Semi-Inclusive DIS in Hall C after the 12 GeV upgrade

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19th International Workshop on Deep-Inelastic Scattering

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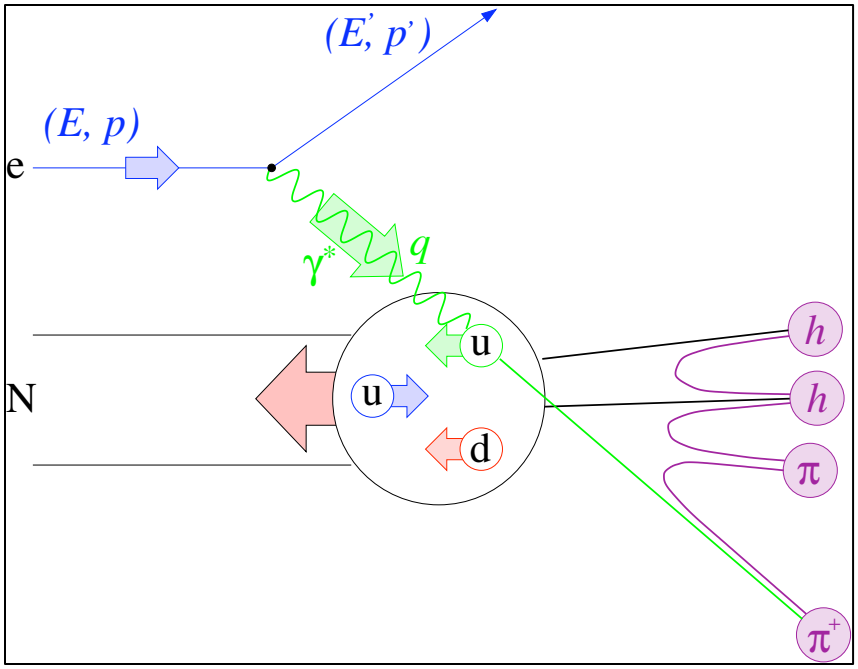
"Beam in 30 minutes or it's free"

Semi-inclusive Processes

Interest in semi-inclusive processes dominated *originally* by potential use in "flavor" tagging
→ deconvolution of polarized PDFs
→ constraints on unpolarized sea

More recently, interest has grown in azimuthal asymmetries
→ Transversity distribution
→ Transverse Momentum Distributions (TMDs)



$$d\sigma^h \propto \sum f^{H\to q}(x)\,\mathbf{d}\sigma_q(y)\,D^{q\to h}(z)$$

$$\downarrow$$

$$d\sigma^h \propto \sum f^{H\to q}(x, k_T) \otimes \mathbf{d}\sigma_q(y) \otimes D^{q\to h}(z, p_\perp)$$

Distribution Functions

N/q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$h_1 h_{1T}^\perp$

quarks

U=unpolarized
L=long. polarized
T=trans. polarized

nucleon

Diagonal elements = usual PDFs

Off-diagonal elements = transverse momentum distributions, require non-zero angular momentum

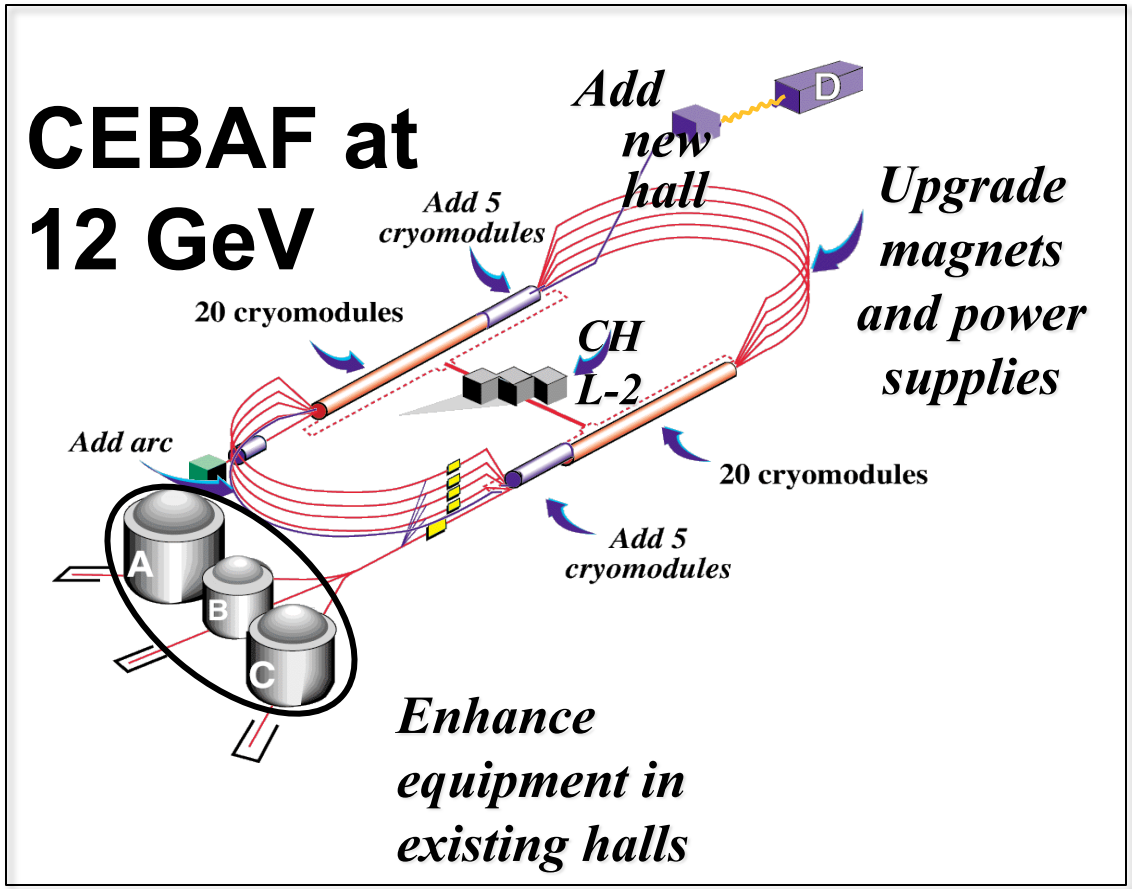
$f_{1T}^\perp$ → Sivers function, describes unpolarized quark in trans. pol. nucleon

$h_1^\perp, h_{1L}^\perp, h_{1T}^\perp$ → Boer-Mulders functions describe transversely polarized quarks in un/long./trans./polarized nucleon

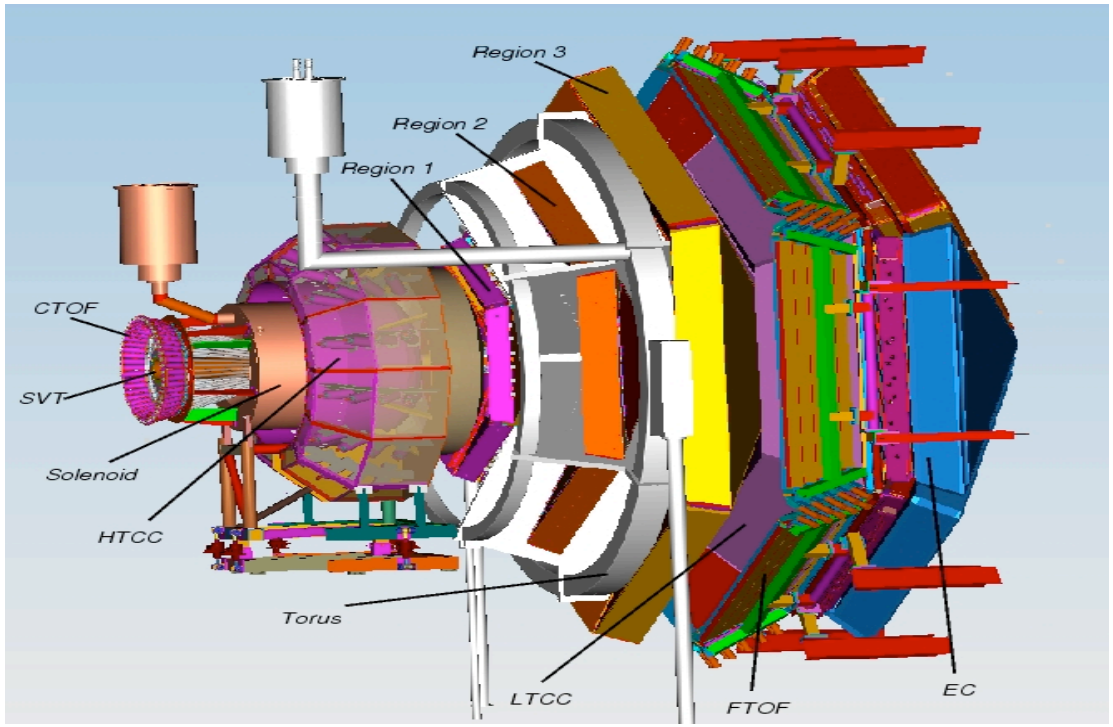
SIDIS and JLab 12 GeV Upgrade

Several studies of semi-inclusive reactions at 6 GeV JLab

→Results more or less consistent with factorization
→"Low" energy still causes some concern
→JLab upgrade to 12 GeV, new experimental equipment will improve available kinematic reach



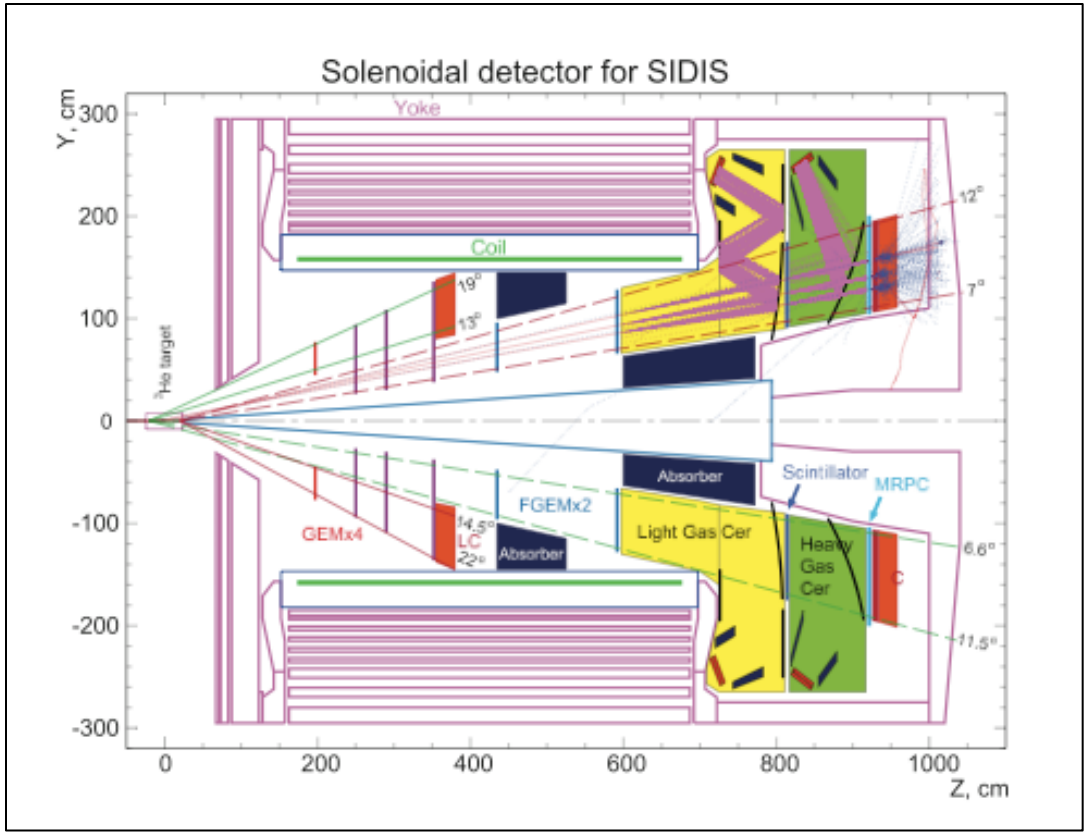
JLab SIDIS Program: Hall B



CLAS 12 Spectrometer
→large acceptance
$L=10^{35}\ cm^{-2}s^{-1}$
→2 sectors of low-threshold Cerenkov can be replaced with RICH for improved kaon ID

CLAS12 in Hall B will be the "workhorse" of SIDIS at JLab
→ Access to large phase space
→ Measurements of cross sections, single-spin, double-spin asymmetries with full azimuthal acceptance
→Polarized proton and deuteron targets

JLab SIDIS Program: Hall A

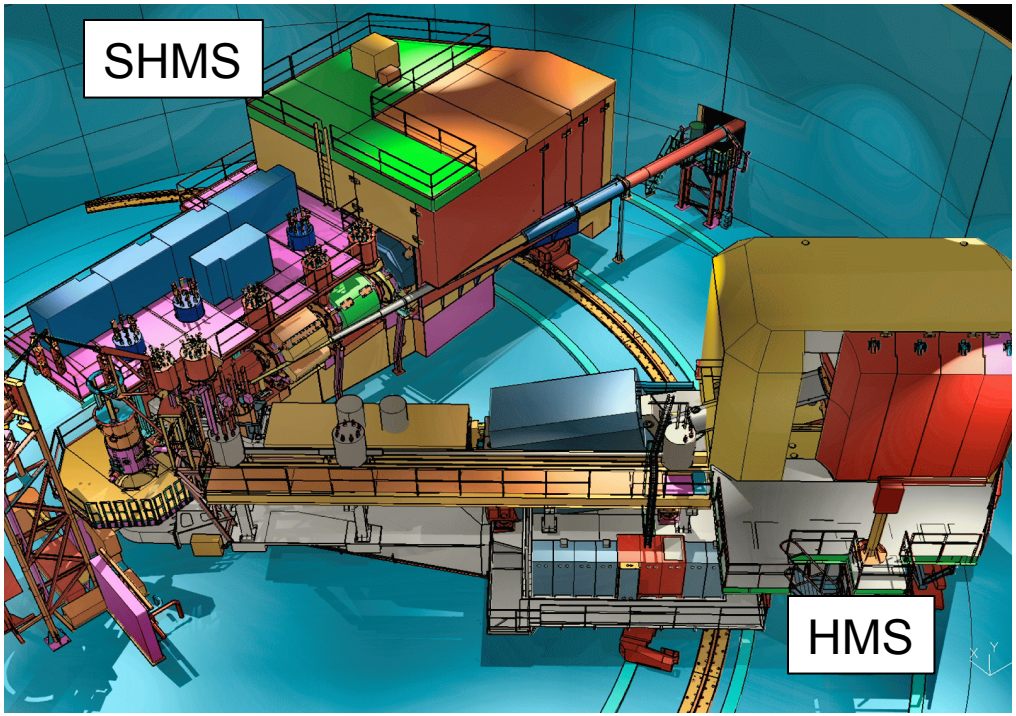


Hall A polarized ^{3}He target will allow access to information on the neutron

→ small holding field means measurements with both longitudinal and transverse targets are straightforward

Proposals using a new, solenoidal detector (SOLID) or new Super-Big Bite magnetic spectrometer will measure pion/kaon production distributions/ asymmetries

JLab SIDIS Program: Hall C



Hall C will provide 2 moderate acceptance, magnetic focusing spectrometers:

HMS:
High Momentum Spectrometer
$d\Omega \sim 6$ msr, $P_0 = 0.5 - 7$ GeV/c
$\theta_0 = 10.5$ to 80 degrees

SHMS:
Super-HMS
$d\Omega \sim 5$ msr, $P_0 = 1 - 11$ GeV/c
$\theta_0 = 5.5$ to 40 degrees

→Spectrometers provide excellent control of systematic uncertainties
→Identical acceptance for positively, negatively charged particles

Ideal for precision cross section or charge-ratio (π/π^+) measurements

Hall C – 12 GeV SIDIS Program

Approved Hall C SIDIS experiments (so far …)

Measurement of the Ratio $R=\sigma_L/\sigma_T$ in Semi-Inclusive Deep-Inelastic Scattering (E12-06-104)
Spokespersons: P. Bosted, R. Ent, H. Mkrtchyan

Transverse Momentum Dependence of Semi-Inclusive Pion Production (E12-09-017)
Spokespersons: P. Bosted, R. Ent, H. Mkrtchyan

Precise Measurement of $\pi+/\pi-$ Ratios in Semi-inclusive Deep Inelastic Scattering: Charge Symmetry violating Quark Distributions (E12-09-002)
Spokespersons: K. Hafidi, D. Dutta, D. Gaskell

$R=\sigma_L/\sigma_T$ in SIDIS

General formalism for (e,e'h) coincidence reaction w. polarized beam:

[A. Bacchetta et al., JHEP 0702 (2007) 093]

$$\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h,t}^2} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Big\{F_{UU,T}+\varepsilon F_{UU,L}+$$

$$\sqrt{2\varepsilon(1+\varepsilon)}\cos\phi_h F_{UU}^{\cos\phi_h}+\varepsilon\cos(2\phi_h)F_{UU}^{\cos(2\phi_h)}+\lambda_e\sqrt{2\varepsilon(1+\varepsilon)}\sin\phi_h F_{LU}^{\sin\phi_h}\Big\}$$

→integrate over ϕ, unpolarized beam, only L and T terms remain

DIS → $F(x,Q^2)$ SIDIS → $F(x,Q^2,z,P_T)$

Knowledge of $R = \sigma_L/\sigma_T$ in SIDIS is essentially non-existing!

Integrated over z, p_T, hadron species $R_{SIDIS} \rightarrow R_{DIS}$

→ R_{SIDIS} may vary with z, p_T

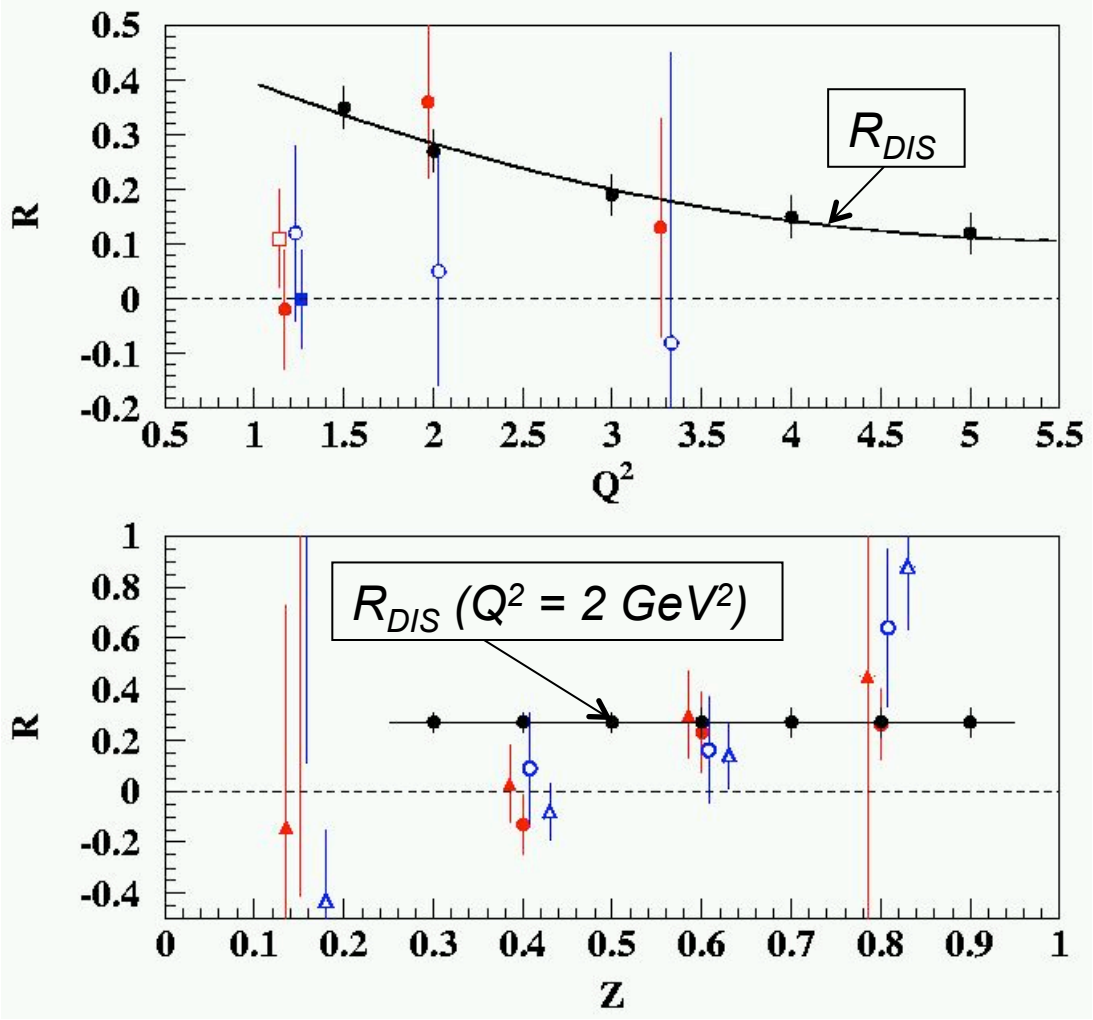
→ Is R_{SIDIS} the same for π^+, π^- (K^+, K^-)? H and D?

→ $R_{SIDIS} = R_{DIS}$ a test of quark fragmentation

→ How does R transition from SIDIS to exclusive?

$R = \sigma_L/\sigma_T$ in SIDIS (ep → e'πX)

Cornell data of 70's



Conclusion: "data both consistent with $R = 0$ and $R =$" R_{DIS}"

Some hint of large R at **large z** in Cornell data?

Measurement of R_{SIDIS} in Hall C

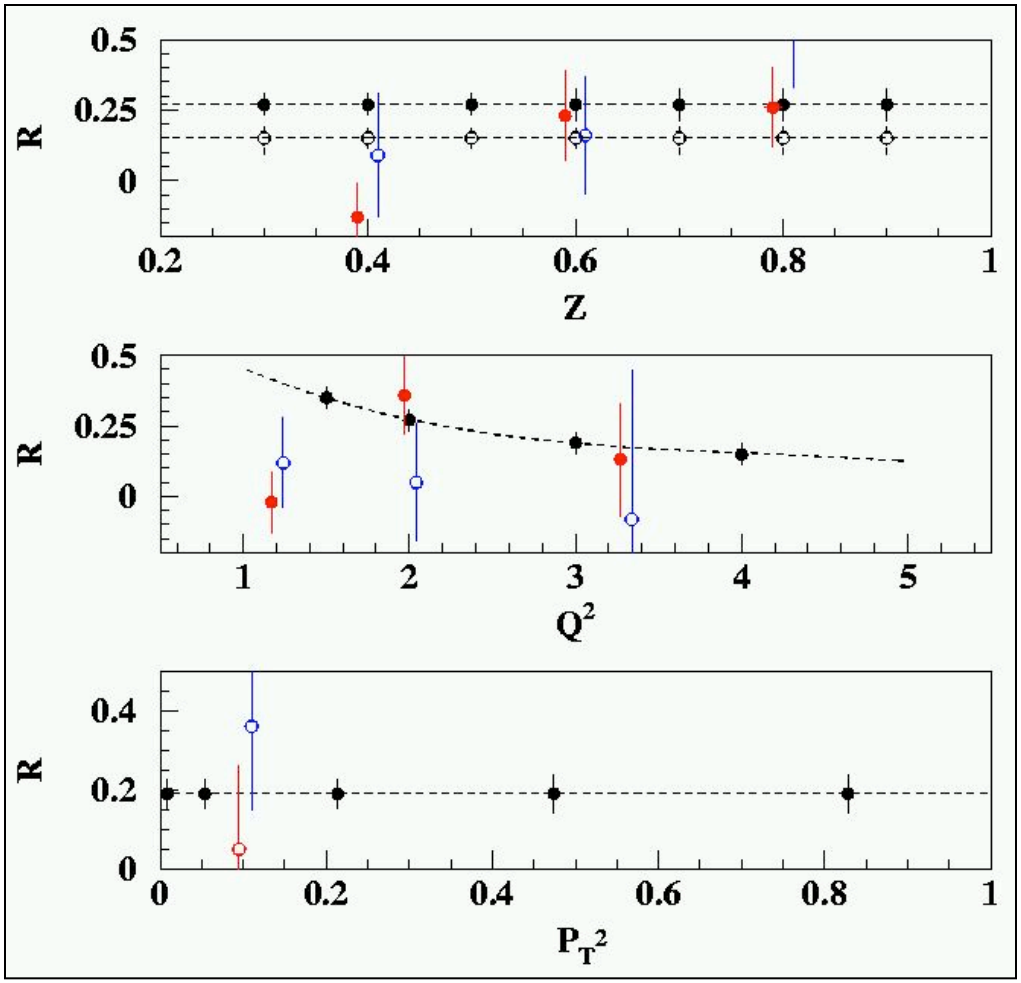
E12-06-104 will make precise measurements of R_{SIDIS} in

$e+p \rightarrow e'+\pi^{+/-}+X$, $e+D \rightarrow e'+\pi^{+/-}+X$

L-T separation requires excellent understanding of acceptance, control of point-to-point systematic errors

→ ideally suited to Hall C equipment at 12 GeV

1. Scans in z at $Q^2 = 2.0$ ($x = 0.2$) and 4.0 GeV^2 ($x = 0.4$) → behavior of σ_L/σ_T for large z.
2. Cover $Q^2 = 1.5 – 5.0$ GeV^2, → both H and D at $Q^2 = 2$ GeV^2
3. P_T up to ~ 1 GeV. Coverage in ϕ is excellent (o.k.) up to $P_T = 0.2$ (0.4) GeV.



Transverse Momentum Dependence of SIDIS

Unpolarized k_T-dependent SIDIS: in framework of Anselmino et al *[hep-ph/0608048]*, described in terms of convolution of quark distributions *f* and (one or more) fragmentation functions *D*, each with own characteristic (Gaussian) width

$$f_1^q(x,k_T) = f_1(x)\frac{1}{\pi\mu_0^2}\exp\left(-\frac{k_T^2}{\mu_0^2}\right)$$

$$D_1^q(z,p_T) = D_1(z)\frac{1}{\pi\mu_D^2}\exp\left(-\frac{p_T^2}{\mu_D^2}\right)$$

μ_0 describes transverse momentum of quarks

μ_D describes p_T dependence of Frag. Func.

(assuming $\mu_{0,u} = \mu_{0,d}$)

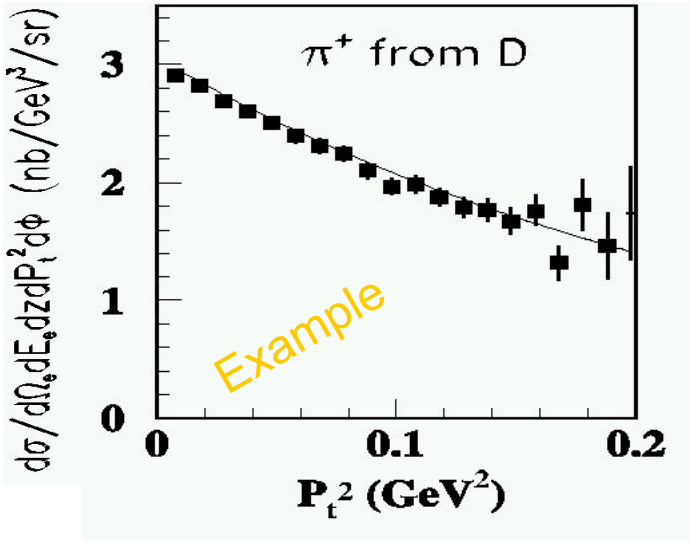
$$\left[1+(1-y)^2-4(2-y)\sqrt{1-y}\frac{z\mu_0^2|\mathbf{P}_{hT}|}{Q(\mu_D^2+\mu_0^2z^2)}\cos\varphi_h\right]\frac{\exp\left(-\frac{\mathbf{P}_{hT}^2}{\mu_D^2+\mu_0^2z^2}\right)}{\mu_D^2+\mu_0^2z^2}\sum_q e_q^2 f_1^q(x)\,D_q^h(z)$$

Possibility to constrain k_T dependence of up and down quarks *separately* by combination of π^+ and π^- final states, proton and deuteron targets

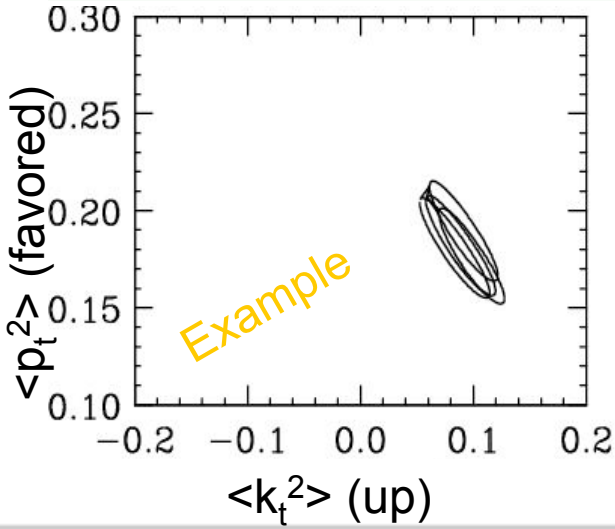
P_T Dependence – E00-108

Hall C experiment E00-108 (6 GeV):
→ Measured P_T dependent cross sections in semi-inclusive pion production
→Measured both π+ and π-
→Proton and deuteron (neutron) targets
→Combination allows (in principle) disentanglement of quark and fragmentation widths

PL B665 (2008) 20



Simple model, with several assumptions:
→ factorization valid
→ fragmentation functions do not depend on quark flavor
→ transverse momentum widths of quark and fragmentation functions are Gaussian and can be added in quadrature
→ more …

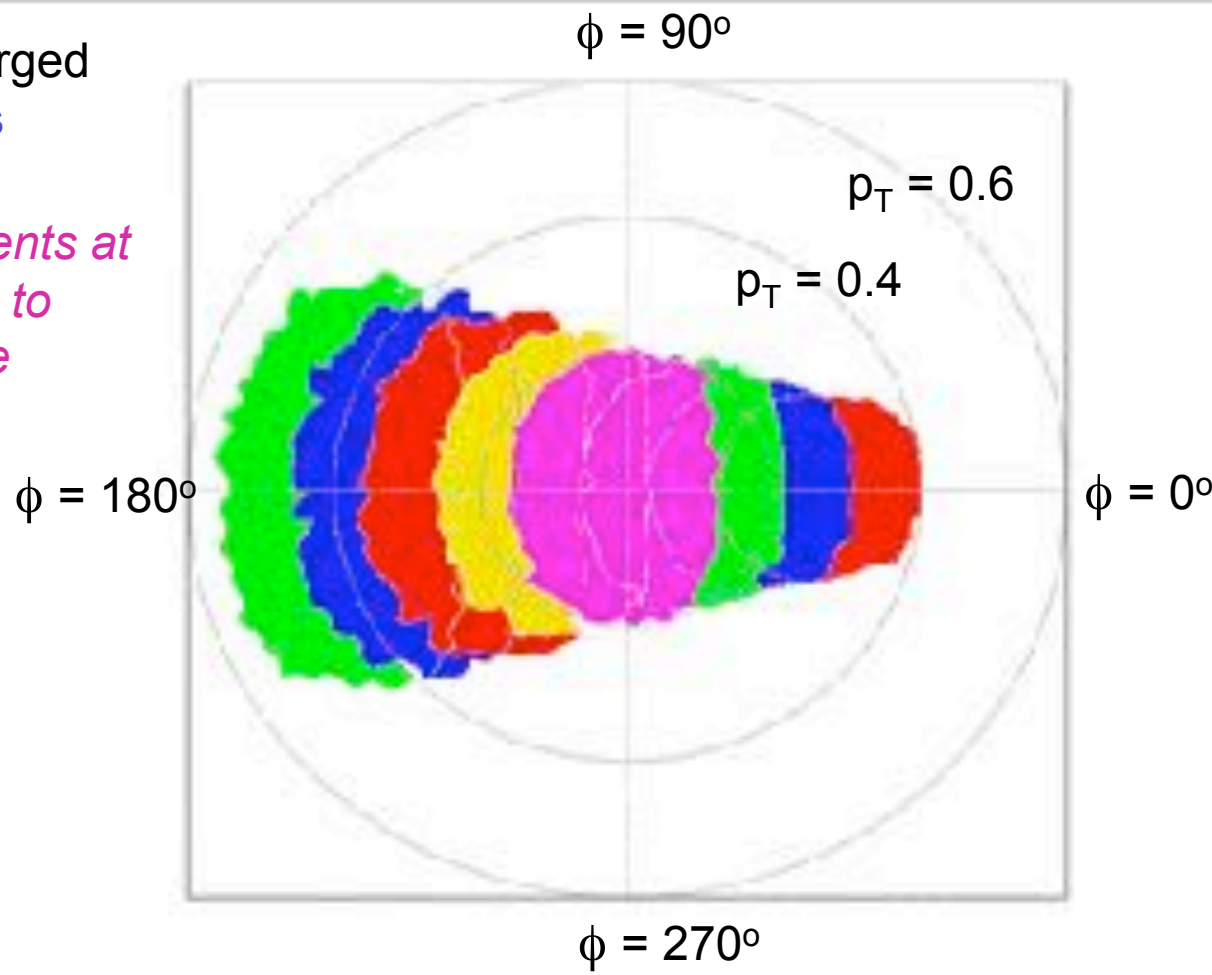


E12-09-017: P_T Dependance of $\pi^{+/-}$ Production

Precise measurements of charged pion cross sections and **ratios**

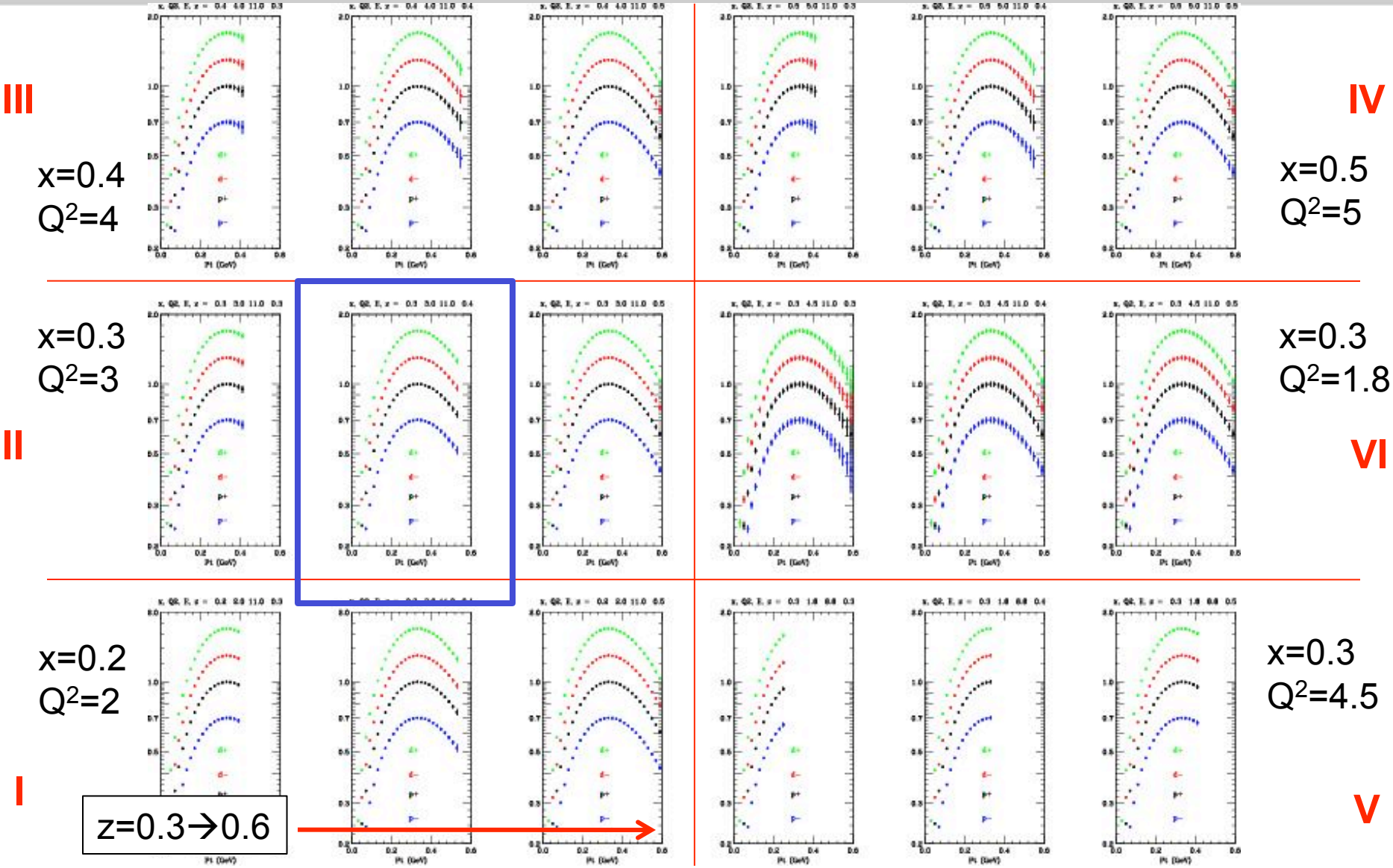
Can do meaningful measurements at low p_T (down to 0.05 GeV) due to excellent momentum and angle resolutions!

- Excellent ϕ coverage up to p_T = 0.2 GeV
- Sufficient ϕ coverage up to p_T = 0.4 GeV
- Limited ϕ coverage up to p_T = 0.5 GeV



*P_T ~ 0.5 GeV: use ϕ dependencies measured in CLAS12 experiments (E12-06-112, **LOI12-09-005**)*

E12-09-017 Kinematics



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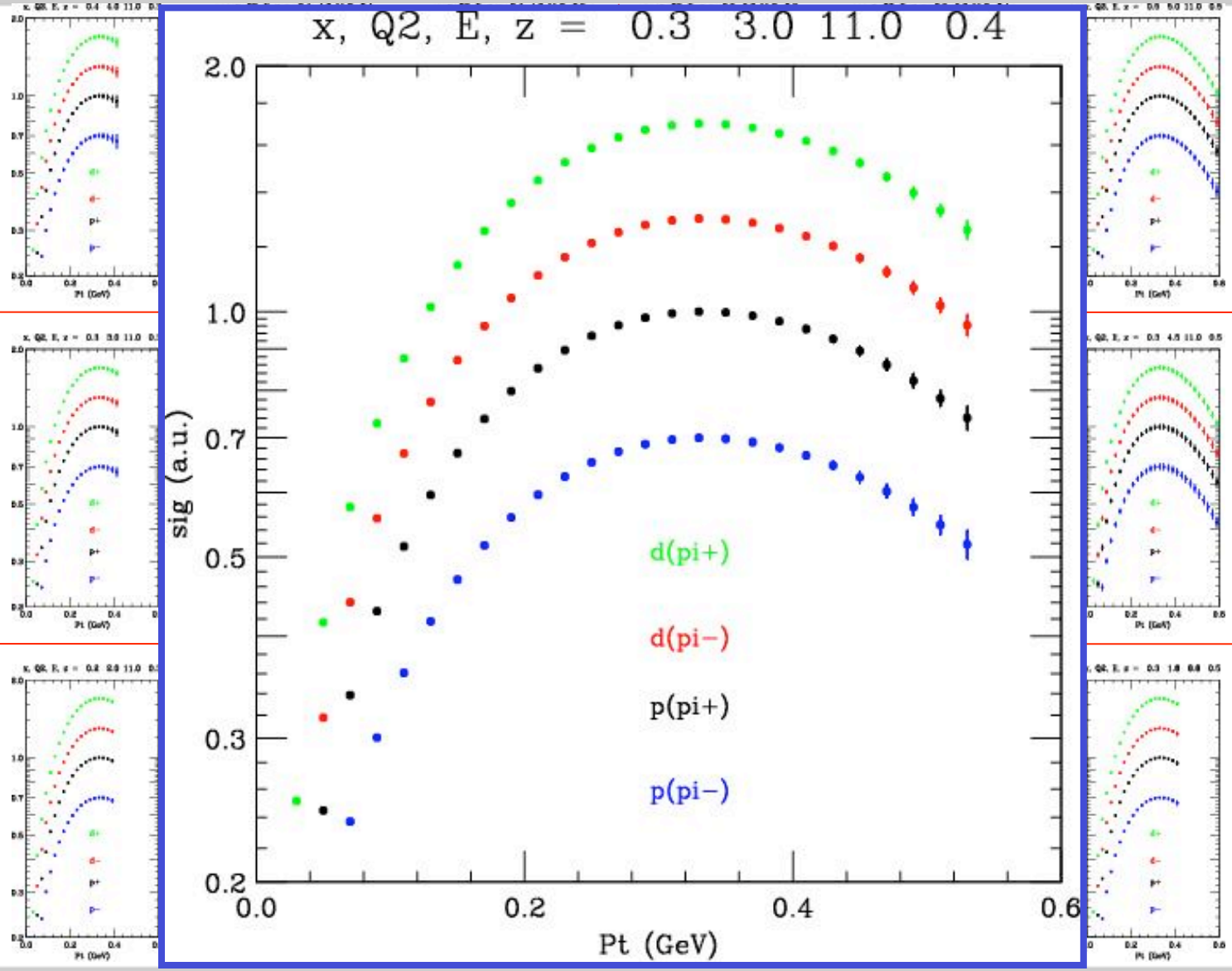


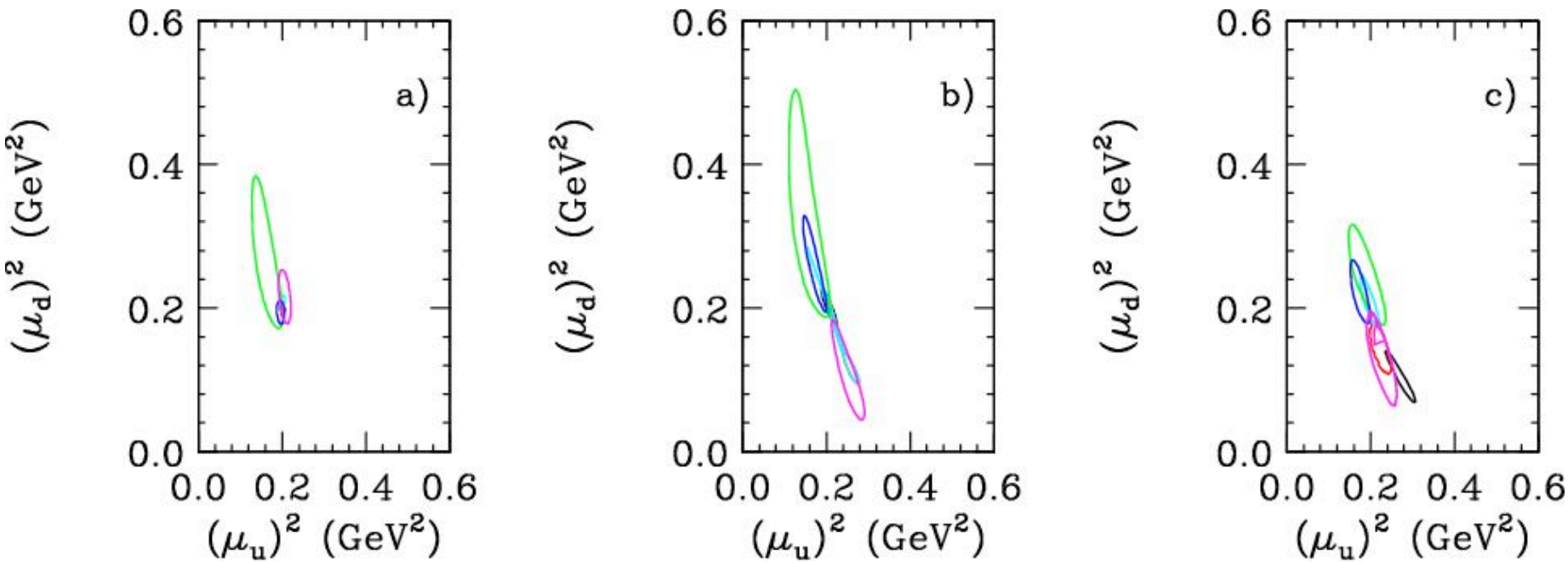
E12-09-017 Projected Results

Simulated data use $(\mu_u)^2 = (\mu_d)^2 = 0.2$, and then fit using statistical errors.

Step 1: Kinematics I-VI fitted separately, (p_T,ϕ) dependency ~ Cahn

Step 2: Add eight parameters to mimic possible HT, but assume Cahn
→ uncertainties grow with about factor of two

Step 3: Simulate with and without Cahn term
→ results remain similar as in step 2



Measurement of Charge Symmetry with SIDIS

Charge symmetry violating quark distributions can be measured using SIDS from an N=Z target *[Londergan, Pang and Thomas PRD54(1996)3154]*

2 key assumptions: factorization + impulse approximation

$$N^{Nh}(x,z) = \sum_q e_q^2 q^N(x) D_q^h(z)$$

$$N^{D\pi}(x,z) = N^{p\pi}(x,z) + N^{n\pi}(x,z)$$

$$R^D_{Meas}(x,z) = \frac{4N^{D\pi^-}(x,z) - N^{D\pi^+}(x,z)}{N^{D\pi^+}(x,z) - N^{D\pi^-}(x,z)}$$

D(z) R(x,z) + A(x) C(x) = B(x,z)

$$\frac{5}{2} + R^D_{Meas}(x,z)$$

$$\delta d(x) - \delta u(x)$$

$$\delta u(x) = u^p(x) - d^n(x)$$

$$\delta d(x) = d^p(x) - u^n(x)$$

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$$\mathbf{D(z)\ R(x,z) + A(x)\ C(x) = B(x,z)}$$

$$\frac{1-\Delta(z)}{1+\Delta(z)}$$

$$\Delta(z) = \frac{D_u^{\pi^-}(z)}{D_u^{\pi^+}(z)}$$

$$\frac{5}{2} + R^D_{Meas}(x,z)$$

$$\frac{-4}{3(u_v(x) + d_v(x))}$$

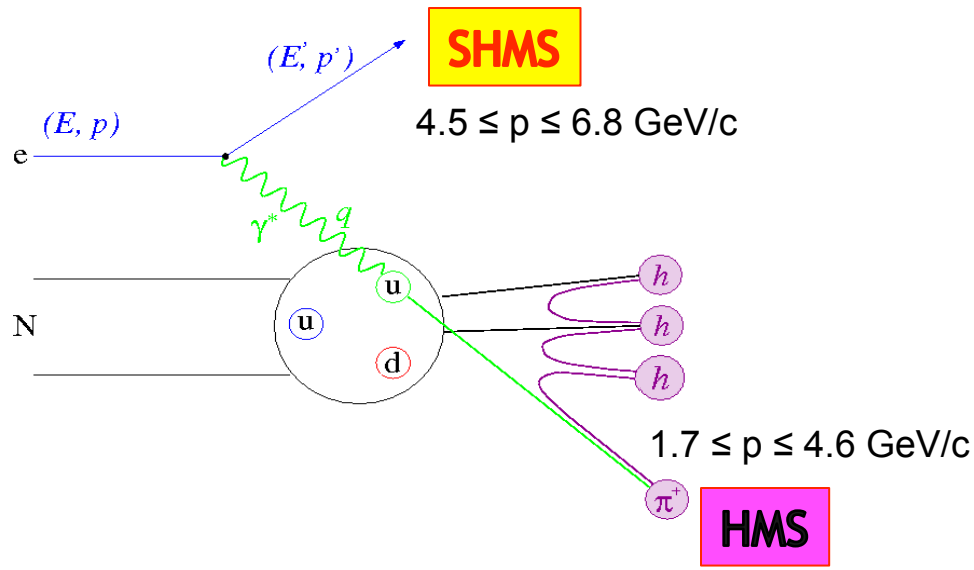
$$\delta d(x) - \delta u(x)$$

$$\frac{5}{2} + \frac{5\left[\bar{u}(x) + \bar{d}(x)\right]}{u_v(x) + d_v(x)} + \frac{\Delta_s(z)\left[s(x) + \bar{s}(x)\right]/\left[1+\Delta(z)\right]}{u_v(x) + d_v(x)}$$

E12-09-002: Precise measurement of D(e,e'π$^{+/-}$)X

$$R_Y(x,z) = \frac{Y^{D\pi^-}(x,z)}{Y^{D\pi^+}(x,z)}$$

$$R^D_{Meas}(x,z) = \frac{4R_Y(x,z)-1}{1-R_Y(x,z)}$$



Measure from *x=0.35* to *x=0.65*

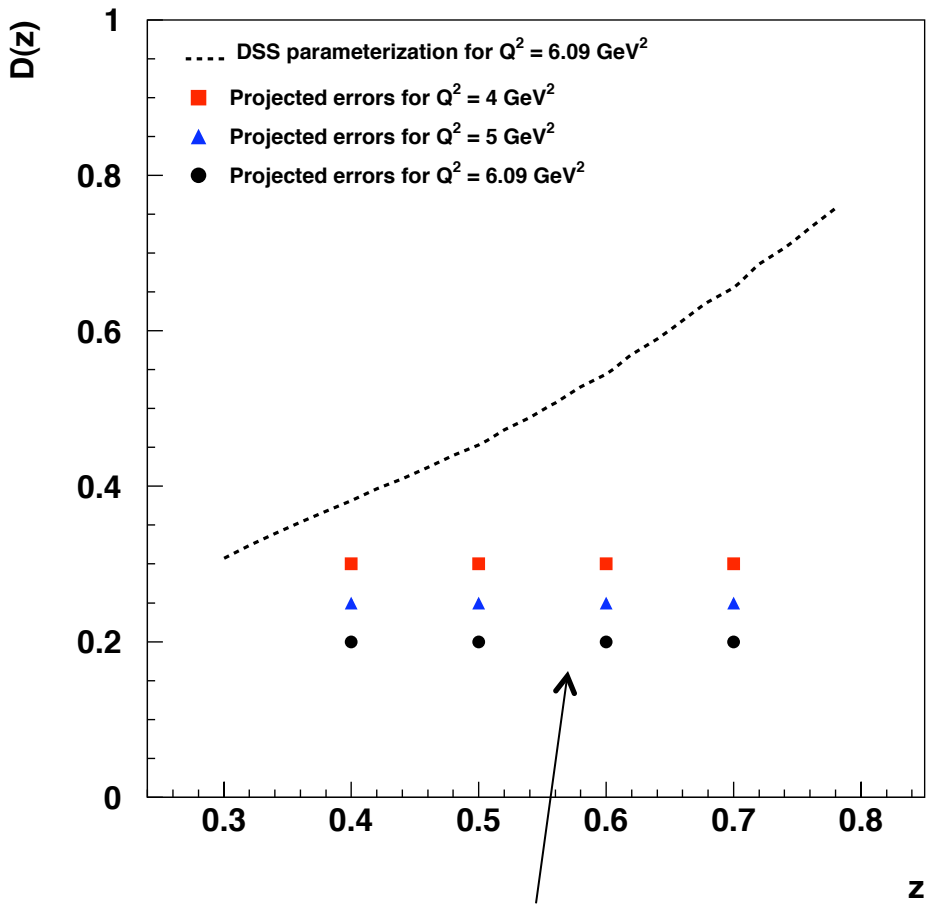
At each *x* setting → 4 *z* measurements (*z = 0.4, 0.5, 0.6, 0.7*)

Q^2 = *4* GeV^2	*x* = 0.35, 0.4, 0.45, 0.5
Q^2 = *5* GeV^2	*x* = 0.45, 0.5, 0.55, 0.6
Q^2 = *6.1* GeV^2	*x* = 0.5, 0.55, 0.6, 0.65

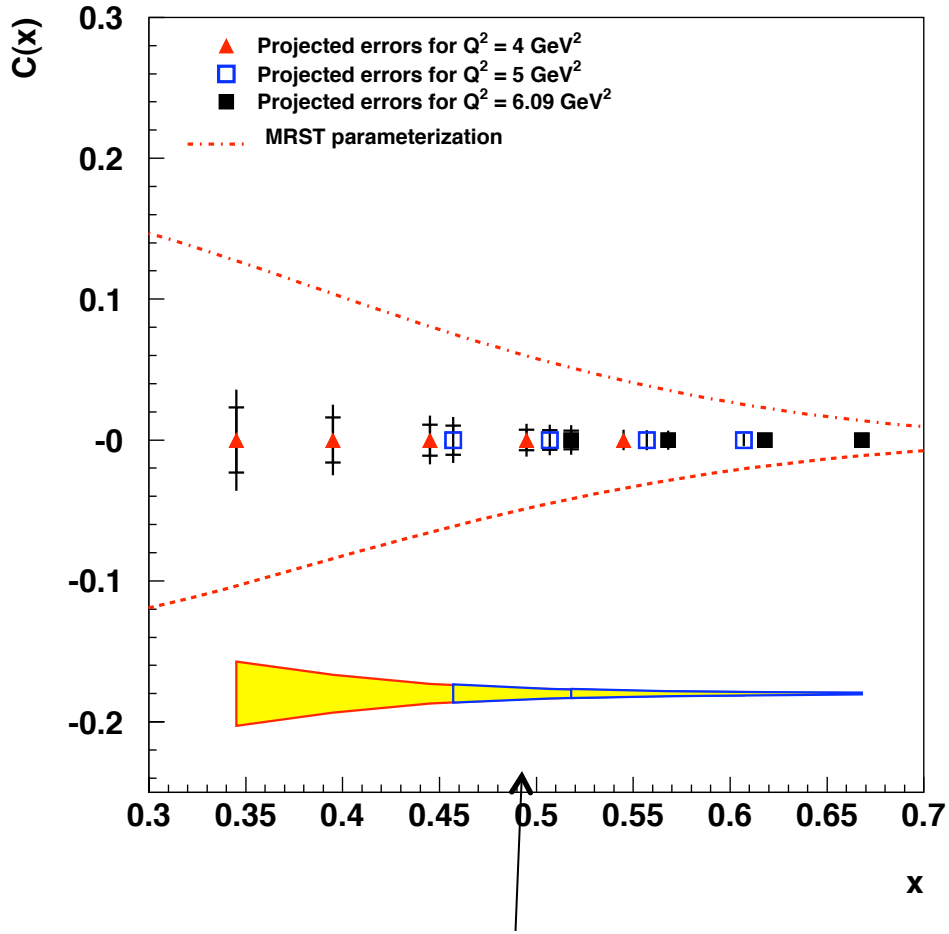
3 Q^2 measurements: for each Q^2 we have 16 equations and 8 unknowns: $D(z_i)$ and $C(x_i)$

$$D(z)\,R(x,z) + A(x)\,C(x) = B(x,z)$$

E12-09-002: Projected Results

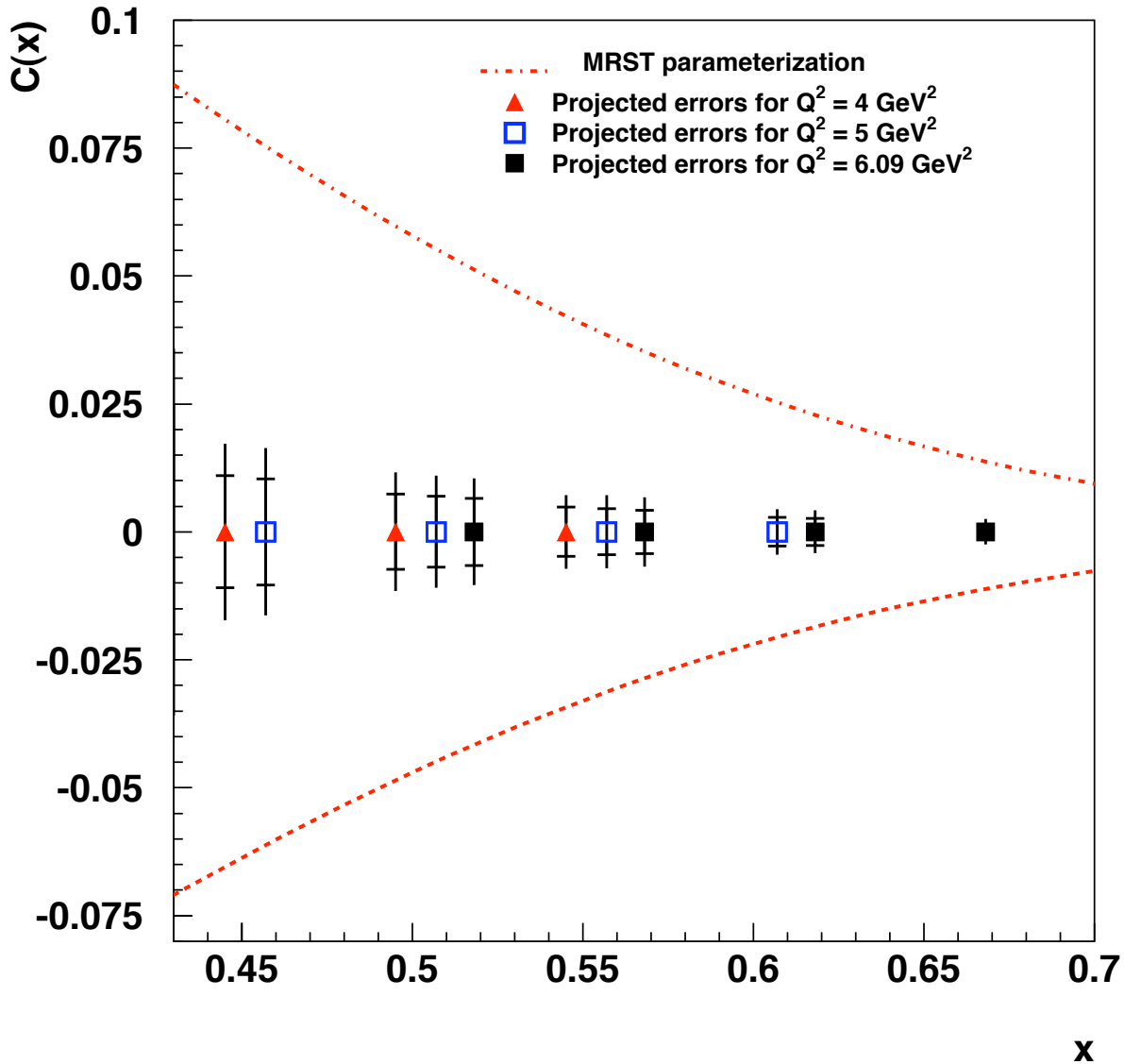


→ Linked to ratio of unfavored/ favored fragmentation functions



Charge symmetry violating term

E12-09-002: Projected Results



Summary

- Hall C will play a crucial role in the JLab 12 GeV SIDIS program
  - Focusing spectrometers provide information complementary to large acceptance devices in Halls B and A
- Key capabilities
  - Precise measurements of absolute cross sections
  - Excellent control of point-to-point systematic errors allow L-T separations
  - Identical acceptance for π^+ and π^- allows precise measurements of charge ratios
  - High luminosity → access to low-rate processes, low cross section "corners" of phase space
- Development of additional experiments still under way → nuclear dependence of charge ratios, R_{NUC} in SIDIS

Extra

JLab 12 GeV SIDIS Program

Hall A

E12-10-006: Target Single Spin Asymmetry in Semi-Inclusive Deep-Inelastic Electro Pion Production on a Transversely Polarized ^{3}He Target at 8.8 and 11 GeV

Hall B

E12-06-112: Probing the Proton's Quark Dynamics in Semi-Inclusive Pion Production at 12 GeV

E12-07-107: Probing the Proton's Quark Dynamics in Semi-Inclusive Pion Production at 12 GeV

E12-09-117: Studies of partonic distributions using semi-inclusive production of kaons

E12-09-118: Studies of the Boer-Mulders Asymmetry in Kaon Electroproduction with Hydrogen and Deuterium Targets

E12-09-009: Studies of Spin-Orbit Correlations in Kaon Electroproduction in DIS with polarized hydrogen and deuterium targets

Super-HMS

Properties:

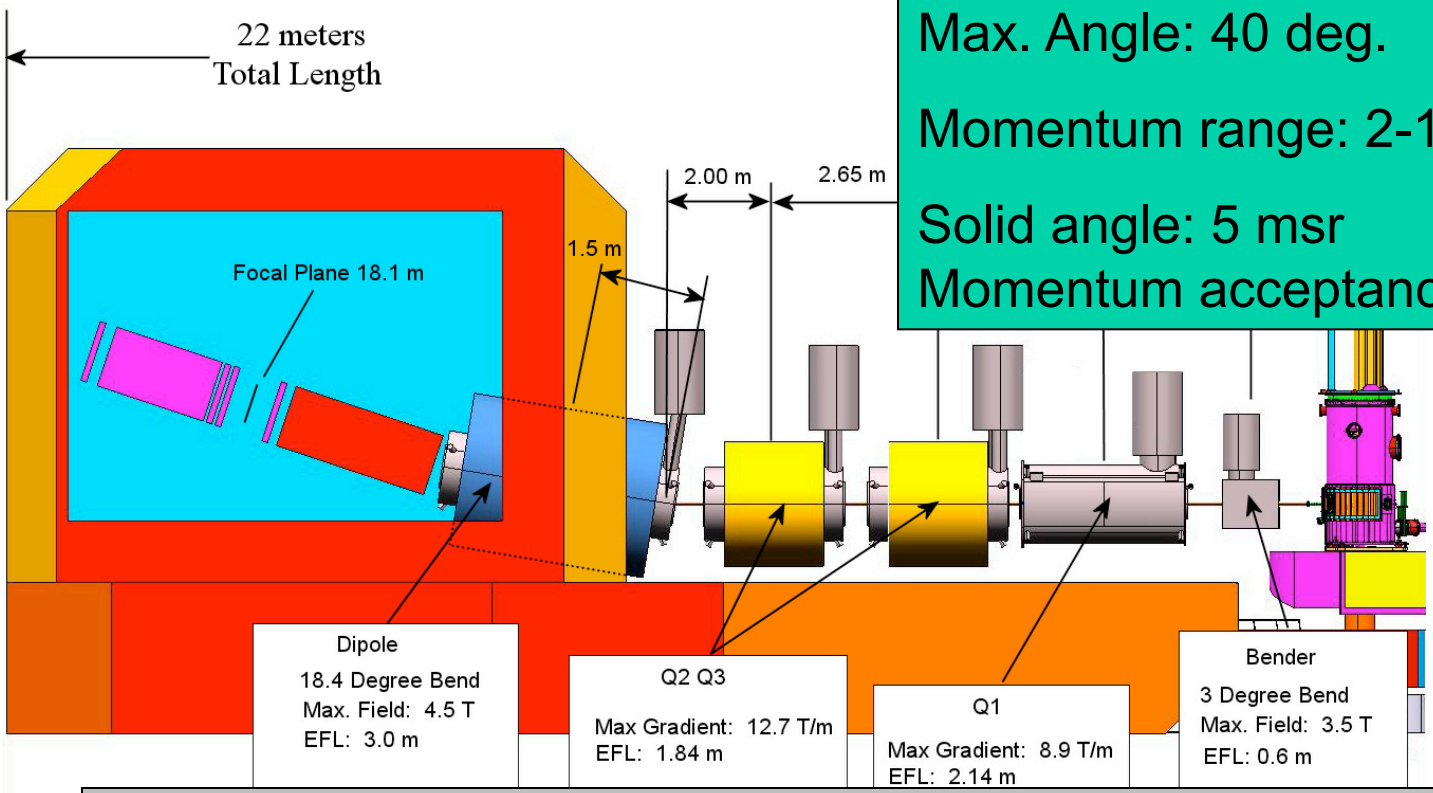
Min. Angle: 5.5 deg.

Max. Angle: 40 deg.

Momentum range: 2-11 GeV/c

Solid angle: 5 msr

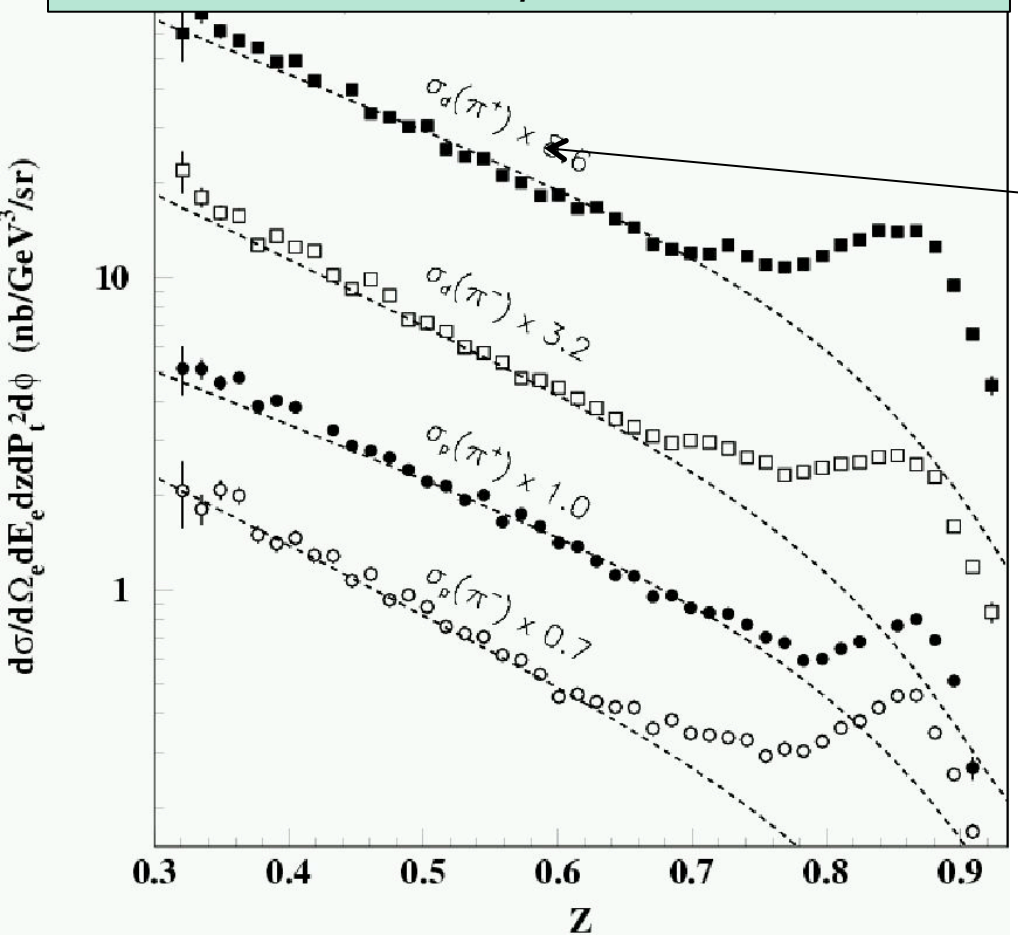
Momentum acceptance: -10%-+22%



Design modeled on HMS:
→Excellent control of acceptance and point-to-point systematics

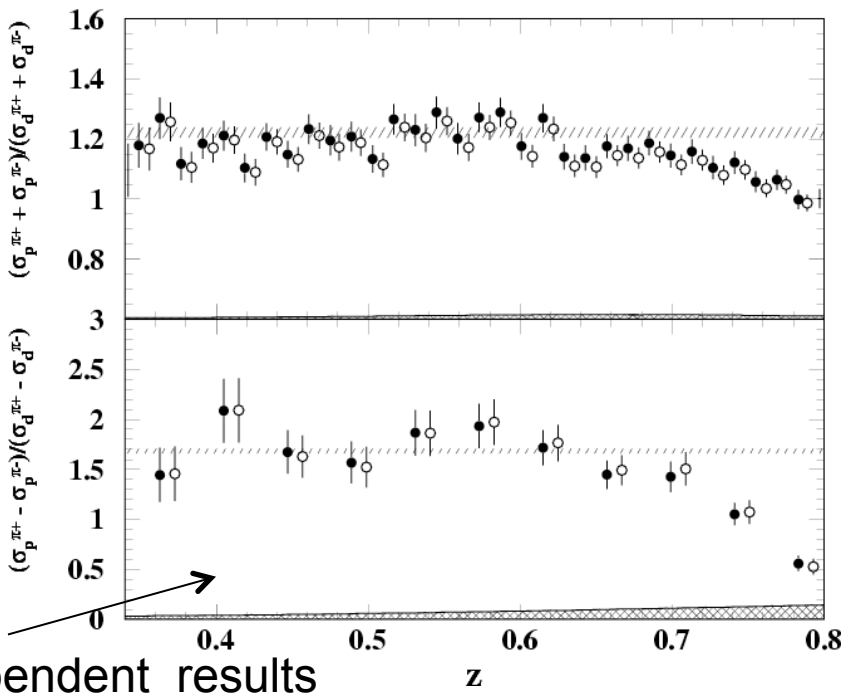
Unpolarized SIDIS in Hall C

Cross sections and ratios consistent with naïve factorization expectations



ep,d→e'$\pi^{+/-}$X in Hall C

Low energy semi-inclusive cross sections consistent with calculation using high energy params. of frag. functions and cteq PDFs (z<0.7)



Combinations of D/p,π^+/π^- yields give z-independent results