The Hall C SIDIS program towards understanding the transverse momentum dependence of valence quarks

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- Description of the Nucleon parton structure in 3D Momentum
- The question of factorization
- Precision $(e,e'\pi^{\pm})$,$(e,e'K^{\pm})$ cross sections at low $P_{h\perp}$
- Precision $(e,e'\pi^{0})$ cross sections at low $P_{h\perp}$
- L/T Separation of SIDIS $(e,e'\pi^{\pm})$ cross section

Exploring the 3D Momentum Structure of the Nucleon

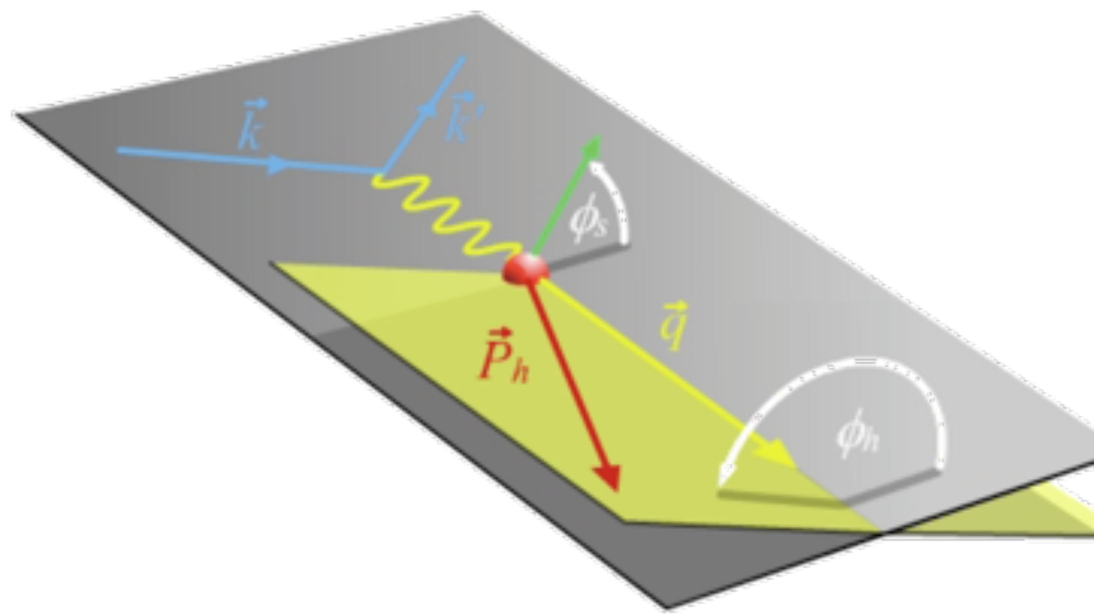
- After decades of study of the partonic structure of the nucleon we finally have the experimental and theoretical tools to move beyond a 1D momentum fraction (x_{Bj}) picture of the nucleon.
  - ✳ High luminosity, large acceptance experiments with polarized beams and targets
  - ✳ Theoretical description of the nucleon in terms of a 5D Wigner distribution that can be used to encode both 3D momentum and transverse spatial distributions
- SIDIS cross sections depend on transverse momentum of hadron, $P_{h\perp}$, but this arises from both intrinsic transverse momentum of parton and transverse momentum created during the fragmentation process.
  - ✳ Important to gain sufficient $P_{h\perp}$ data with different hadronic final states to allow momentum dependent fragmentation to be studied.

SIDIS Cross Section

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

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

Q^2 = Virtual Photon Mass
ε = Virtual Photon Polarization
λ = Long. Beam Polarization



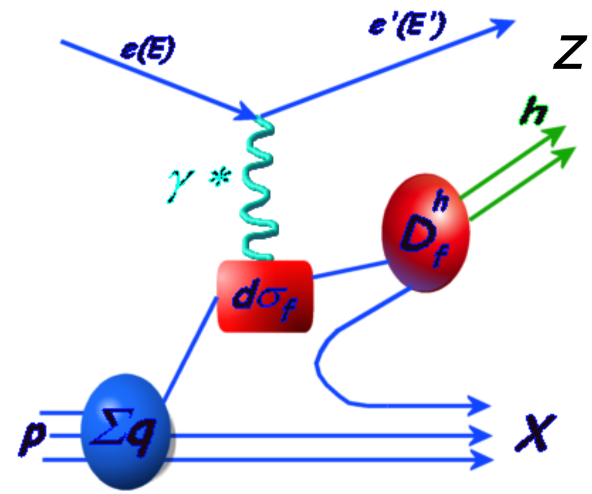
General formalism for (e,e'h) coincidence reaction w. polarized beam: [A. Bacchetta et al., JHEP 0702 (2007) 093]

(Ψ = azimuthal angle of e' around the electron beam axis w.r.t. an arbitrary fixed direction)

Do parton distributions and fragmentation functions factorize at Jefferson Lab energies?

Flavor Decomposition of SIDIS

$$\frac{1}{\sigma_{(e,e')}}\frac{d\sigma}{dz}(ep \rightarrow hX) = \frac{\sum_q e_q^2 f_q(x) D_q^h(z)}{\sum_q e_q^2(x) f_q(x)}$$



$z = E_h/\nu$

$f_q(x)$: parton distribution function

$D_q^h(z)$: fragmentation function

$$M_x^2 = W'^2 \sim M^2 + Q^2\,(1/x - 1)(1 - z)$$

- Leading-Order (LO) QCD
- after integration over $p_{h\perp}$ and ϕ_h
- NLO: gluon radiation mixes x and z dependences
- Target-Mass corrections at large z
- ln(1-z) corrections at large z

Brief Overview of SIDIS Program at Jefferson Lab

- Hall B
  - ➡ CLAS12 with good acceptance for precise determination of azimuthal distributions
  - ➡ Broad program of measurements including polarization, and investigation of target fragmentation region
- Hall A
  - ➡ Pol. ^{3}He targets for neutron TMDs (SOLID & BB+SBS)
- Hall C
  - ➡ High luminosity for precise measurement of kinematic dependences: testing the validity of flavor decomposition framework at 11 GeV kinematics with R and cross sections

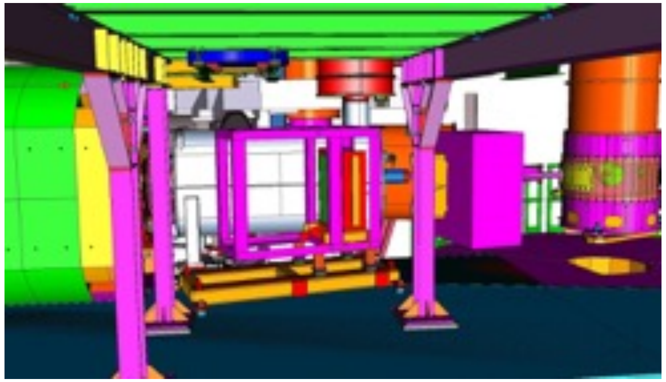
Precision SIDIS in Hall C

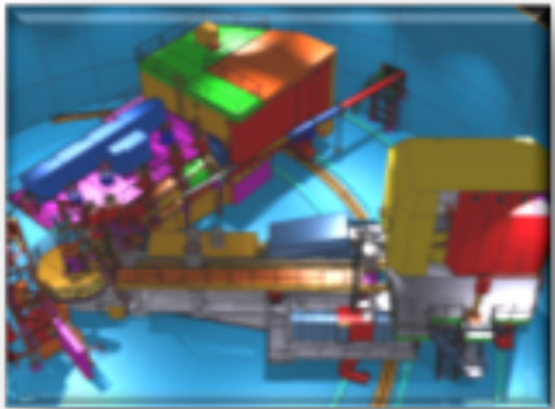
- Using magnetic spectrometers one can explore the highest luminosities! Hall C has SHMS and HMS.
- Common pivot allows most precise L/T separations
- New Neutral Particle Spectrometer adds π^0 capability with good acceptance

➡Precise cross sections/ratios for (e,e' $\pi^{\pm}$) and (e,e' $\pi^{0)}$ measurements at DIS kinematics

➡New cross sections/ratios for (e,e' $K^{\pm}$)

➡First direct determination of L/T ratio for SIDIS cross sections!



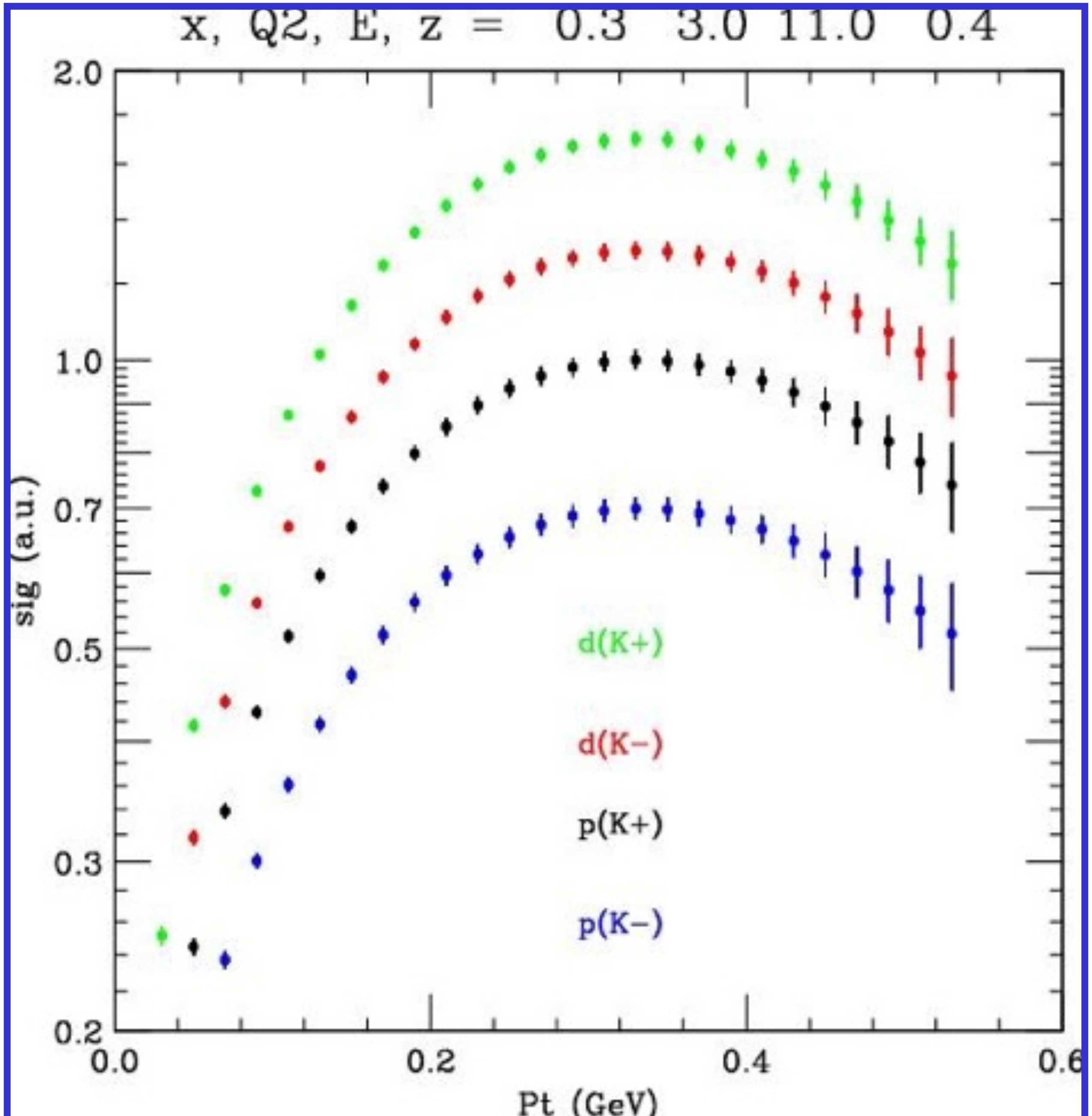


Precision $(e,e'\pi^{\pm})$,$(e,e'K^{\pm})$ cross sections at low $P_{h\perp}$

- Precision measurements to test the assumptions in factorization of SIDIS
- Explore assumptions of favored/disfavored fragmentation of different flavor quarks
- Look for target mass effects
- Higher twist effect
- Complementary to Hall B SIDIS measurements

Experiment E12-09-017

Example of Expected Charged Kaon Precision



Precision $(e,e'\pi^0)$ cross sections at low $P_{h\perp}$

- Neutral pions are a good test and consistency check of flavor assumptions in extraction of TMDs with TM fragmentation
- Experimental measurement cleaner in terms of ρ (vector meson) contamination, exclusive pole contributions and hadron EM radiation effects
- Combined with charged pion/kaon data provides important constraint for analyzing future SIDIS experiments and TMD extraction

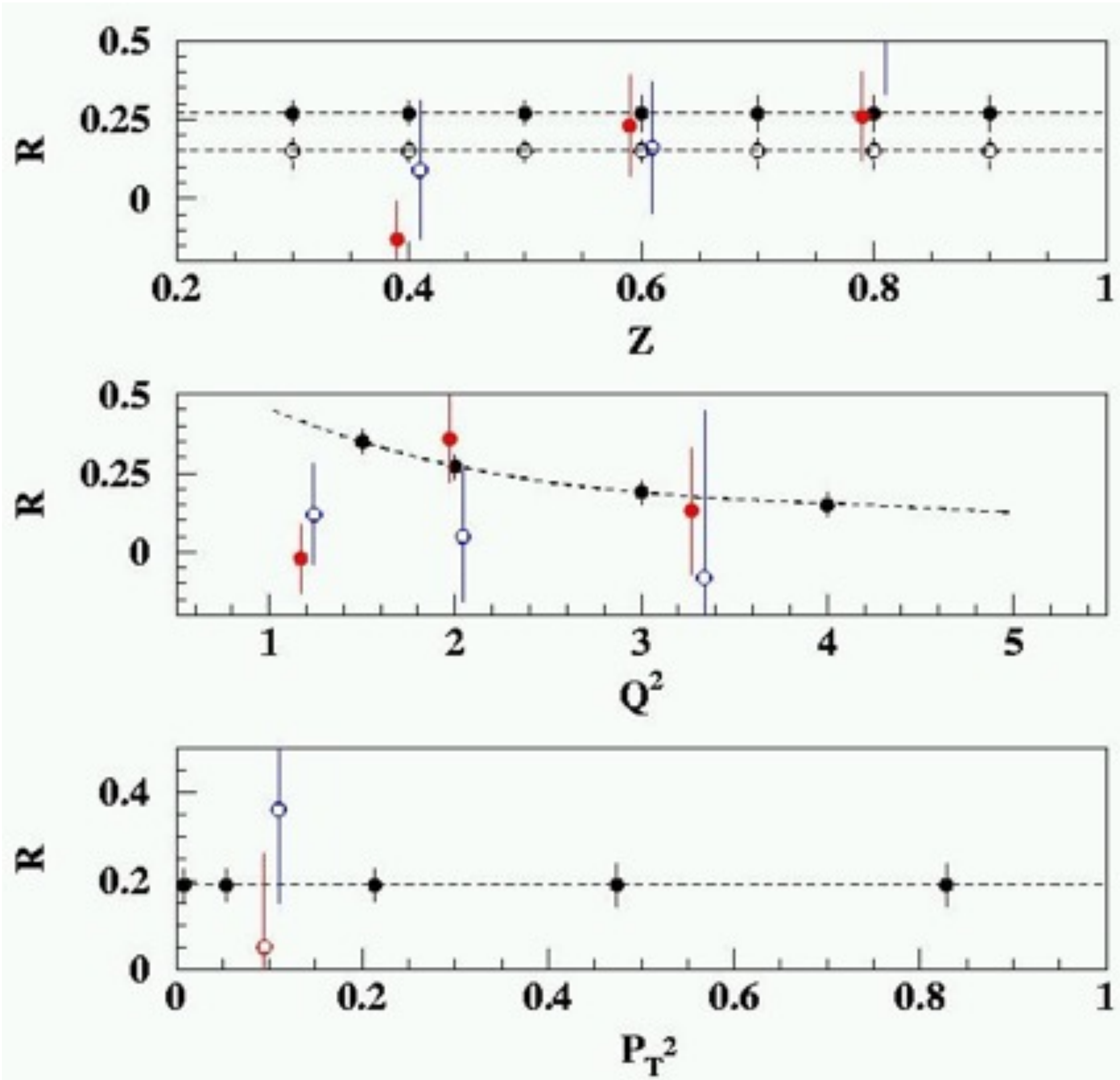
Experiment E12-13-007

L/T Separation of SIDIS $(e,e'\pi^{\pm})$ cross section

- All SIDIS flavor analyses assume a value of $R_{SIDIS} = \sigma_L/\sigma_T$ as it has never been measured!
- Common assumption is $R_{SIDIS} = R_{DIS}$
- How does R_{SIDIS} depend on z?
- How does R_{SIDIS} depend on $P_{h\perp}$?
- Do we understand Q^2 dependence in SIDIS and in Exclusive $(z \rightarrow 1)$ regimes?
- Hall C spectrometers ideal for precise R measurement

Experiment E12-06-104

Expected R = σ_L/σ_T Results



Planned scans in z at $Q^2 = 2.0$ (x = 0.2) and 4.0 GeV^2 (x = 0.4) → should settle the behavior of σ_L/σ_T for large z.

Planned data cover range $Q^2 = 1.5 – 5.0\ GeV^2$, with data for both H and D at $Q^2 = 2\ GeV^2$

Planned data cover range in P_T up to ~ 1 GeV.
The coverage in ϕ is excellent (o.k.) up to $P_T = 0.2$ (0.4) GeV.

Solid black points are simulation results; colored points are from 70's experiments at Cornell.

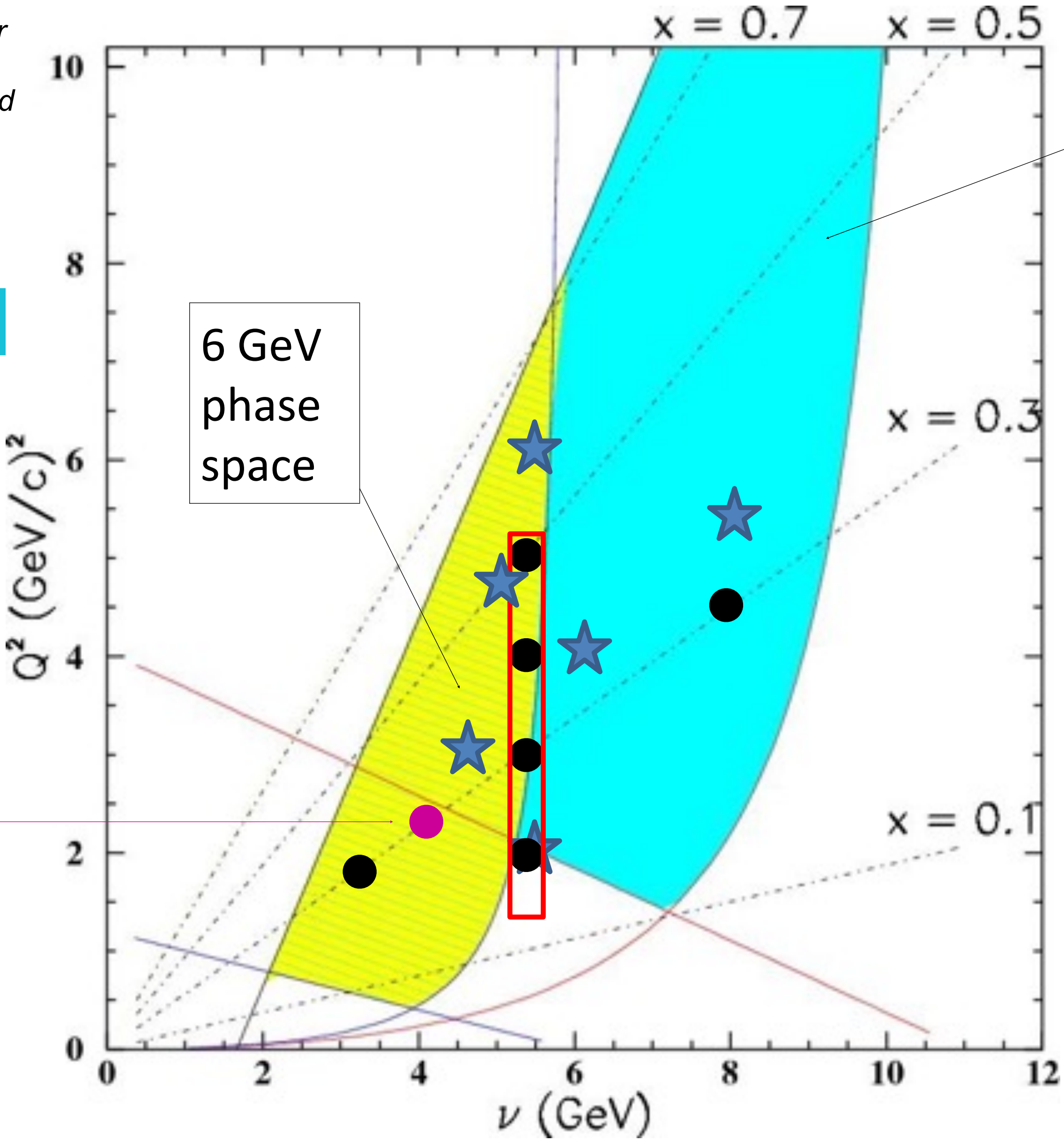
Hall C Kinematic Reach

HMS + SHMS (or NPS) Accessible Phase Space for SIDIS

Accurate cross sections for validation of SIDIS factorization framework and for L/T separations

E12-13-007
Neutral pions:
Scan in (x,z,P_T)
Overlap with E12-09-017

E00-108
(6 GeV)



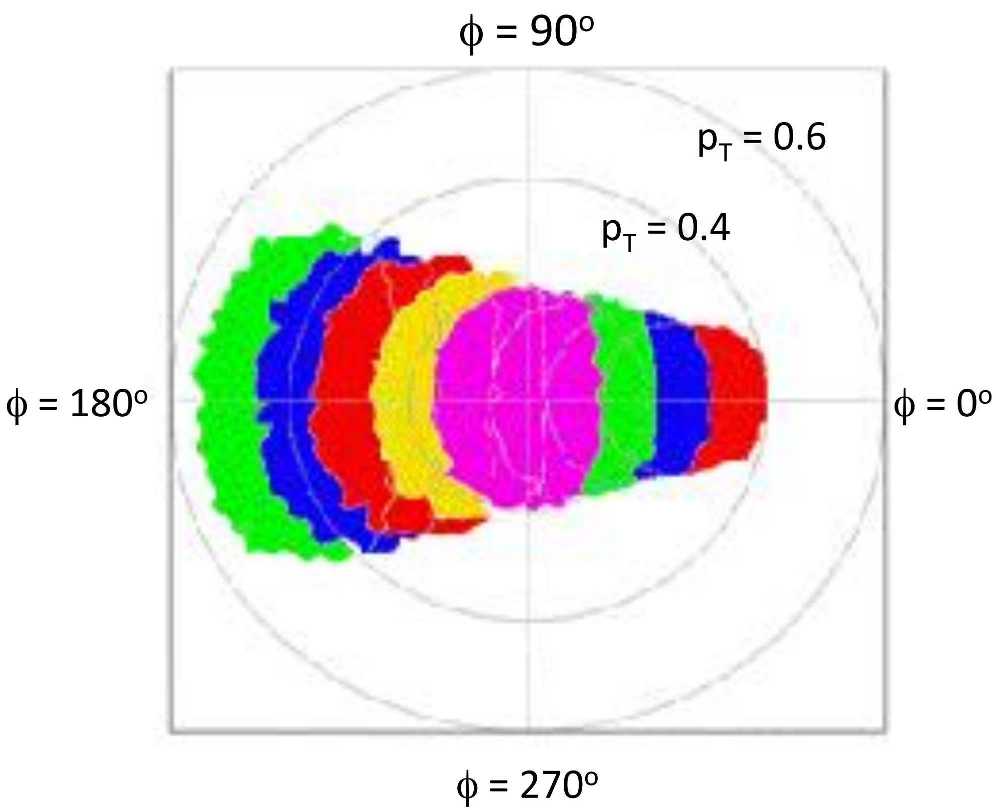
Charged pions:

E12-06-104
L/T scan in (z,P_T)
No scan in Q^2 at fixed x: $R_{DIS}(Q^2)$ known

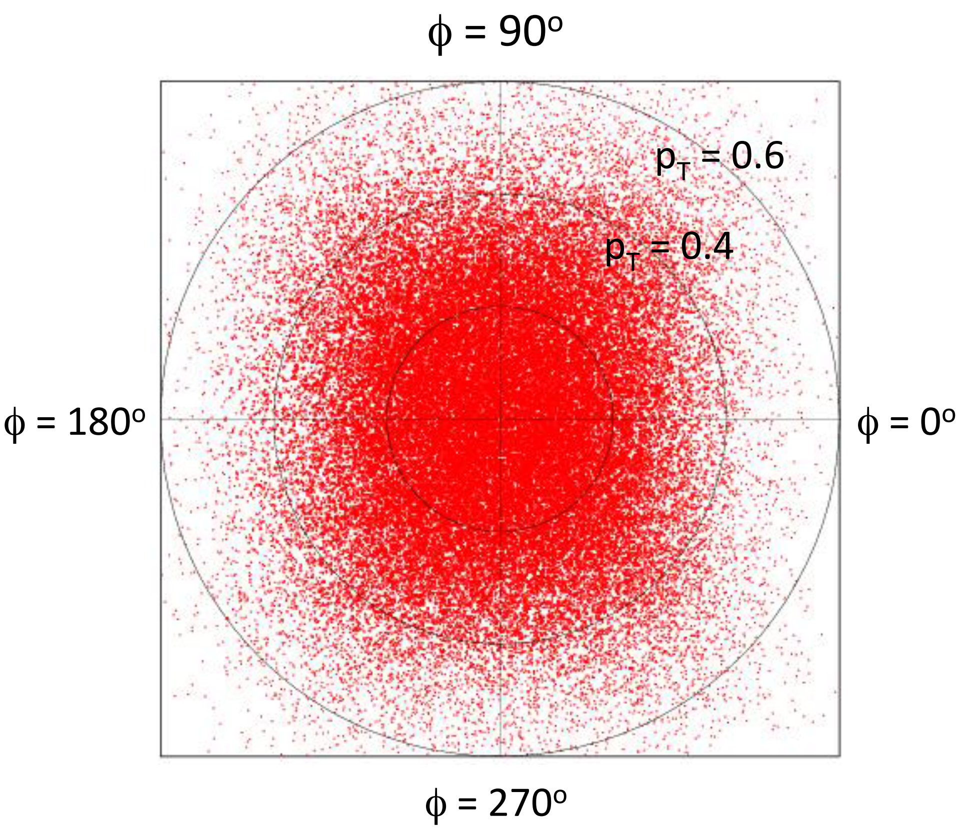
E12-09-017
Scan in (x,z,P_T)
+ scan in Q^2 at fixed x

$P_{h\perp}$ Coverage of SIDIS experiments

$(e,e'\pi^0)$ with SHMS
E12-09-017



$(e,e'\pi^0)$ with NPS
E12-13-007



Timescales

- Charge pion measurements in late 2016/early 2017
- Neutral pion measurements as soon as 2019
- R measurements to be scheduled after first commissioning Hall C measurements are analyzed in order to obtain the best accuracy

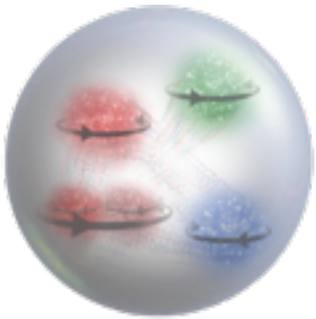
Summary

- Broad program at Jefferson Lab to determine the flavored partonic 3D momentum and spatial structure of the nucleon

- Important to verify the theoretical framework in this kinematic region with precise experimental determination of dependences on hadron momentum in SIDIS

- E12-09-017, E12-13-007, and E12-06-104 will provide SIDIS data to make these tests and explore new territory with (e,e'π^0) and R_{SIDIS} measurements

Features of partonic 3D non-perturbative distributions



$$f^a(x, k_T^2; Q^2)$$

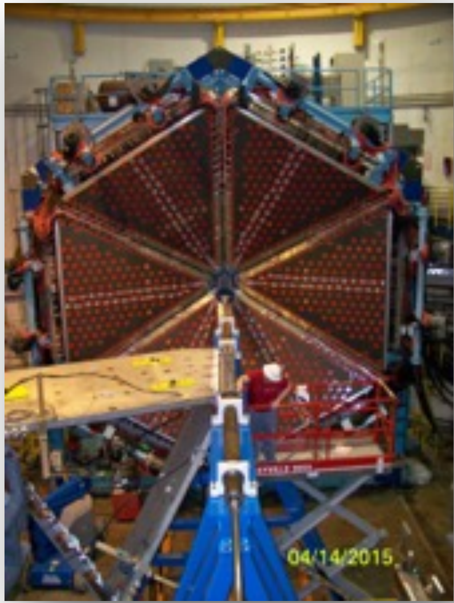
Ex. TMD PDF for a given combination of parton and nucleon spins

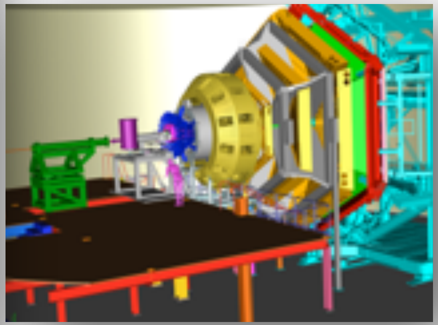
nucleon polarization \ quark polarization	U	L	T
U	f_1		$h_1^\perp$ Boer-Mulders
L		g_1 helicity	$h_{1L}^\perp$ worm-gear
T	$f_{1T}^\perp$ Sivers	g_{1T} worm-gear	h_1 transversity, $h_{1T}^\perp$ pretzelosity

- transverse position and momentum of partons are correlated with the spin orientations of the parent hadron and the spin of the parton itself
- transverse position and momentum of partons depend on their flavor
- transverse position and momentum of partons are correlated with their longitudinal momentum
- spin and momentum of struck quarks are correlated with remnant
- quark-gluon interaction play a crucial role in kinematical distributions of final state hadrons, both in semi-inclusive and exclusive processes

12 GeV Scientific Capabilities

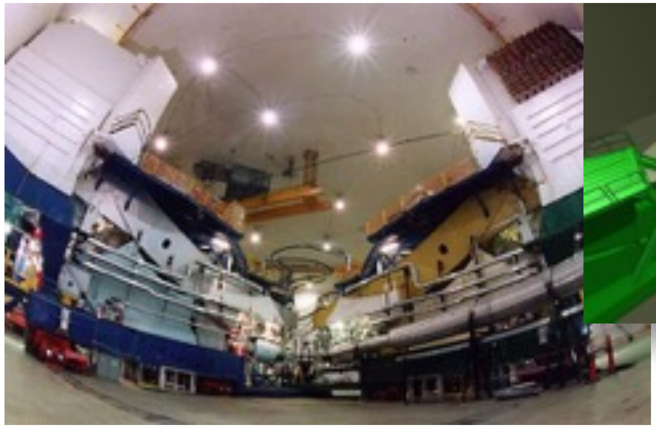
Hall B **– understanding nucleon structure via generalized parton distributions**

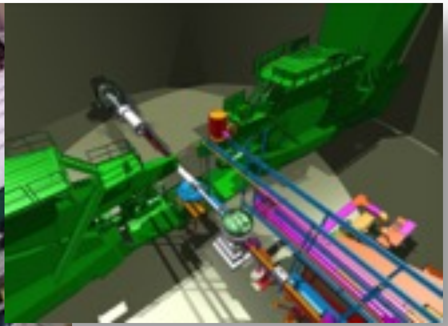




Hall D **– exploring origin of confinement by studying exotic mesons**

Hall A **– form factors, future new experiments (e.g., SoLID and MOLLER)**





Hall C **– precision determination of valence quark properties in nucleons/nuclei**