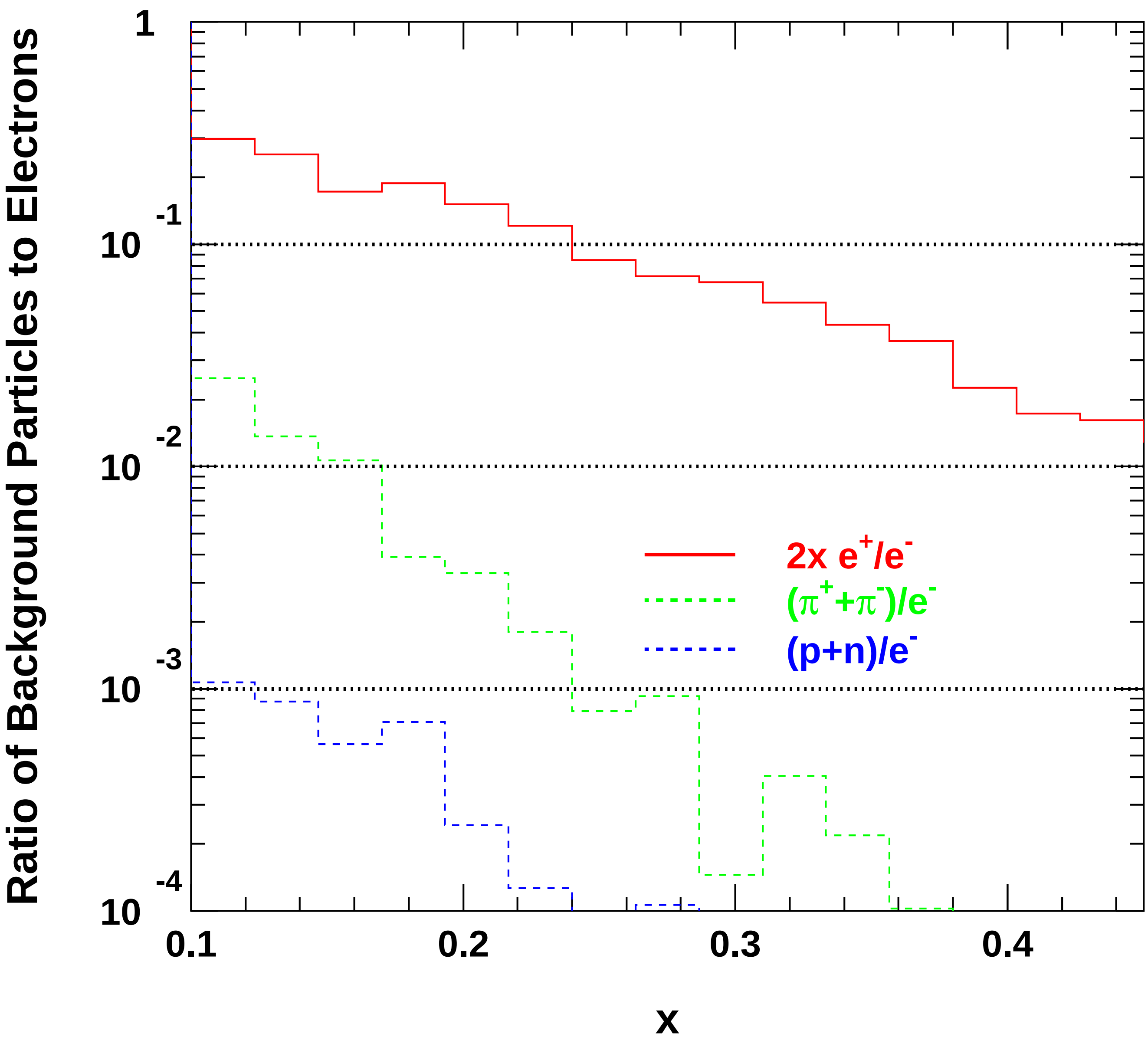
Jefferson Lab physics in a new direction, complimentary to HERMES, COMPASS and RHIC-spin.

Requesting 28 days

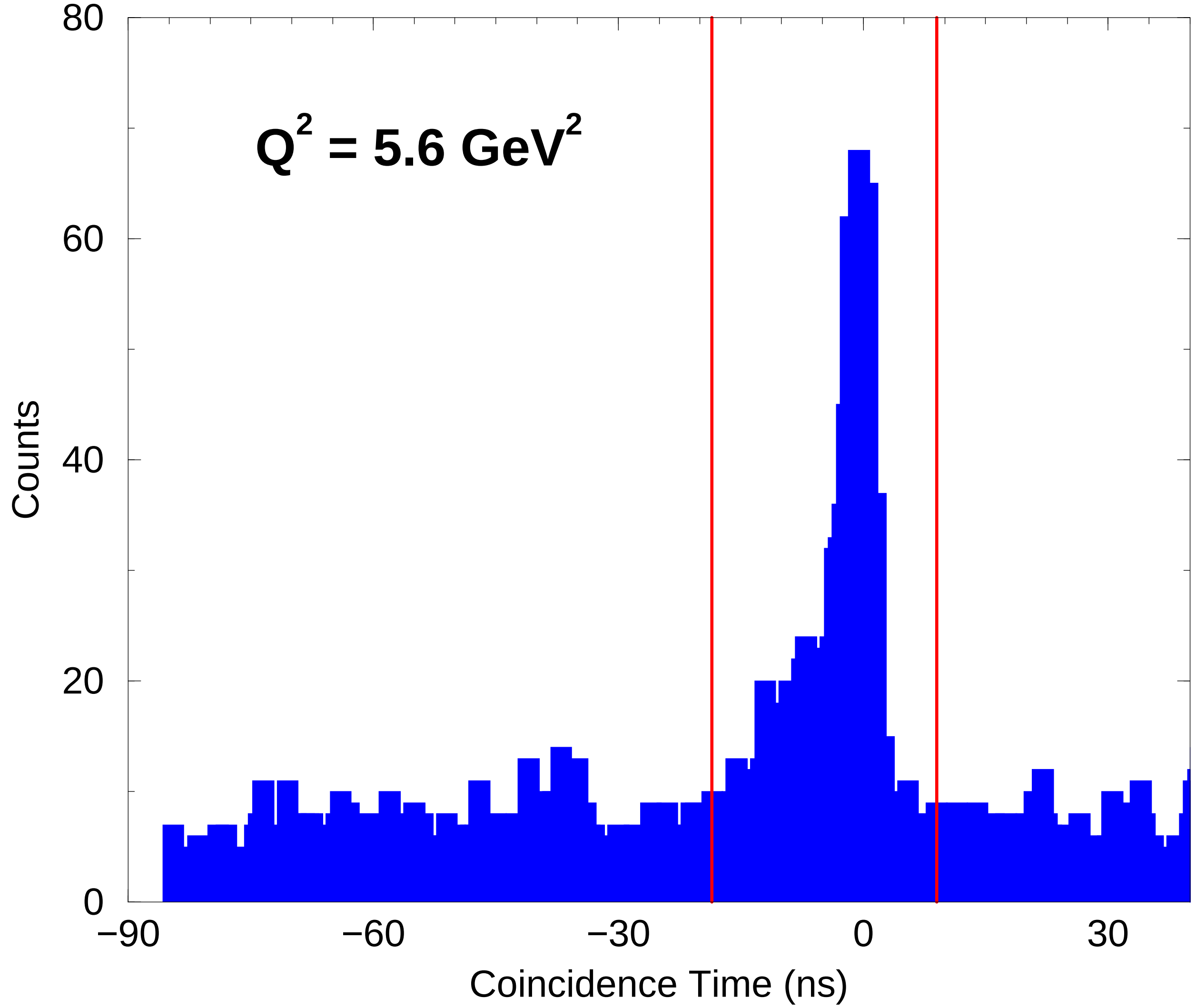
(24 days data taking and 4 days target overhead, checkouts etc.)

Positron background

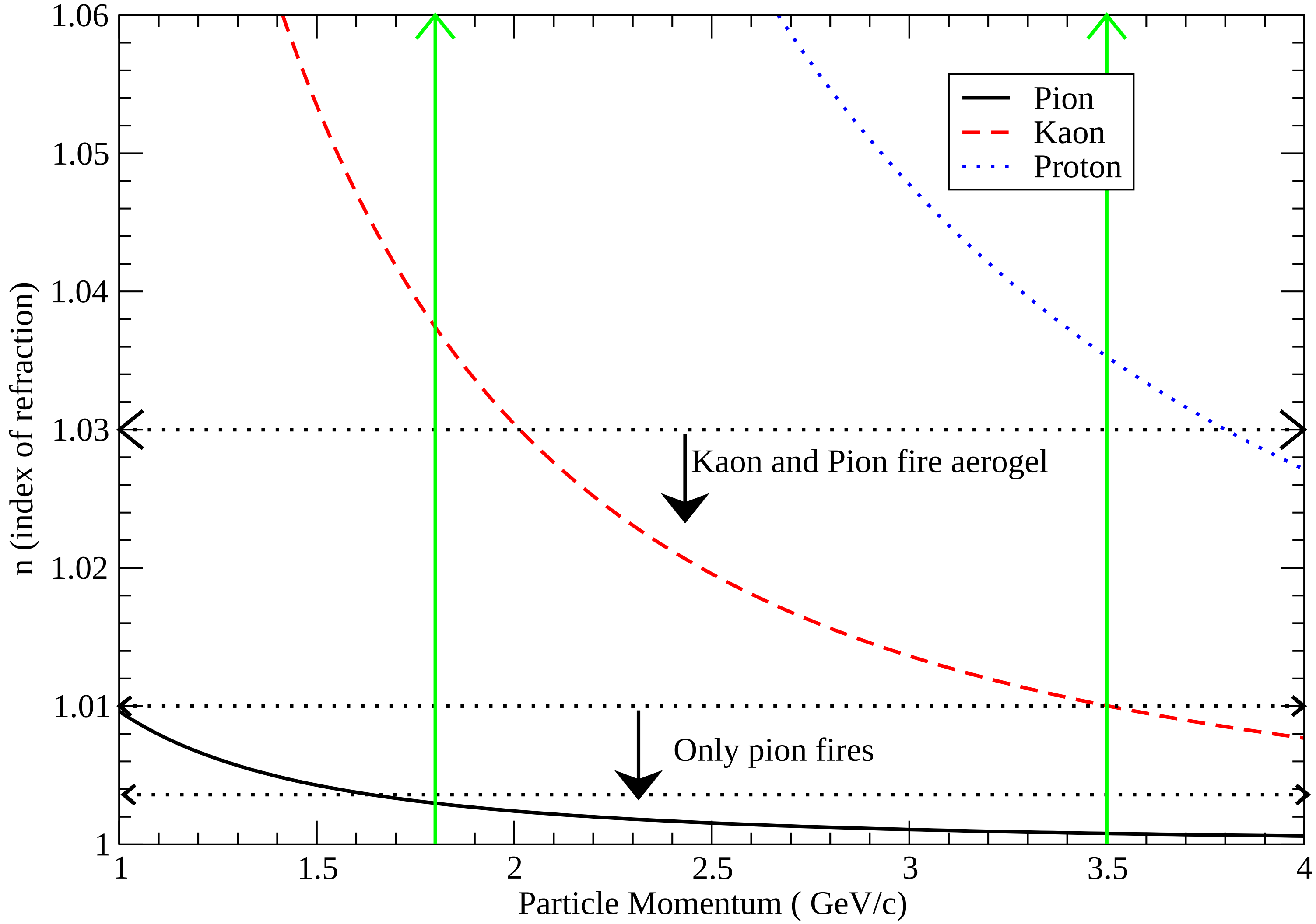
- Geant simulation of expected positron rates in Electron arm using the SLAC parametrization.
- Ratio for inclusive in low x bins in 30% and drops to 2% at high x. True coincidence rate must lower.
- Random coincidence rate is like any other background which will have to be subtracted.



Time resolution in Lead-Glass



Aerogel Index versus Momentum



Trigger rates

- Singles rates on E-arm Cerenkov.

Particle type	e^++e^-	π^++π^-	Trigger
Rate (kHz)	0.79	543.03	6.22

- Singles rates on E-arm Calorimeter.

Particle type	e^++e^-	π^++π^-	π^0+p+n	Trig
Rate (kHz)	0.66	31.48	228.51	260.65

- For E-arm single arm rate of Cerenkov and Calorimeter coincidences in 200ns window.

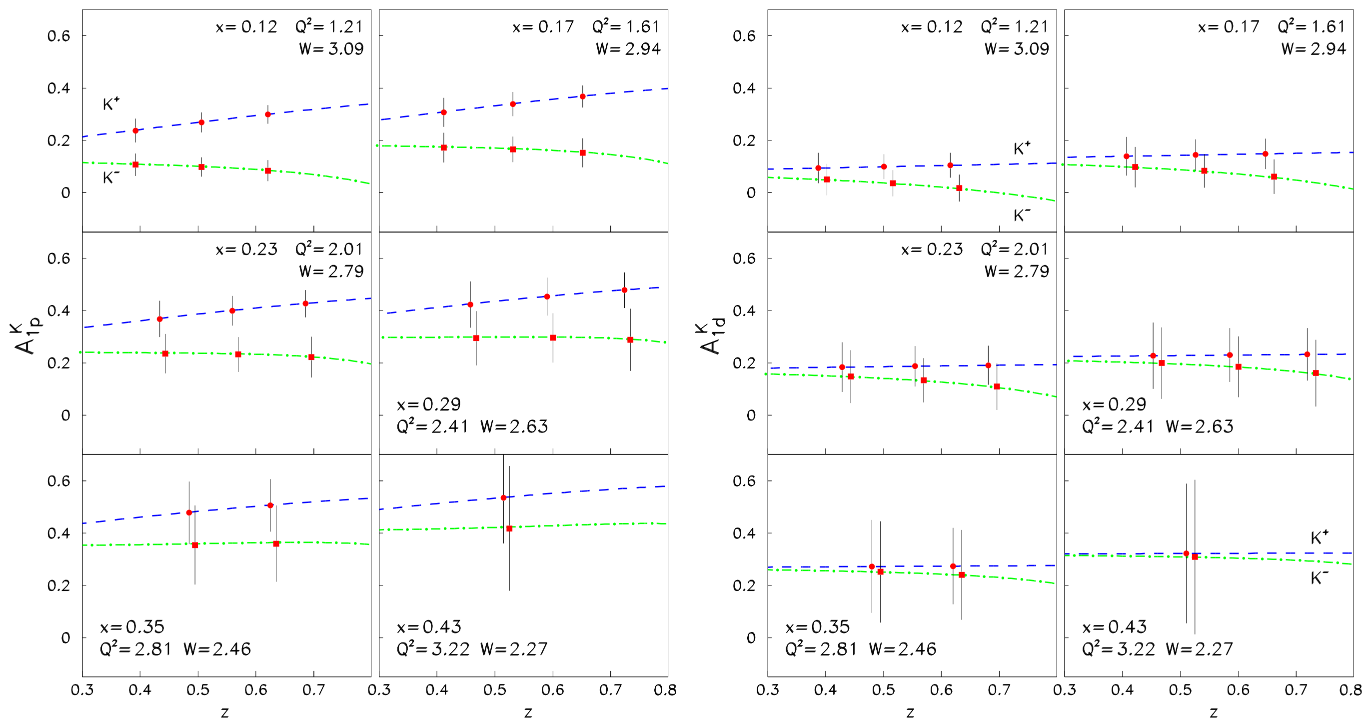
	Real single	Accidental single
Rate (kHz)	0.97	0.32

- For H-arm single rates $<$ 10 kHz.

- E-arm and H-arm coincidence rates

	Real coin	Acc. Coin with Software cuts
Rate (Hz)	0.12 - 5.4	0.005

Spin Asymmetries A_1^K



Requested Time

P_{HMS}	NH_3 target		LiD target	
GeV/c	Time-h^+ hour	Time-h^- hour	Time-h^+ hour	Time-h^- hour
2.00	22	44	22	44
2.61	28	70	30	68
3.22	36	86	36	86
sub-total	**86**	**200**	**88**	**198**

Beam on polarized targets	572
Optics and detector check	8
Target overhead, Möller runs, dilution factor measurements and HMS momentum change	92
Total Time Request	**672 (28 days)**

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