Physics Opportunities of Semi-inclusive Measurements with a 12 GeV Beam at Jefferson Lab Hall A

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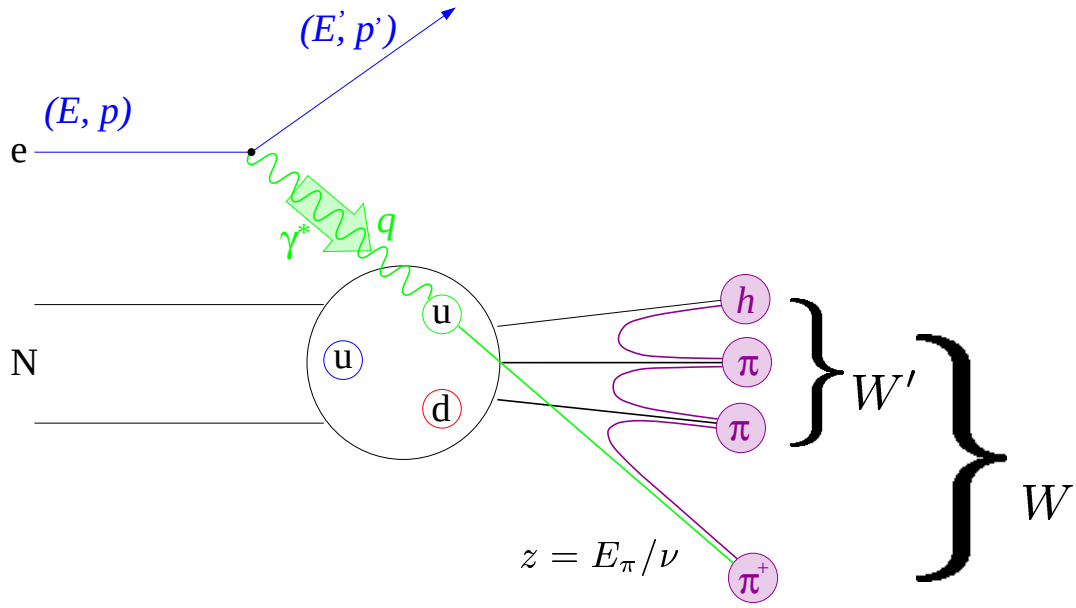


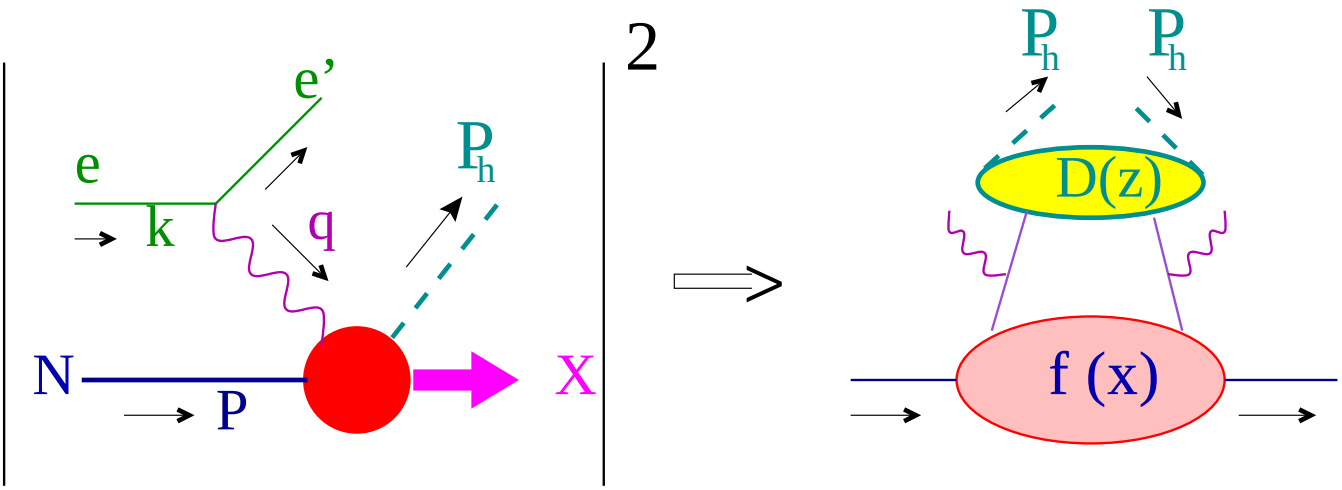
Consider deep-inelastic $(e, e'h)$ reaction, $h = \pi, K$ ...

- quark scattering followed by "free" fragmentation.
- flavor tagging: current fragmentation products.

Semi-Inclusive DIS opportunities at JLab Hall A:

- double-spin asymmetries: $A^h_{LL} \to \Delta q$, $A^h_{LT} \to \Delta q_{1T}$.
- single-spin asymmetries: $A^h_T \to \delta q$, time-odd fragmentation function $H_1^\perp$.
- many ways to demonstrate factorization.
- nucleon sea: $\bar{d}(x)/\bar{u}(x)$.

Assumption: Independent Factorization



$$Y^h(x, Q^2, z) \propto \sum_q e_q^2 q(x, Q^2) \otimes D_{q\to h}(z, Q^2)$$

$q(x, Q^2)$: universal parton distributions.

$D_{q\to h}(z, Q^2)$: universal fragmentation functions.

with a polarized beam and a polarized target:

$$\Delta Y^h(x, Q^2, z) \propto \sum_q e_q^2 \Delta q(x, Q^2) \otimes D_{q\to h}(z, Q^2)$$

$\Delta q(x, Q^2)$: parton polarization distributions.

$\Longrightarrow$ To obtain parton distributions, one needs:

- demonstrate the validity of factorization.
- knowledge of fragmentation functions.
- measure $Y^h(x, Q^2, z)$ and $\Delta Y^h(x, Q^2, z)$.

For example: HERMES SIDIS talk in this conference.

- $\Delta u(x)$, $\Delta d(x)$ and $\Delta q_{sea}(x)$, $\Delta\bar{u}(x) - \Delta\bar{d}(x)$.
- single-spin asymmetry A_T and transversity $\delta q(x)$.

With the planned 12 GeV upgrade in Jefferson Lab, the precision of SIDIS measurements can be improved by one order of magnitude.

This talk is limited to the SIDIS physics oppertunities in Hall A ...

After the 12 GeV upgrade at Jefferson Lab...

Hall A: $\vec{e}$ beam $P_e = 75\%$, $E_0 = 11.0$ GeV up to 40 μA.
For semi-inclusive DIS experiments, a typical setup:

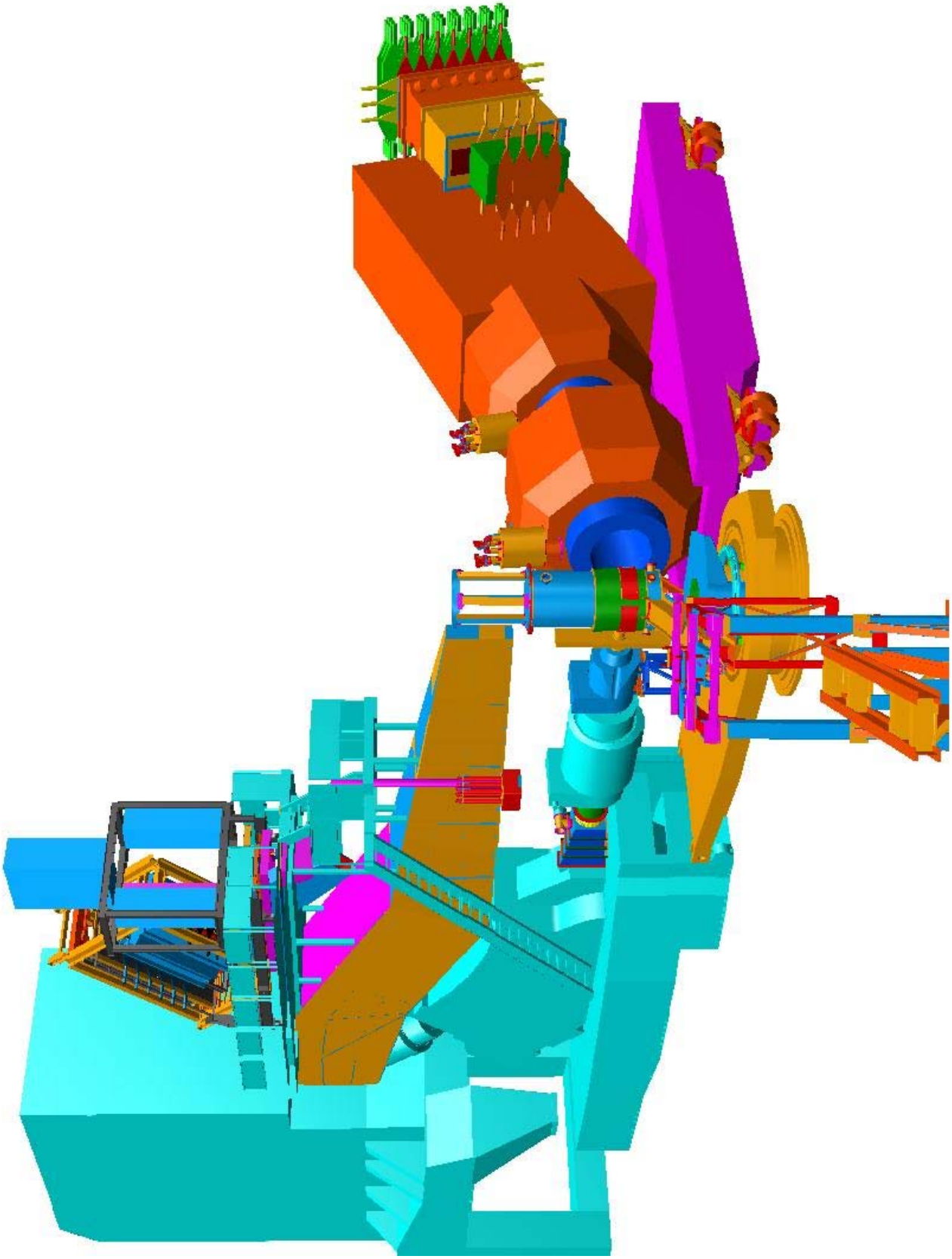
- e-arm: a new Medium Acceptance Device (MAD).
  6 GeV/c supper conducting spectrometer
  $\Delta p/p_0 = \pm 15\%$, bend angle 32°.
  $\Delta\Omega = 6$ msr @$13°$, $\Delta\Omega = 35$ msr @$35°$.
- hadron-arm: the existing HRS spectrometer.
  4.3 GeV/c QQD spectrometer, $\Delta p/p_0 = \pm 4.5\%$,
  $\Delta\Omega = 6$ msr, capable to access $6°$.
  Good PID: $e/\pi^-/K^-$ and $\pi^+/K^+/p$ separation.

Targets:

- liquid H_2 and liquid D_2 targets, $\mathcal{L} = 10^{38}/cm^2/s$.
- pol. ^{3}He target, $\mathcal{L}(^3He) = 10^{36}/cm^2/s$, $P_T = 45\%$.
- pol. NH_3 target, $\mathcal{L}(\vec{p}) = 10^{35}/cm^2/s$, $P_T = 80\%$.
- pol. ND_3 target, $\mathcal{L}(\vec{d}) = 10^{35}/cm^2/s$, $P_T = 20\%$.

In comparison, HERMES has:

- unpolarized H and D targets,
  $\mathcal{L} = 1 \sim 5 \times 10^{32}/cm^2/s$.
- pol. ^{3}He target, $\mathcal{L}(^3He) = 2 \sim 8 \times 10^{31}/cm^2/s$.
- pol. H target, $\mathcal{L}(\vec{p}) = 2 \sim 8 \times 10^{30}/cm^2/s$.



Luminosity: Jefferson Lab Hall A $\mathcal{L}_J$ vs HERMES $\mathcal{L}_H$

$$\mathcal{L}_J(p,d) \geq 200000.0 \times \mathcal{L}_H(p,d)$$

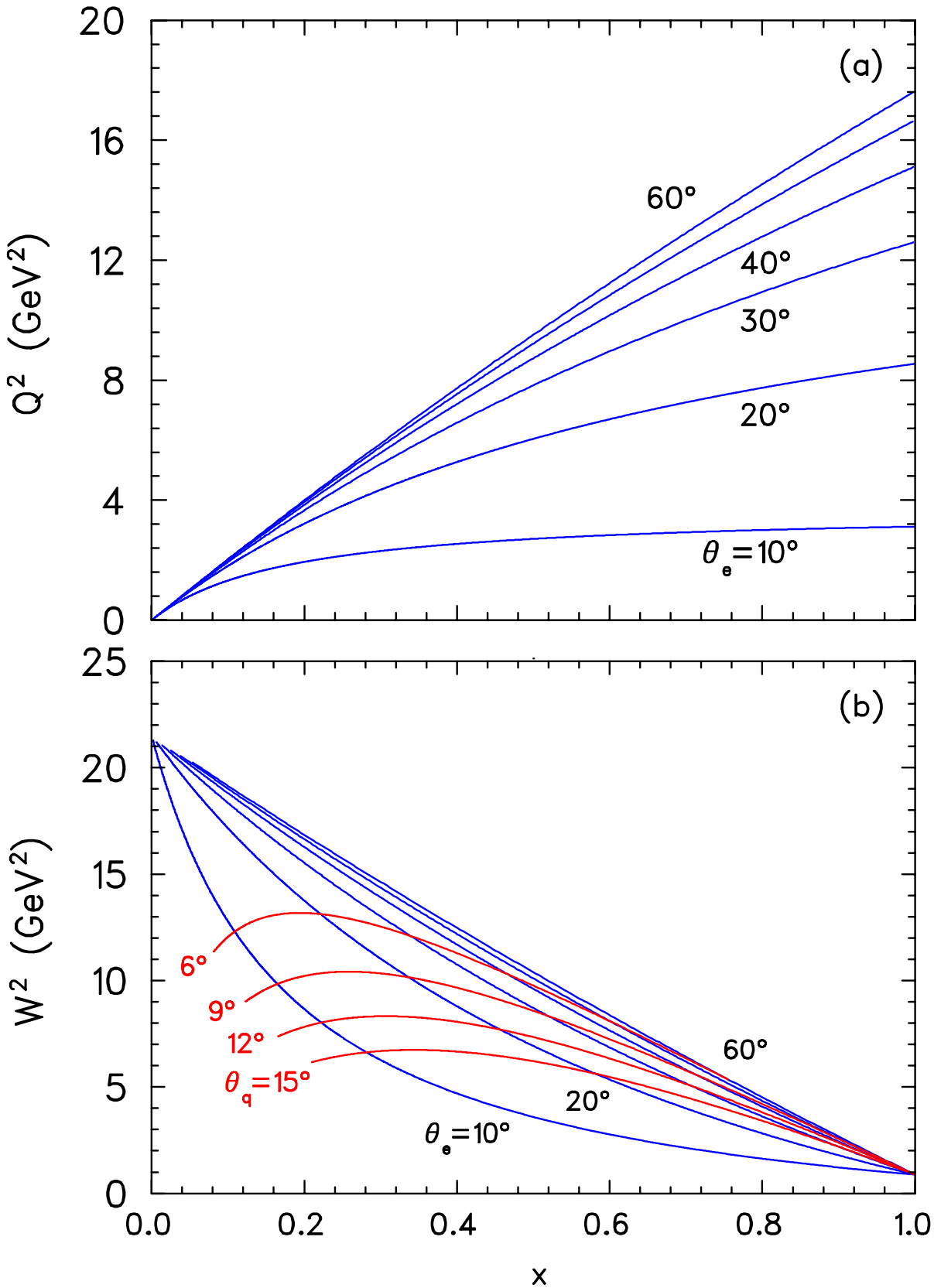
$$\mathcal{L}_J(^3\vec{H}e) \geq 12500.0 \times \mathcal{L}_H(^3\vec{H}e)$$

$$\mathcal{L}_J(\vec{p}) \geq 12500.0 \times \mathcal{L}_H(\vec{p})$$

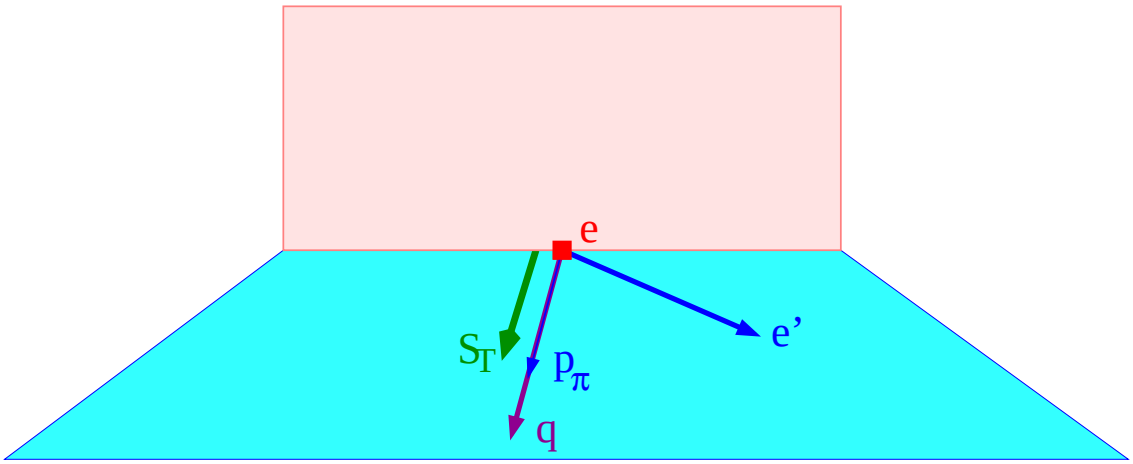
The HERMES detector is an open-geometry forward angle spectrometer:
$\Delta\theta = \pm 170$ mrad, $\Delta\phi = \pm(40 \sim 140)$ mrad $\Rightarrow$ $\Delta\Omega = 68$ msr.

$\Delta\Omega_H \approx (2 \sim 10) \times \Delta\Omega_{MAD}$, $\Delta\Omega_H \approx 11 \times \Delta\Omega_{HRS}$.

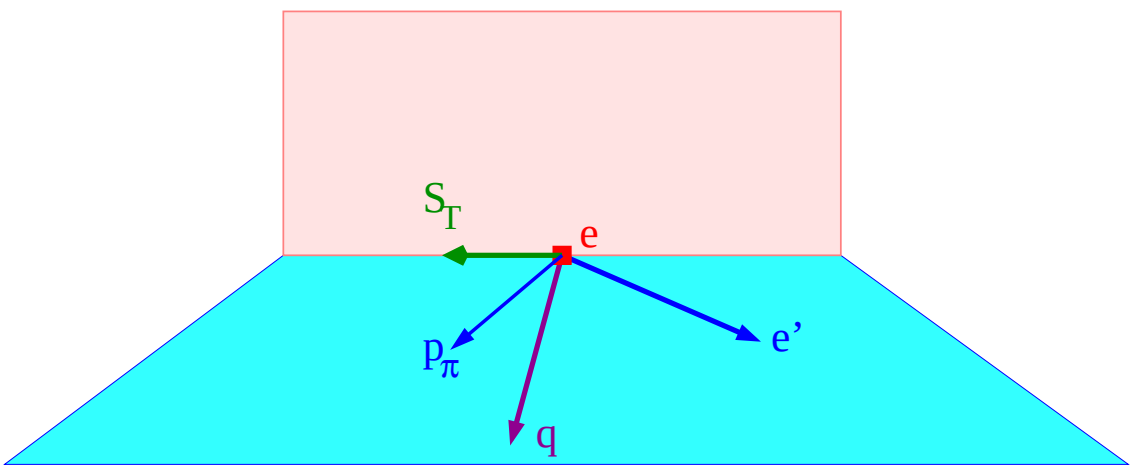
Kinematics of SIDIS at 11.0



Double-Spin Asymmetries: A^h_{LL} and A^h_{LT}



$$A^h_{LL}(x,z) = P_e \cdot P_T \cdot \frac{y(1-\frac{1}{2}y)}{1-y+\frac{1}{2}y^2} \cdot \frac{\sum_q e_q^2 \; \Delta q(x) D^h_q(z)}{\sum_q e_q^2 \; q(x) D^h_q(z)} \; .$$

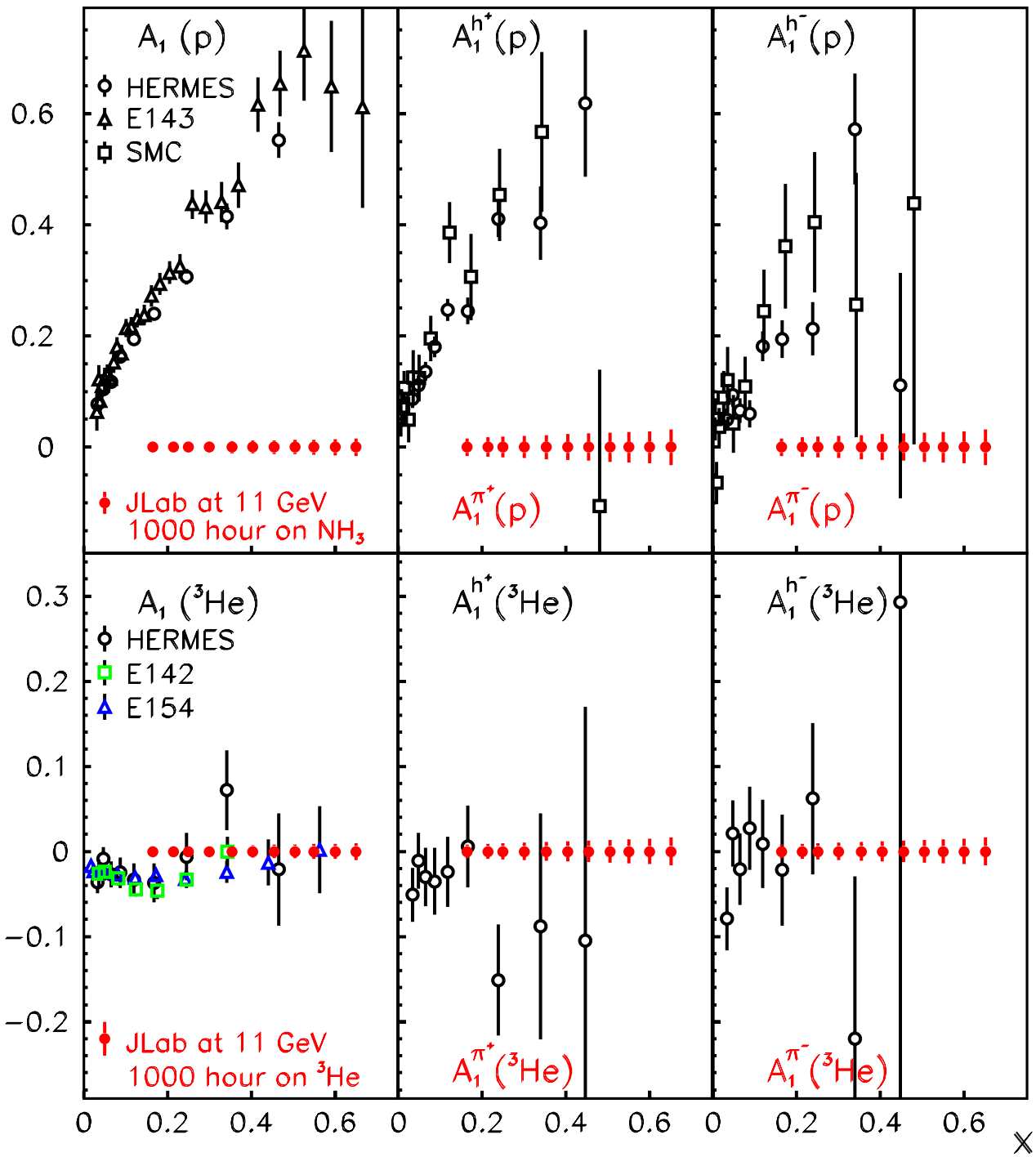


$$A^h_{LT}(x,z) = P_e \cdot \frac{\vec{p}_h \cdot \vec{P}_T}{M} \cdot \frac{y(1-\frac{1}{2}y)}{1-y+\frac{1}{2}y^2} \cdot \frac{\sum_q e_q^2 \; \Delta q_{1T}(x) D^h_q(z)}{\sum_q e_q^2 \; q(x) D^h_q(z)} \; .$$

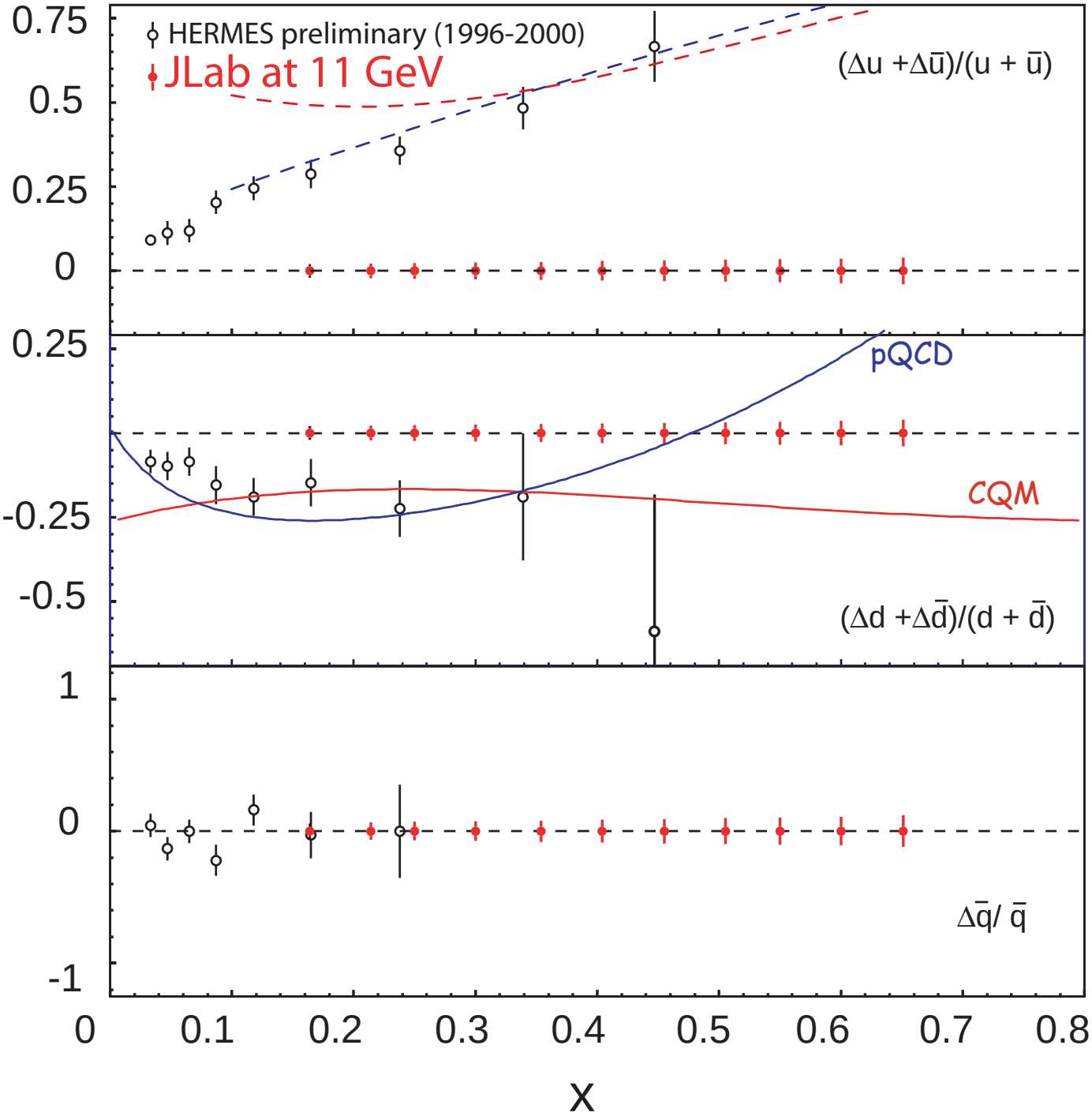
Δq_{1T} (or g_{1T}): longitudinal quark polarization in a transversely polarized nucleon.

Expected Sensitivity: A_{LL}^{π} (or A_1^{π})

Error bars are statistical only.



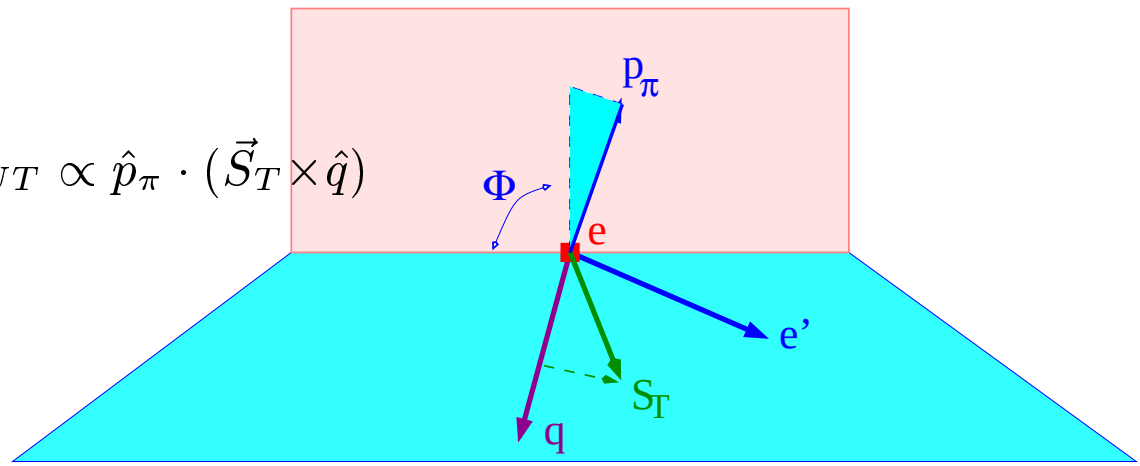
Translated into Quark Polarizations

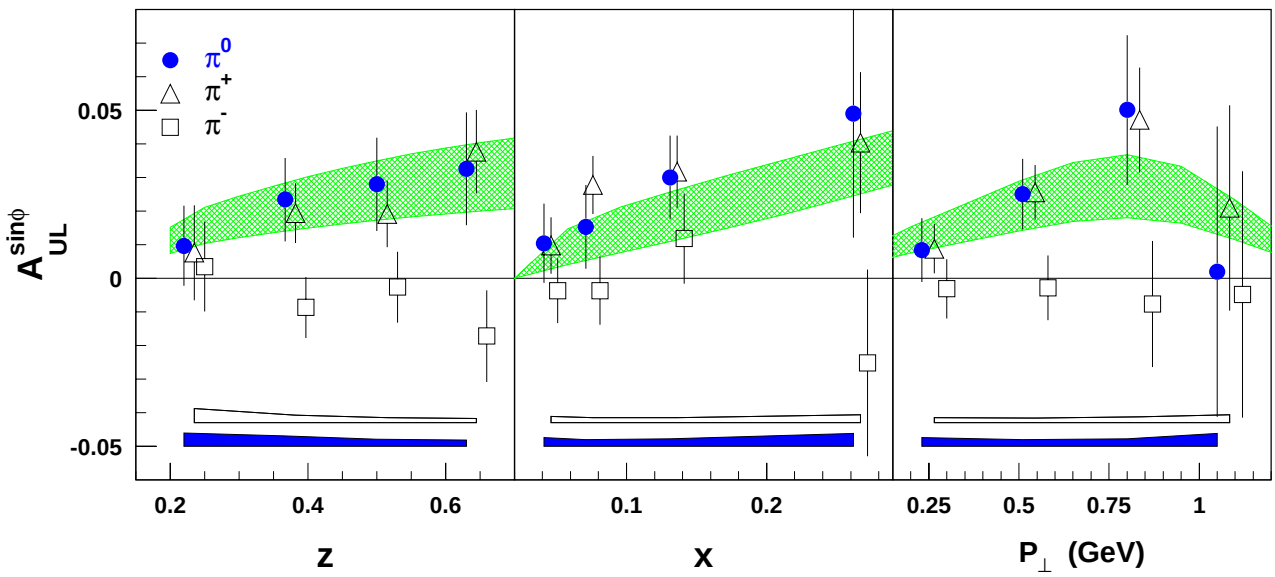


Single-Spin Asymmetry: A_T^h

recall the HERMES Single-Spin Asymmetry on $\vec{p}$:

$$\sigma_{UT} \propto \hat{p}_\pi \cdot (\vec{S}_T \times \hat{q})$$



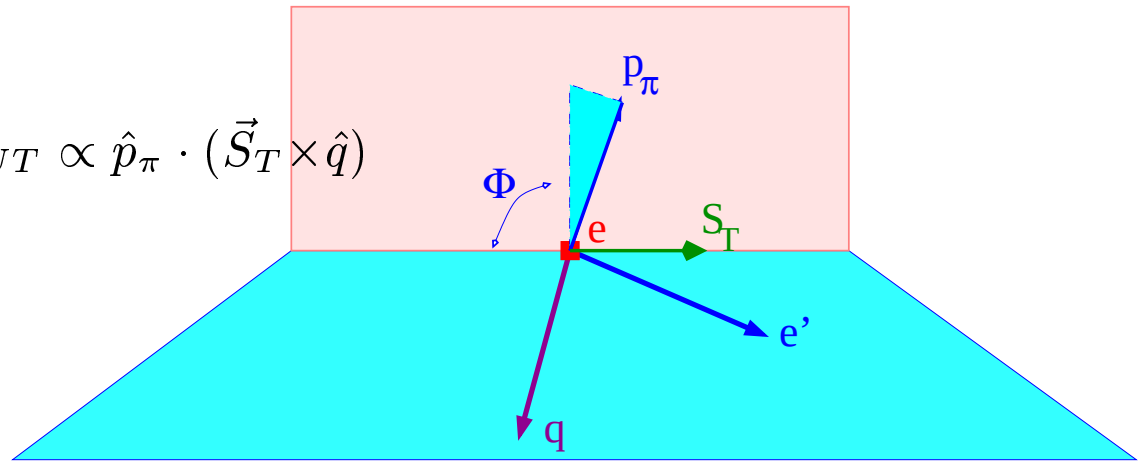


$$A_{UT}^h(x,z,p_\perp) = P_T \cdot D_{nn} \cdot \frac{\sum_q e_q^2 \cdot \delta q(x) \cdot H_{1q}^{\perp h}(z,p_\perp)}{\sum_q e_q^2 \cdot q(x) \cdot D_q^h(z,p_\perp)}.$$

involves products of chiral-odd spin distribution functions $\delta q(x)$, chiral-odd and time-odd fragmentation function $H_{1q}^{\perp h}(z,p_\perp)$ that is sensitive to the transverse polarization of the fragmenting quark.

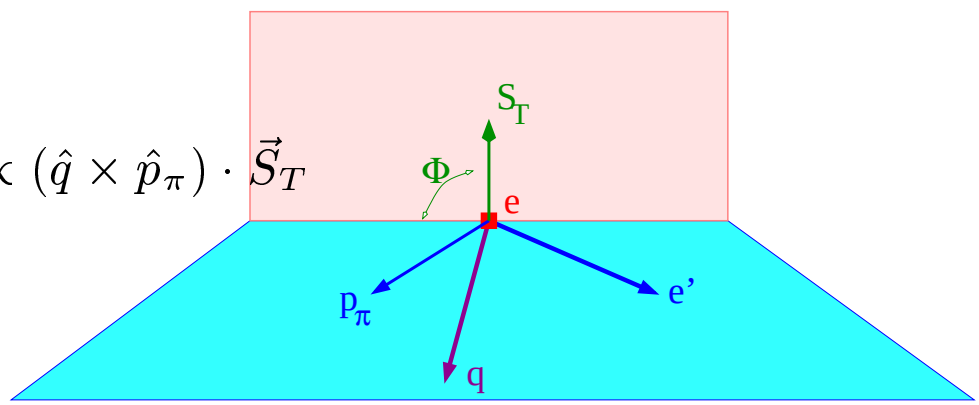
A^h_{UT} reaches the maximum when the target spin is normal to the $\vec{q} \wedge \vec{p}_\pi$ plane, if one has out-of-plane capability.
HERMES run with a transverse target:

$$\sigma_{UT} \propto \hat{p}_\pi \cdot (\vec{S}_T \times \hat{q})$$

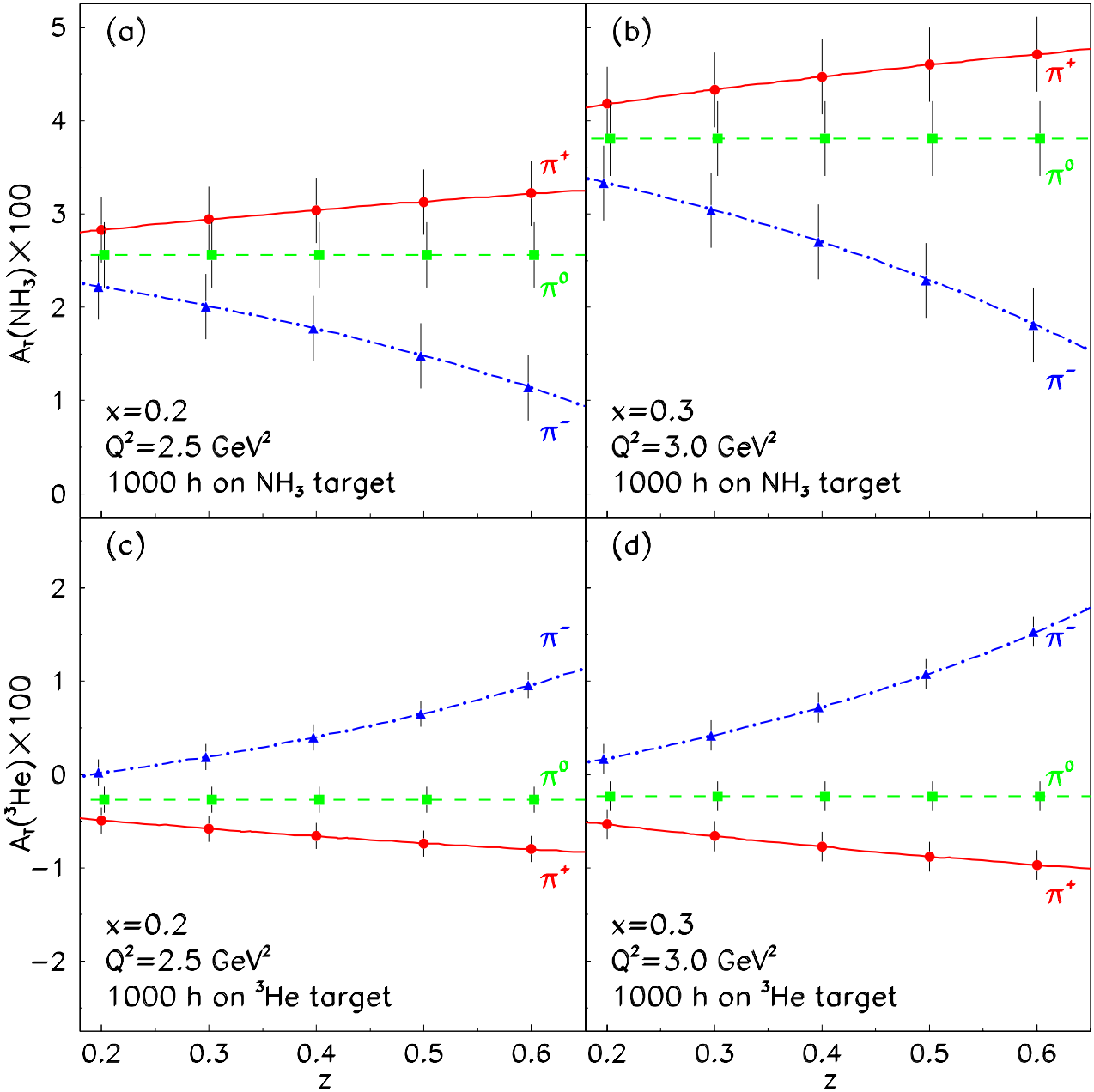


or one can turns his head around:

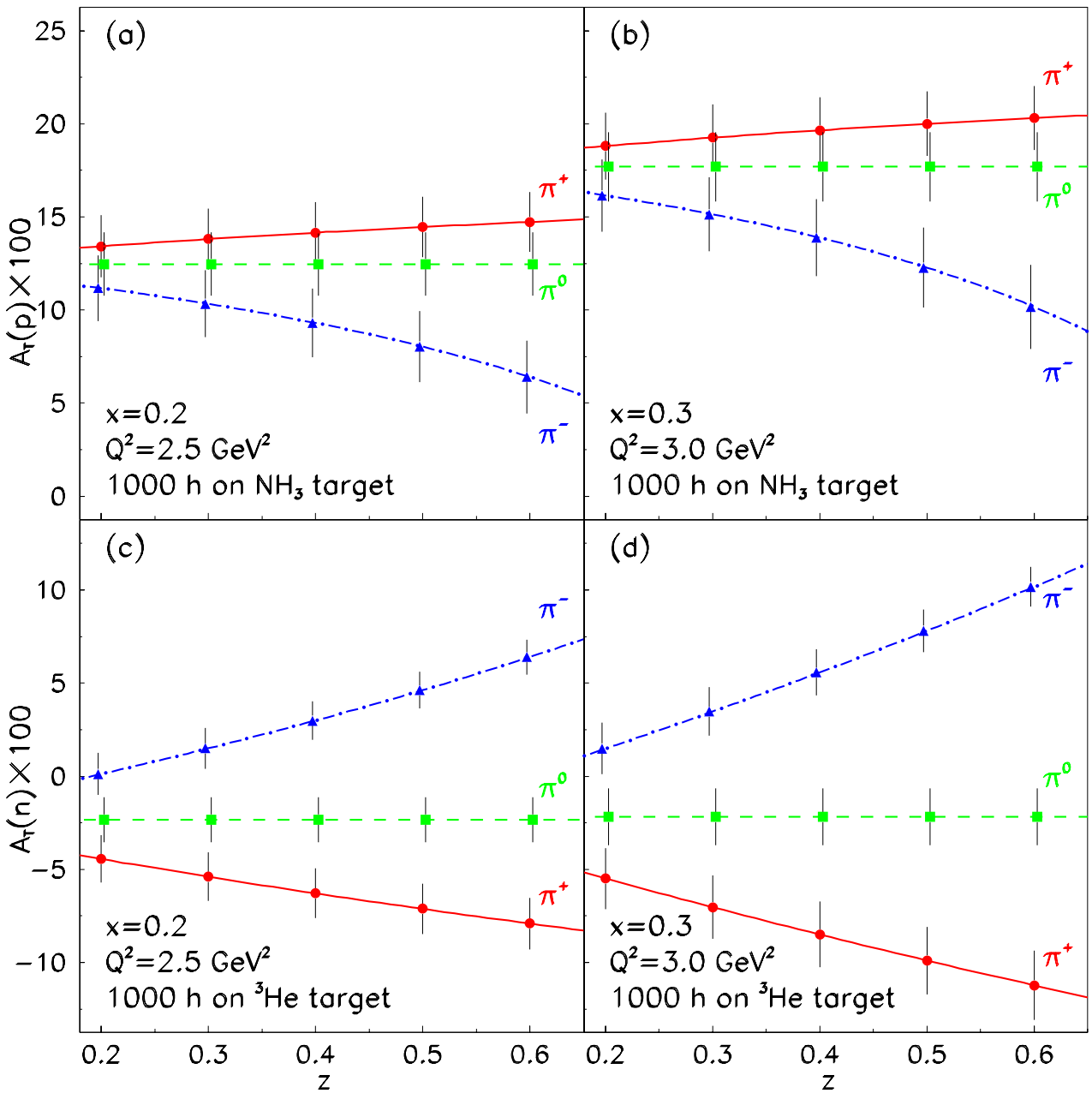
$$\sigma_{UT} \propto (\hat{q} \times \hat{p}_\pi) \cdot \vec{S}_T$$



The Expected Sensitivities
Hall A Single-Spin Asymmetry: A_T^h



The Expected Sensitivities
Single-Spin Asymmetry of Nucleon: A_T^h



Factorization: Cornell Data 1978

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

$E_0 = 11.5$ GeV, $\langle Q^2 \rangle = 2.8$ GeV^2,

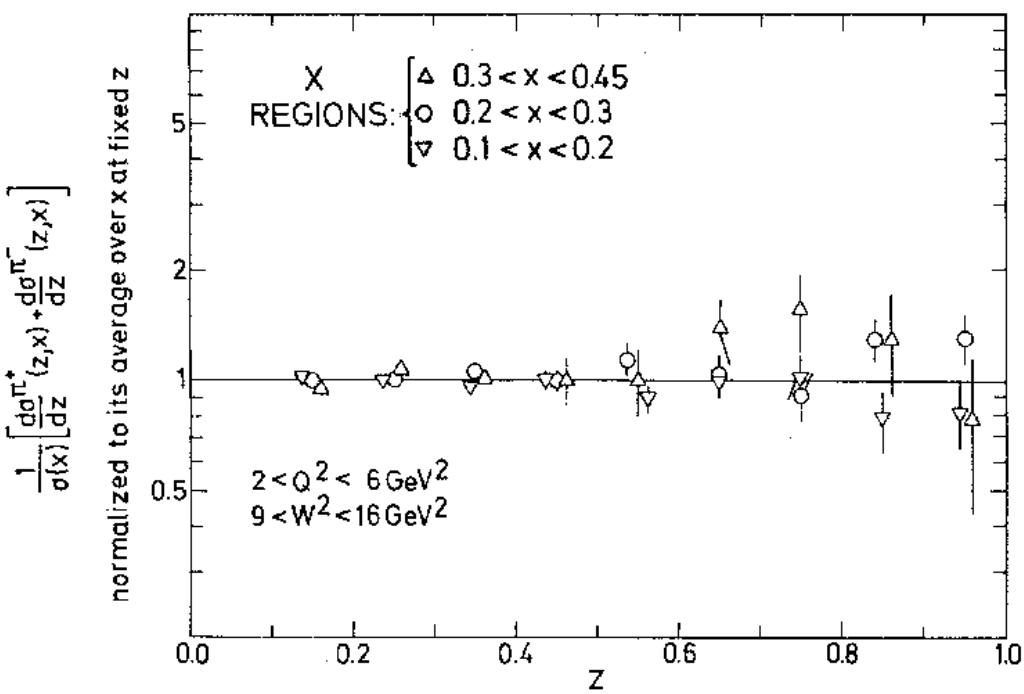
$(e, e'\pi^+)$ and $(e, e'\pi^-)$ reaction on proton.

isospin symmetry and charge conjugation:

$$D^+(z, Q^2) \equiv D_u^{\pi^+} = D_d^{\pi^-} = D_{\bar{u}}^{\pi^-} = D_{\bar{d}}^{\pi^+}$$
$$D^-(z, Q^2) \equiv D_u^{\pi^-} = D_d^{\pi^+} = D_{\bar{u}}^{\pi^+} = D_{\bar{d}}^{\pi^-}$$

$$\frac{d\sigma}{dz}^{\pi^+}(x, z) \propto 4u(x)D^+(z) + d(x)D^-(z) + 4\bar{u}(x)D^-(z) + \bar{d}(x)D^+(z)$$
$$\frac{d\sigma}{dz}^{\pi^-}(x, z) \propto 4u(x)D^-(z) + d(x)D^+(z) + 4\bar{u}(x)D^+(z) + \bar{d}(x)D^-(z)$$

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



No $x-$dependence.

Observables that could Indicate Factorization

Independent Factorization:

$$Y^h(x, Q^2, z) \propto \sum_q e_q^2 q(x, Q^2) \otimes D_{q\to h}(z, Q^2)$$

Assuming isospin symmetry and charge conjugation, neglect heavy quarks in the valence region, at a fixed Q^2

$$Y_p^{\pi^+}(x,z) = A\left(4u(x)D^+(z) + d(x)D^-(z) + 4\bar{u}(x)D^-(z) + \bar{d}(x)D^+(z)\right),$$
$$Y_p^{\pi^-}(x,z) = A\left(4u(x)D^-(z) + d(x)D^+(z) + 4\bar{u}(x)D^+(z) + \bar{d}(x)D^-(z)\right),$$

$$Y_n^{\pi^+}(x,z) = A\left(4d(x)D^+(z) + u(x)D^-(z) + 4\bar{d}(x)D^-(z) + \bar{u}(x)D^+(z)\right),$$
$$Y_n^{\pi^-}(x,z) = A\left(4d(x)D^-(z) + u(x)D^+(z) + 4\bar{d}(x)D^+(z) + \bar{u}(x)D^-(z)\right).$$

$\Rightarrow$ two z-independent ratios can be formed:

$$t_1(x,z) = \frac{Y_p^{\pi^+}(x,z) + Y_p^{\pi^-}(x,z)}{Y_n^{\pi^+}(x,z) + Y_n^{\pi^-}(x,z)} = \frac{4u(x)+d(x)+4\bar{u}(x)+\bar{d}(x)}{4d(x)+u(x)+4\bar{d}(x)+\bar{u}(x)},$$

$$t_2(x,z) = \frac{Y_p^{\pi^+}(x,z) - Y_p^{\pi^-}(x,z)}{Y_n^{\pi^+}(x,z) - Y_n^{\pi^-}(x,z)} = \frac{4u(x)-d(x)-4\bar{u}(x)+\bar{d}(x)}{4d(x)-u(x)-4\bar{d}(x)+\bar{u}(x)}.$$

A clear indication of factorization:
$\Rightarrow$ $t_1(x,z)$ and $t_2(x,z)$ become z-independent.

Notice that:
$\Rightarrow$ $t_1(x,z)$ and $t_2(x,z)$ are unrelated to D^+ and D^-.

$\Rightarrow$ $t_1(x,z)$ and $t_2(x,z)$ are sensitive to $\bar{d}/\bar{u}$.

Demonstration of Factorization in Semi-Inclusive Reaction

The assumption of Independent Factorization in $N(e, e'h)$ reaction can be demonstrated by the z-independent behavior of the following observables:

- Yield ratio of $(e, e'\pi^+)$ and $(e, e'\pi^-)$ on unpolarized proton and deuteron targets.
- Double spin asymmetry of $A_{LL}^{\pi^0}$ on a polarized target.
- "Double"-double spin asymmetry of $A_{LL}^{\pi^+\pi^-}$ on a polarized target.

The advantages of the above three methods:

- Don't need to know the fragmentation functions.
- Don't need to know the parton distributions.
- Only need to measure yield ratios, not absolute cross sections.

Demonstration of Factorization Through $\vec{N}(\vec{e}, e'\pi^0)$ Reaction

In double spin asymmetry of $\vec{N}(\vec{e}, e'h)$:

$$A_{LL}^h(x, Q^2, z) = \frac{\sum_i e_i^2 \left[\Delta q_i(x, Q^2) D_{q_i}^h(z, Q^2) + \Delta \bar{q}_i(x, Q^2) D_{\bar{q}_i}^h(z, Q^2)\right]}{\sum_i e_i^2 \left[q_i(x, Q^2) D_{q_i}^h(z, Q^2) + \bar{q}_i(x, Q^2) D_{\bar{q}_i}^h(z, Q^2)\right]}$$

Isospin symmetry and charge conjugation:

$$D_u^{\pi^0} = D_d^{\pi^0}, \quad D_{\bar{u}}^{\pi^0} = D_{\bar{d}}^{\pi^0}, \quad D_u^{\pi^0} = D_{\bar{u}}^{\pi^0}, \quad D_d^{\pi^0} = D_{\bar{d}}^{\pi^0}$$

If neglecting contributions from Δs and $\Delta \bar{s}$, only one Fragmentation Function is involved in $\vec{N}(\vec{e}, e'\pi^0)$ reaction,

$$A_{LL}^{\pi^0}(x, Q^2, z) = \frac{\sum_i e_i^2 \left[\Delta q_i(x, Q^2) D^{\pi^0}(z, Q^2) + \Delta \bar{q}_i(x, Q^2) D^{\pi^0}(z, Q^2)\right]}{\sum_i e_i^2 \left[q_i(x, Q^2) D^{\pi^0}(z, Q^2) + \bar{q}_i(x, Q^2) D^{\pi^0}(z, Q^2)\right]}$$

$$A_{LL}^{\pi^0}(x, Q^2) = \frac{\sum_i e_i^2 \left[\Delta q_i(x, Q^2) + \Delta \bar{q}_i(x, Q^2)\right]}{\sum_i e_i^2 \left[q_i(x, Q^2) + \bar{q}_i(x, Q^2)\right]} = A_1(x, Q^2)$$

Factorization $\Rightarrow$ $A_{LL}^{\pi^0}$ is independent of z, and $A_{LL}^{\pi^0} = A_1$.

Demonstration of Factorization: the Combined Asymmetries

Form a "double"-double spin asymmetry with $\vec{N}(\vec{e}, e'\pi^+)$ and $\vec{N}(\vec{e}, e'\pi^-)$:

$$A_{LL}^{\pi^+\pi^-}(x, Q^2, z) = \frac{(Y_+^{\pi^+} + Y_+^{\pi^-}) - (Y_-^{\pi^+} + Y_-^{\pi^-})}{(Y_+^{\pi^+} + Y_+^{\pi^-}) + (Y_-^{\pi^+} + Y_-^{\pi^-})}$$

Isospin symmetry and charge conjugation:

$$D_u^{\pi^+} = D_d^{\pi^-} = D_{\bar{u}}^{\pi^-} = D_{\bar{d}}^{\pi^+} = D^+, \; D_u^{\pi^-} = D_d^{\pi^+} = D_{\bar{u}}^{\pi^+} = D_{\bar{d}}^{\pi^-} = D^-.$$

If neglecting contributions from Δs and $\Delta\bar{s}$, Fragmentation Functions always show up in the form of $(D^+ + D^-)$ in $A_{LL}^{\pi^+\pi^-}$ and cancel-out exactly.

Therefore:

$$A_{LL}^{\pi^+\pi^-}(x, Q^2) = A_{LL}^{\pi^0}(x, Q^2) = A_1(x, Q^2)$$

Factorization $\Rightarrow$ $A_{LL}^{\pi^+\pi^-}$ is independent of z, and $A_{LL}^{\pi^+\pi^-} = A_{LL}^{\pi^0} = A_1$.

Summary

With the JLab 12 GeV upgrade, in Hall A :

- polarized targets (NH_3, ND_3 and ^{3}He) with high luminosity.
- new medium acceptance device (35 msr) as e-arm in SIDIS.
- access to high-x, while $W > 2.5$, $W' > 2.0$ GeV and $Q^2 > 2.5$ GeV^2, comparable to HERMES.

SIDIS physics, one order of magnitude improvements on :

- $u(x)$, $d(x)$, $\bar{d}(x)$, $\bar{u}(x)$, $\Delta u(x)$, $\Delta d(x)$, $\Delta\bar{u}(x)$, $\Delta\bar{d}(x)$.
- with $(e, e'K^+)$ and $(e, e'K^-)$, access to $s(x)$, $\bar{s}(x)$, $\Delta s(x)$, $\Delta\bar{s}(x)$.
- new distributions: $\delta u(x)$, $\delta d(x)$ and $\Delta u_{1T}(x)$, $\Delta d_{1T}(x)$.

And, there're many ways to demonstrate factorization with unpolarized observables and double-spin observables.