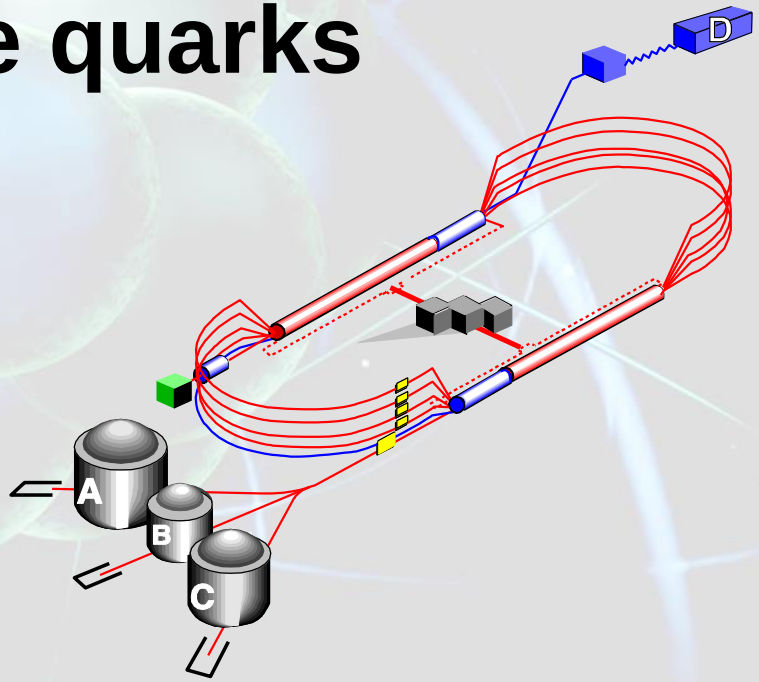
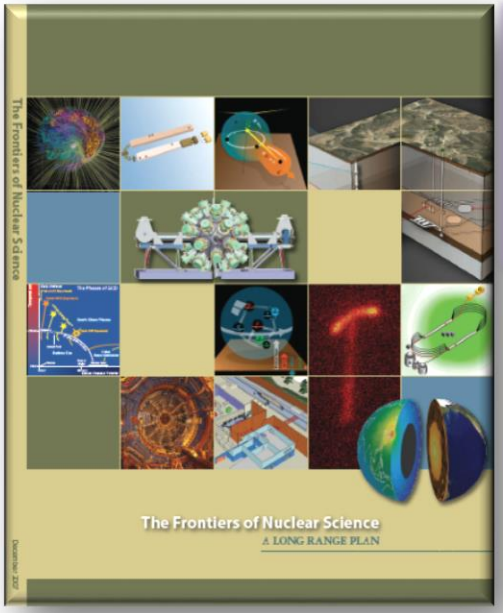
The Halls B and C semi-inclusive deep inelastic scattering program towards the transverse momentum dependence of valence quarks

Rolf Ent
Jefferson Lab



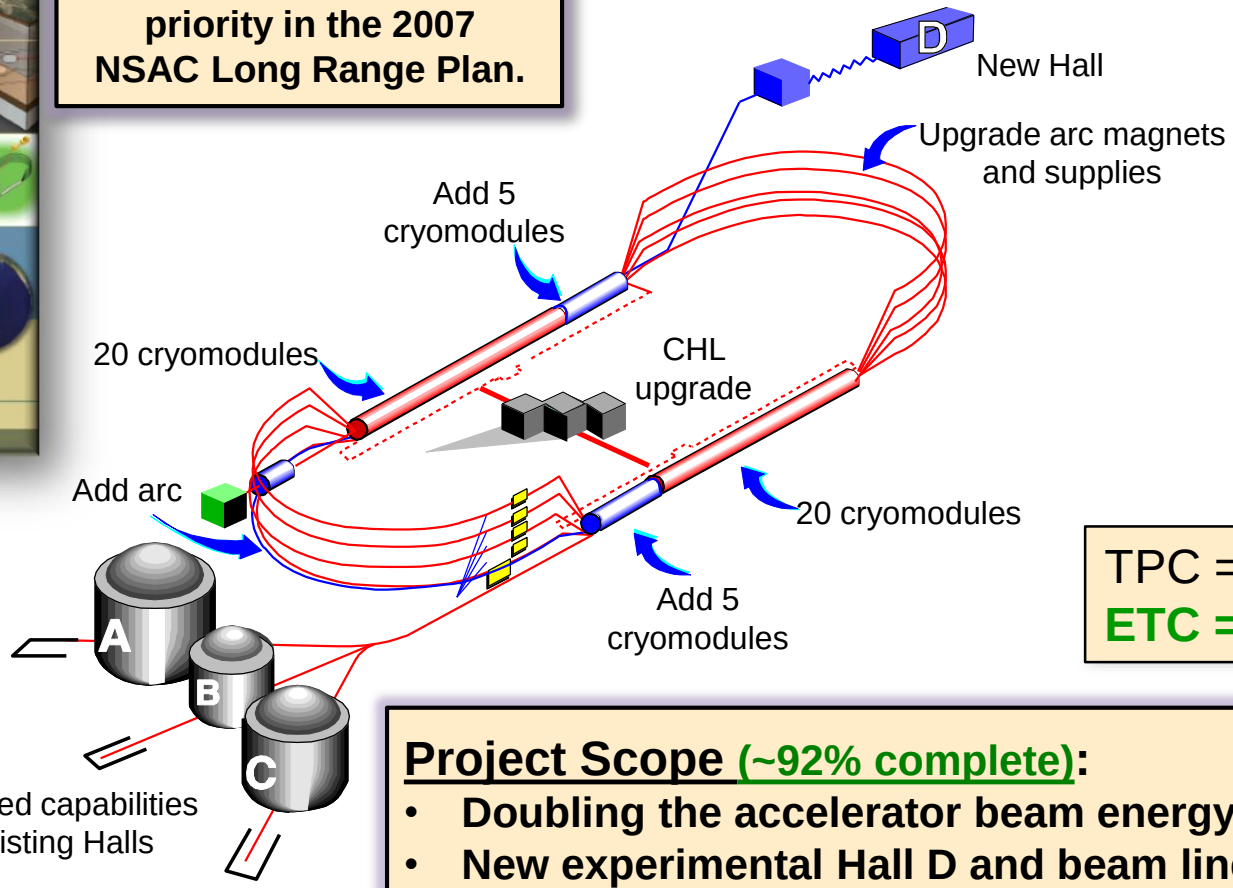
DIS2015, Southern Methodist University, Dallas
April 27- May 2, 2015

12 GeV Upgrade Project



Completion of the 12 GeV CEBAF Upgrade was ranked the highest priority in the 2007 NSAC Long Range Plan.

Upgrade is designed to build on existing facility: vast majority of accelerator and experimental equipment have continued use.



TPC = $338M
ETC = ~$26M

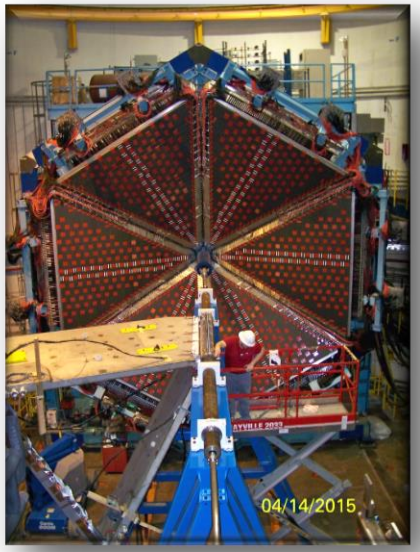
Maintain capability to deliver lower pass beam energies: 2.2, 4.4, 6.6….

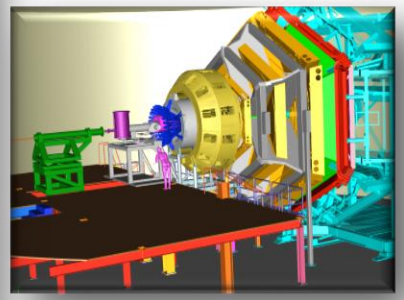
Project Scope (~92% complete):

- **Doubling the accelerator beam energy - DONE**
- **New experimental Hall D and beam line - DONE**
- **Civil construction including Utilities - ~97%**
- **Upgrades to Experimental Halls B & C - ~80%**

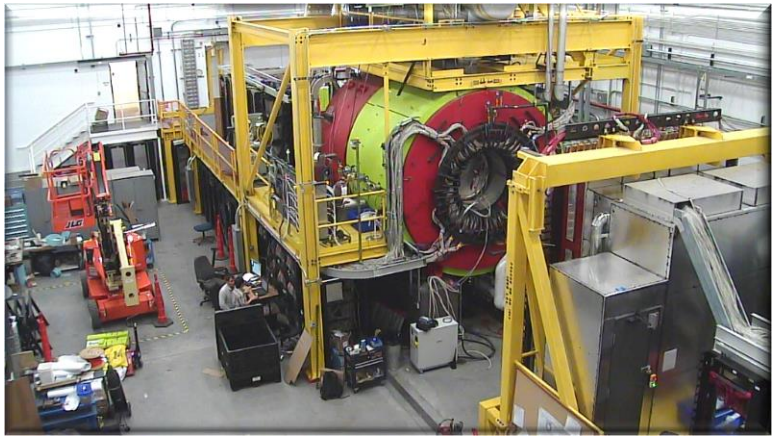
12 GeV Scientific Capabilities

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

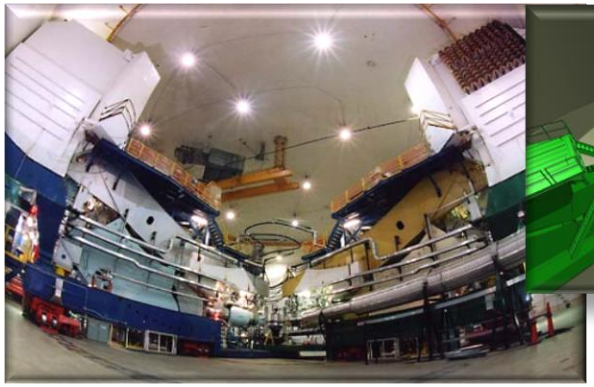


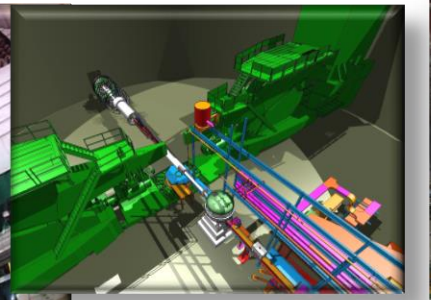


Hall D **– exploring origin of confinement by studying exotic mesons**

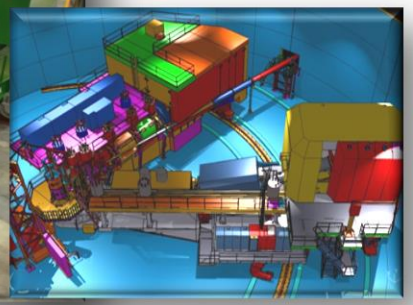


Hall A **– form factors, future new experiments (e.g., SoLID and MOLLER)**



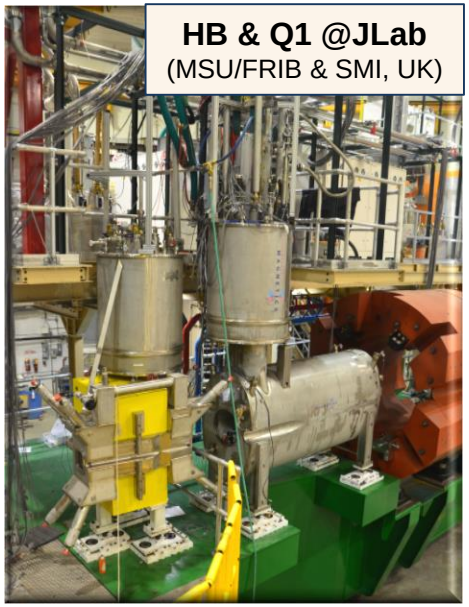


Hall C **– precision determination of valence quark properties in nucleons/nuclei**

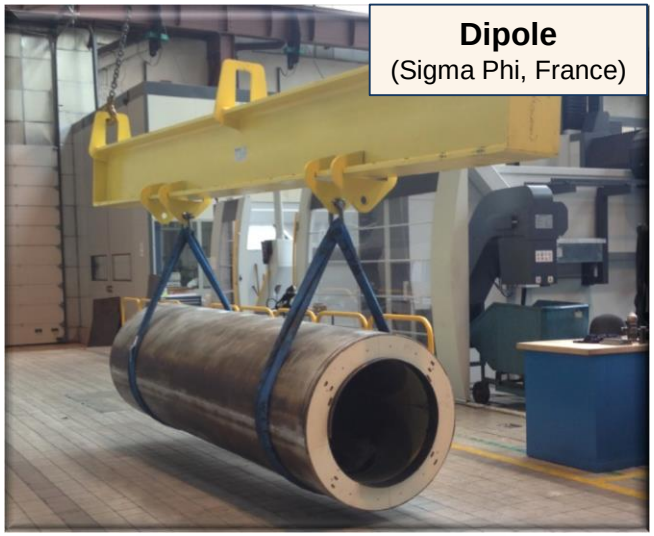


12 GeV Upgrade: Halls B and C

Hall C

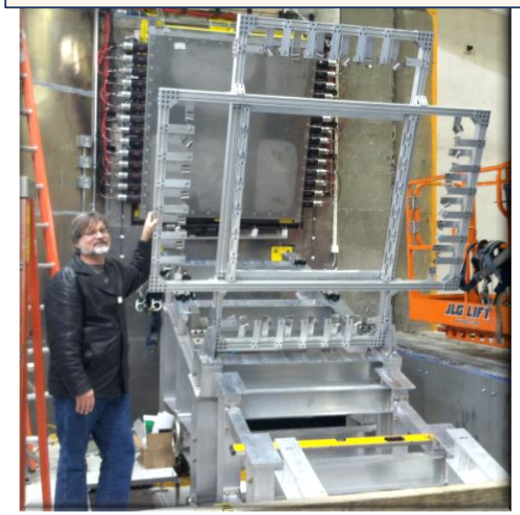


HB & Q1 @JLab
(MSU/FRIB & SMI, UK)

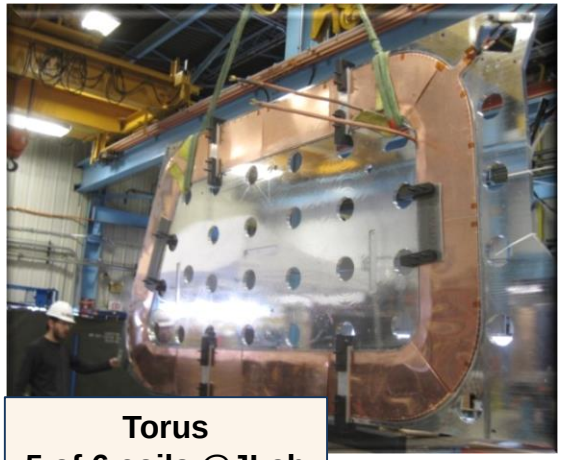


Dipole
(Sigma Phi, France)

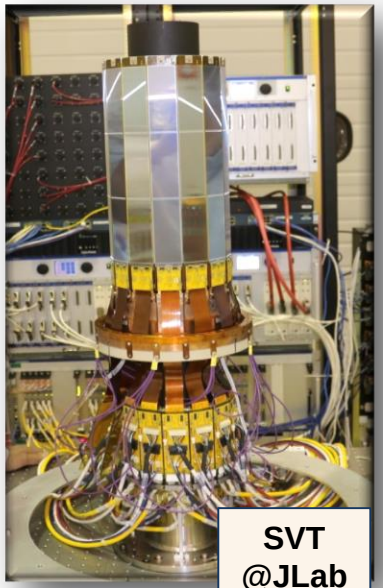
Pre-shower & shower counters and detector stands installed



Hall B



Torus
5 of 6 coils @JLab
(FNAL)



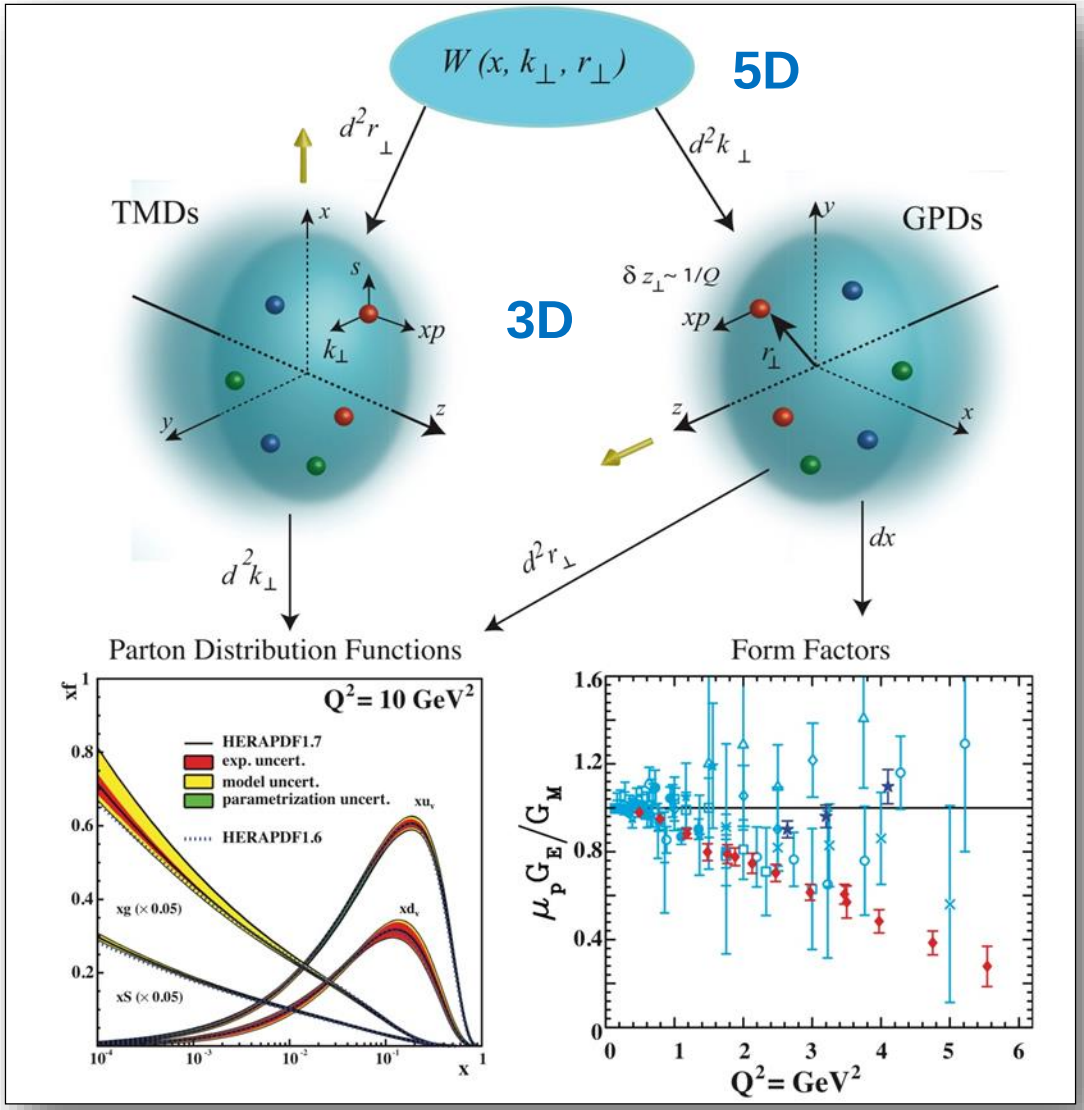
SVT
@JLab

HTCC
@JLab

JLab: 21st Century Science Questions

- What is the role of gluonic excitations in the spectroscopy of light mesons? Can these excitations elucidate the origin of quark confinement?
- Where is the missing spin in the nucleon? Is there a significant contribution from valence quark orbital angular momentum?
- Can we reveal a novel landscape of nucleon substructure through measurements of new multidimensional distribution functions?
- What is the relation between short-range N-N correlations , the partonic structure of nuclei, and the nature of the nuclear force?
- Can we discover evidence for physics beyond the standard model of particle physics?

New Paradigm for Nucleon Structure



- TMDs
  - Confined motion in a nucleon (semi-inclusive DIS)
- GPDs
  - Spatial imaging (exclusive DIS)
- Requires
  - High luminosity
  - Polarized beams and targets

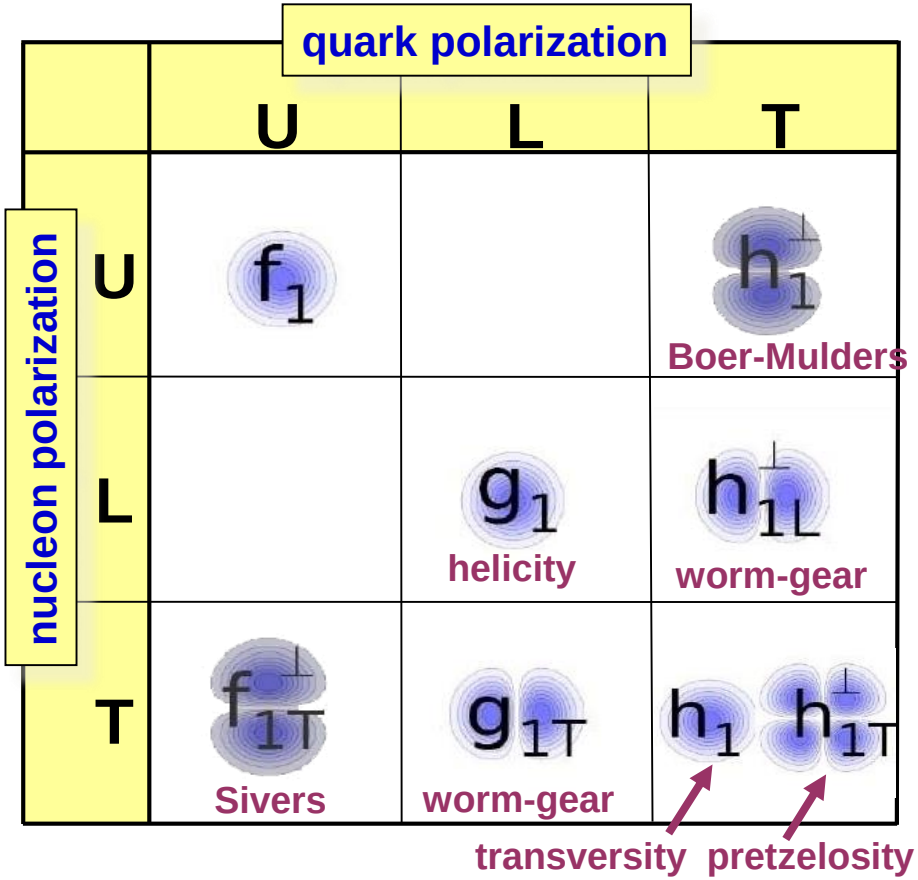
Major new capability with JLab12

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

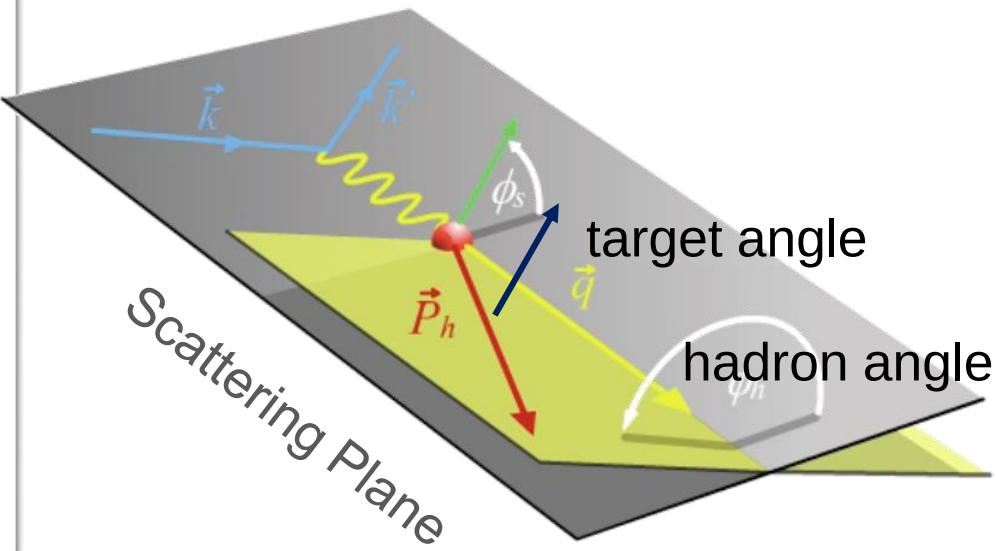
Understanding of the 3D structure of nucleon requires studies of spin and flavor dependence of quark transverse momentum and space distributions



- 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

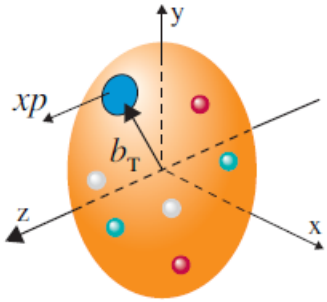
TMDs Accessible through Semi-Inclusive Physics

- Separate Sivers and Collins effects



Naturally, two scales:
- High Q: localized probe to "see" quarks and gluons
- Low P_T: sensitive to confining scale to "see" their confined motion

+ Theory input: TMD QCD factorization
TMD QCD evolution

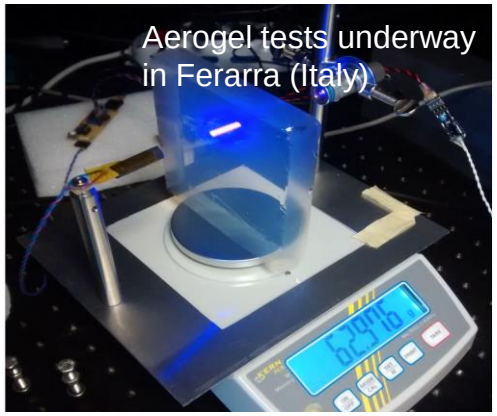


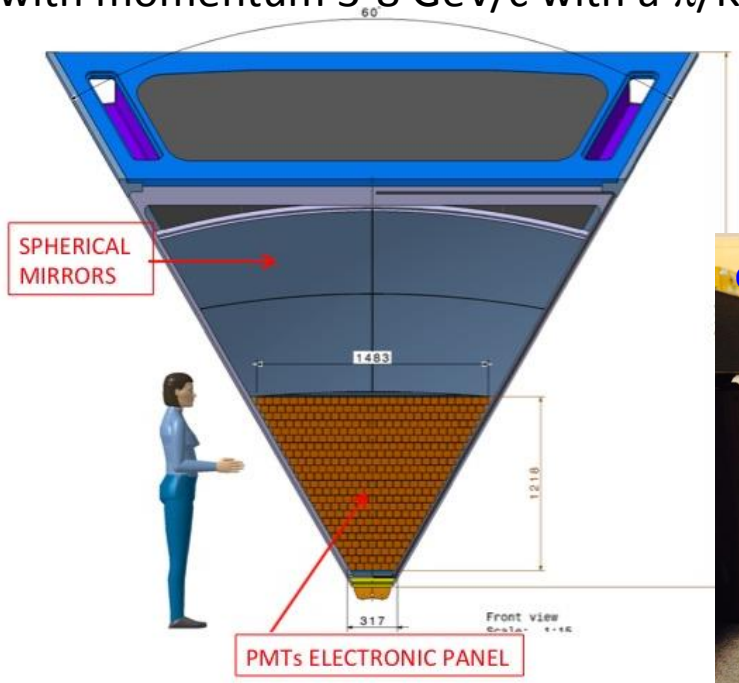
- **Sivers** angle, effect in distribution function: $(\phi_h - \phi_s)$

  Or other combinations: Pretzelosity: $(3\phi_h - \phi_s)$
- **Collins** angle, effect in fragmentation function: $(\phi_h + \phi_s)$
- *Kaons enabled by Hall B RICH (INFN/DOE) and Hall C Aerogel (NSF)*

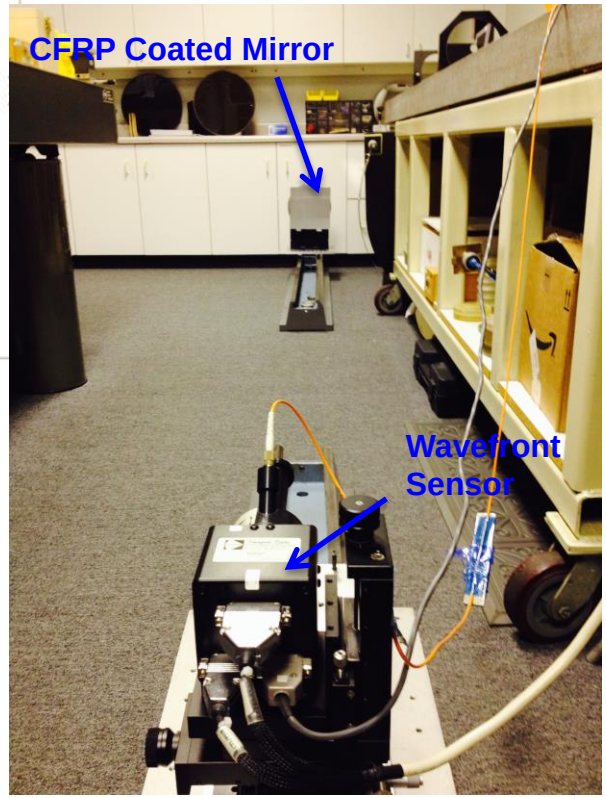
CLAS12 – Ring Imaging Cherenkov

- Two (of six) sectors: INFN-led project with funds from INFN, JLab/DOE, Chile
- ID of kaons vs π and p with momentum 3-8 GeV/c with a π/K rejection factor 1:500



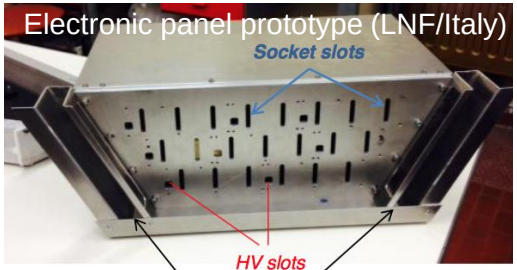


Optical test of the spherical mirror prototype at the CMA (Tucson-USA)



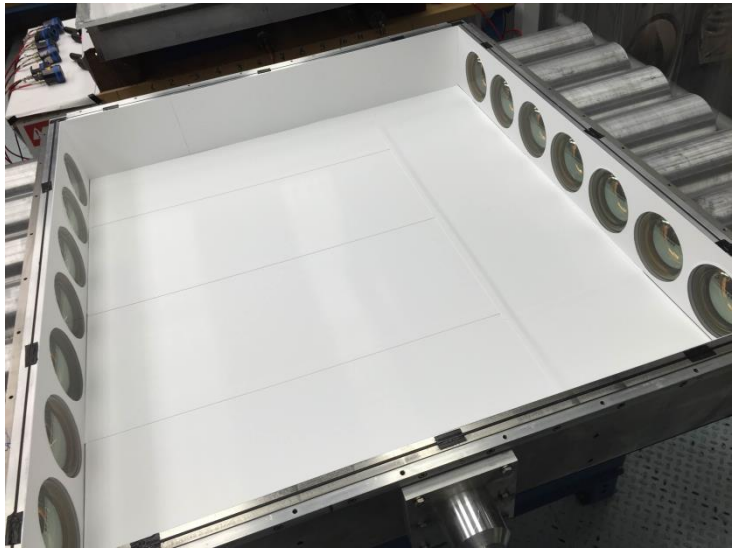
3 x ASIC BOARD (INFN) matching the

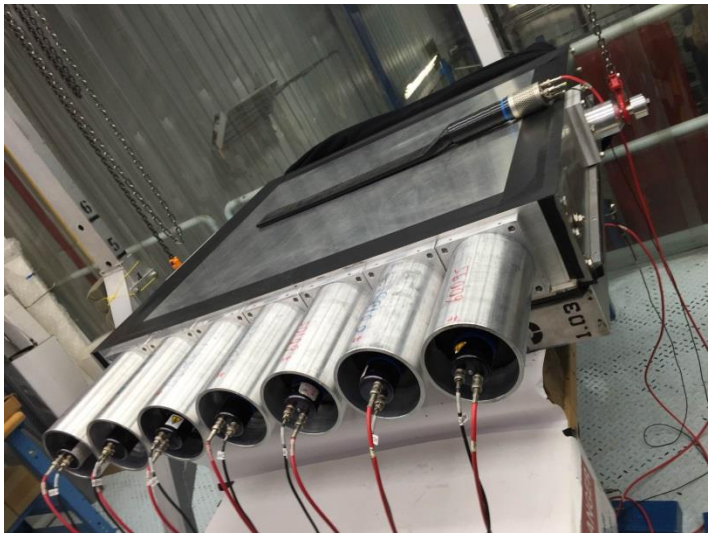
Universal FPGA BOARD (JLab)



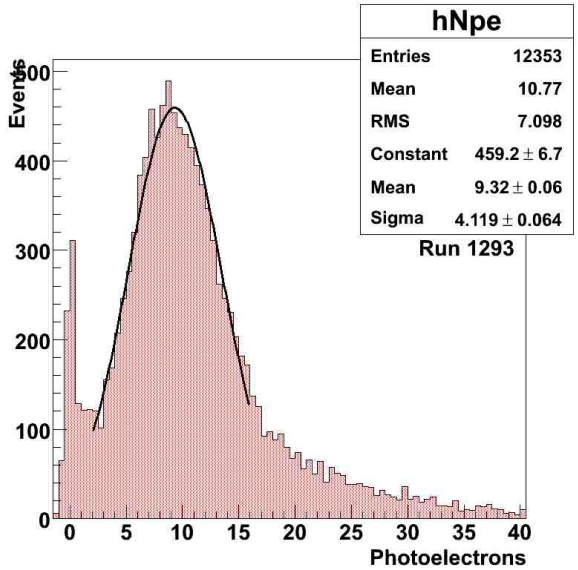
Cable routing

Hall C – Aerogel Detector (kaon PID)





CUA



Good performance with cosmic ray tests with tray of n=1.03 Aerogel with “wrong way” muons.

(In spectrometer, particles will pass through Aerogel before the diffusion box. In cosmic tests, Aerogel on bottom.)

Essentially ready for installation in SHMS. Trays with n = 1.011, 1.015, 1.02, 1.03 available (inner tray only for n = 1.011). Some from Matsushita (ex-MIT/BLAST), some from Japanese Fine Ceramics Center

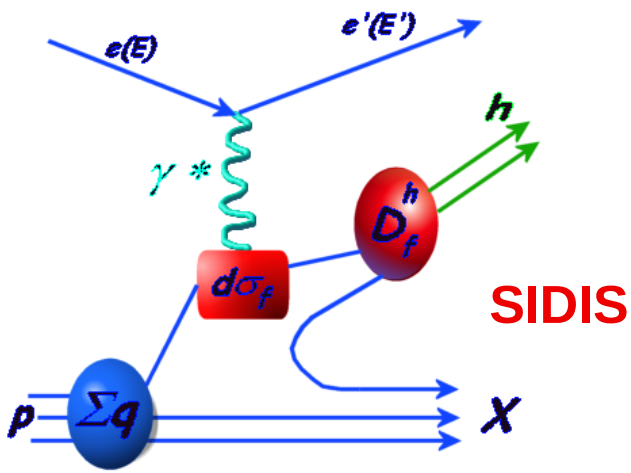
Overall Goal of Halls B and C SIDIS Program

validate basic reaction mechanism of SIDIS at JLab energies

and then

spin and flavor dependence of quark transverse momentum distributions

SIDIS – Flavor Decomposition



SIDIS

DIS probes only the sum of quarks and anti-quarks → requires assumptions on the role of sea quarks $\sum e_q^2(q+\bar{q})$

Solution: Detect a final state hadron in addition to scattered electron

→ Can 'tag' the flavor of the struck quark by measuring the hadrons produced: 'flavor tagging'

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

$Z = E_h/\nu$

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

$f_q(x)$: parton distribution function

$D_q^h(z)$: fragmentation function

Measure inclusive (e,e') at same time as (e,e'h)

- Leading-Order (LO) QCD
- after integration over p_T and ϕ
- NLO: gluon radiation mixes x and z dependences
- Target-Mass corrections at large z
- ln(1-z) corrections at large z

TMDs and SIDIS – General Formalism

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

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

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

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

If beam is unpolarized, and the (e,e'h) measurements are fully integrated over ϕ, only the $F_{UU,T}$ and $F_{UU,L}$ responses, or the usual transverse (σ_T) and longitudinal (σ_L) cross section pieces, survive.

$R = \sigma_L/\sigma_T$ in DIS

- R_{DIS} is in the naïve parton model related to the parton's transverse momentum: $R = 4(M^2x^2 + \langle k_T^2\rangle)/(Q^2 + 2\langle k_T^2\rangle)$.

- $R_{DIS} \rightarrow 0$ at $Q^2 \rightarrow \infty$ is a consequence of scattering from free spin-½ constituents

- Of course, beyond this, at finite Q^2, R_{DIS} sensitive to gluon and higher-twist effects

- No distinction made up to now between diffractive and non-diffractive contributions in R_{DIS}

- $R_{DIS}^H = R_{DIS}^D$, to very good approximation (experimentally)
  - from formal point of view they should not be identical!
    (u not equal to d at large x + evolution in Q^2,
    H = spin-1/2 and D = spin-1, at low Q^2)

$R = \sigma_L/\sigma_T$ in (e,e'π) SIDIS

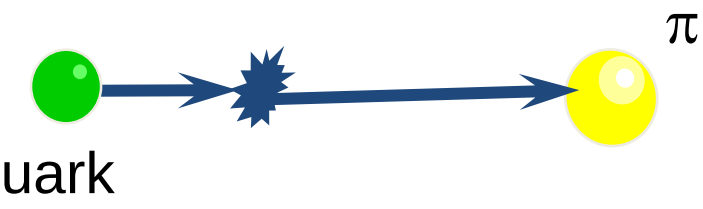
Knowledge on $R = \sigma_L/\sigma_T$ in SIDIS is essentially non-existing!

- If integrated over z (and p_T, ϕ, hadrons), $R_{SIDIS} = R_{DIS}$
- $R_{SIDIS} = R_{DIS}$ test of dominance of quark fragmentation
- R_{SIDIS} may vary with z
- At large z, there are known contributions from exclusive and diffractive channels: *e.g.*, pions from Δ and $\rho \rightarrow \pi^+\pi^-$
- R_{SIDIS} may vary with transverse momentum p_T
- Is $R_{SIDIS}^{\pi^+} = R_{SIDIS}^{\pi^-}$? Is $R_{SIDIS}^{H} = R_{SIDIS}^{D}$?
- Is $R_{SIDIS}^{K^+} = R_{SIDIS}^{\pi^+}$? Is $R_{SIDIS}^{K^+} = R_{SIDIS}^{K^-}$?

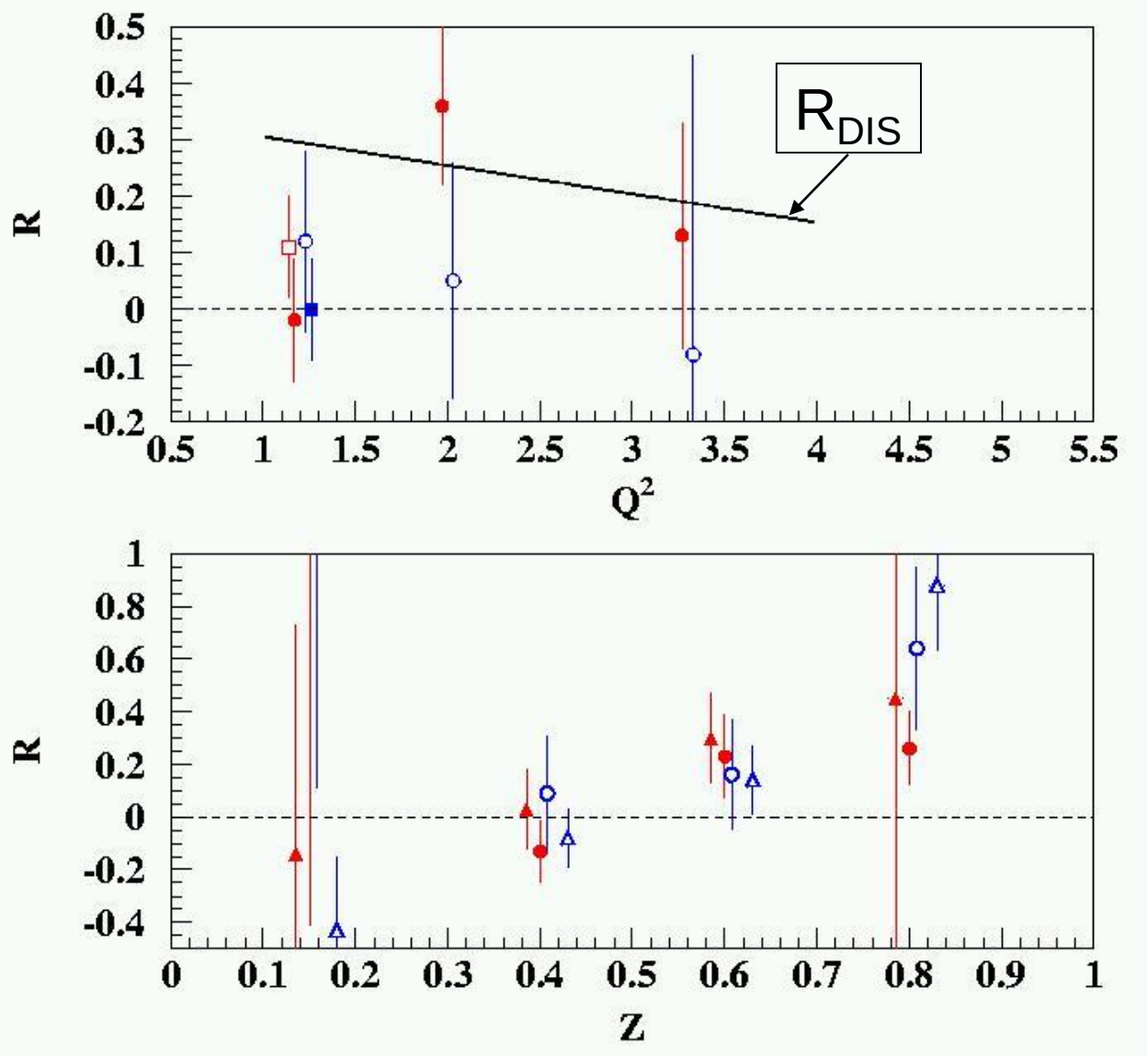
E12-06-104 measures kaons too! (with ~20% of pion statistics)

"A skeleton in our closet"

$$\sigma = \sum_q e_q^2 f(x) \otimes D(z)$$



$R = \sigma_L/\sigma_T$ in SIDIS ($ep \rightarrow e'\pi^{+/-}X$)



Only existing data: Cornell 70's data (H and D, π^+ and π^-)

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

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

So what about R = σ_L/σ_T for pion electroproduction?

"Semi-inclusive DIS"

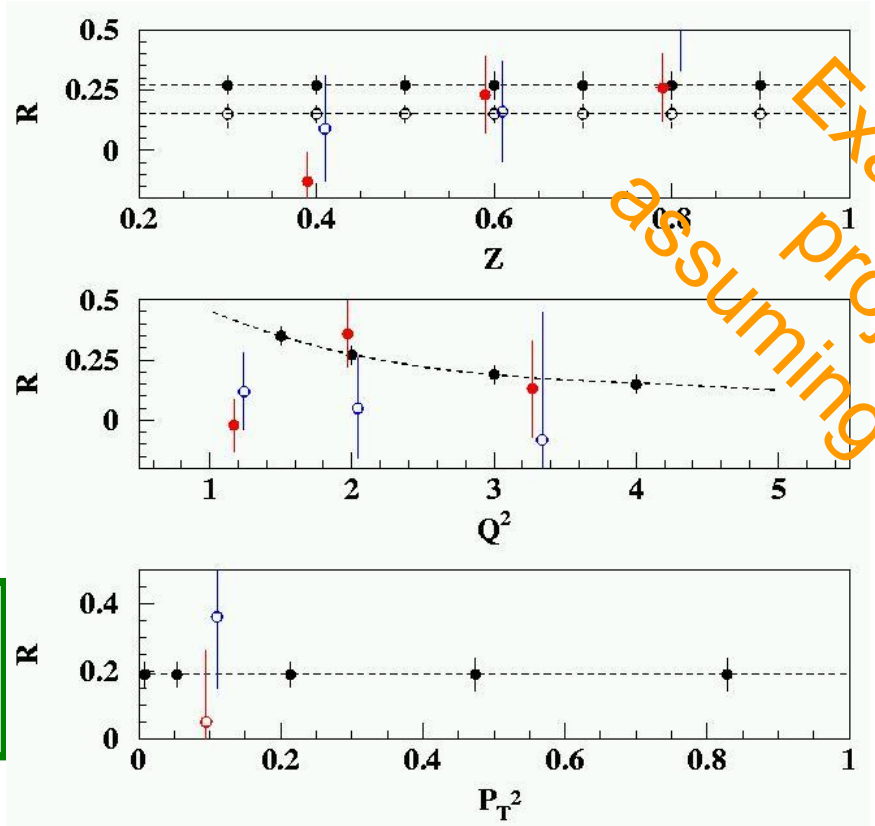
quark $\Sigma e_q^2 q(x)\, D_q^p(z)$

Here, $R_{SIDIS} \rightarrow R_{DIS}$ disappears with Q^2

"Deep exclusive scattering" is the z → 1 limit of this "semi-inclusive DIS" process

Here, $R = \sigma_L/\sigma_T \sim Q^2$ (at fixed x)

Not including a comparable systematic uncertainty: ~1.6%



Have no idea at all how R will behave at large p_T

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.

Example of 12-GeV projected data assuming $R_{SIDIS} = R_{DIS}$

Hall C SIDIS Program – basic (e,e'π) cross sections

Why need for (e,e'π) cross sections?

PAC37 Report: "the **cross sections** are **such basic tests of the understanding of SIDIS** at 11 GeV kinematics that they will play a **critical role** in establishing the entire SIDIS program of studying the partonic structure of the nucleon. In particular they complement the CLAS12 measurements in areas where the precision of spectrometer experiments is essential, being able to separate P_T and ϕ-dependence for small P_T."

$$\sigma = \sum_q e_q^2 f(x) \otimes D(z)$$

Basic precision cross section measurements:

- Crucial information to validate theoretical understanding
  - Convolution framework requires validation for most future SIDIS experiments and their interpretation
  - Can constrain TMD evolution
  - Questions on target-mass corrections and ln(1-z) re-summations require precision large-z data

Goal: Measure the basic SIDIS cross sections of **π^+, π^-, π^0 (and K^+)** production off the proton (and deuteron), including a map of the P_T dependence ($P_T \sim \Lambda < 0.5$ GeV), to validate(*) a flavor decomposition and the k_T dependence of (unpolarized) up and down quarks

(*) Can only be done using spectrometer setup capable of %-type measurements (an essential ingredient of the global SIDIS program!)

TMDs and SIDIS – General Formalism

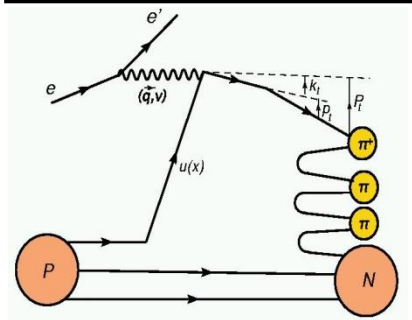
General formalism for (e,e'h) coincidence reaction w. polarized beam: [A. Bacchetta et al., JHEP 0702 (2007) 093]

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

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

If beam is unpolarized, and the (e,e'h) measurements are fully integrated over ϕ, only the $F_{UU,T}$ and $F_{UU,L}$ responses, or the usual transverse (σ_T) and longitudinal (σ_L) cross section pieces, survive.

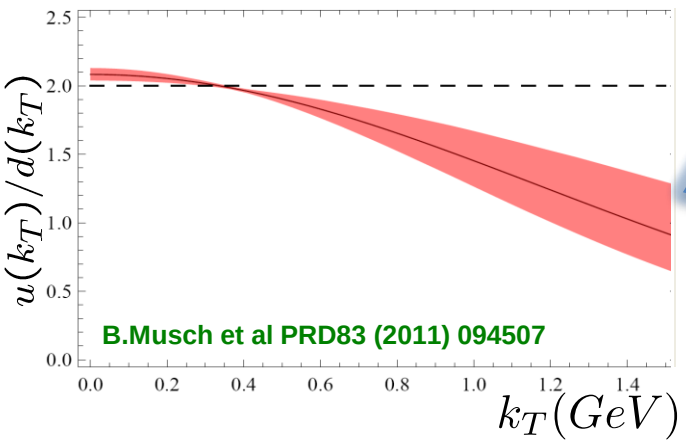
Unpolarized k_T-dependent SIDIS: $F_{UU}^{\cos(\phi)}$ and $F_{UU}^{\cos(2\phi)}$, in framework of Anselmino et al. described in terms of *convolution of quark distributions f and (one or more) fragmentation functions D*, each with own characteristic (Gaussian) width. Transverse momentum widths of quarks with **different flavor (and polarization)** can be different.



Final transverse momentum of the detected pion $\mathbf{P}_t$ arises from convolution of the struck quark transverse momentum $\mathbf{k}_t$ with the transverse momentum generated during the fragmentation $\mathbf{p}_t$.

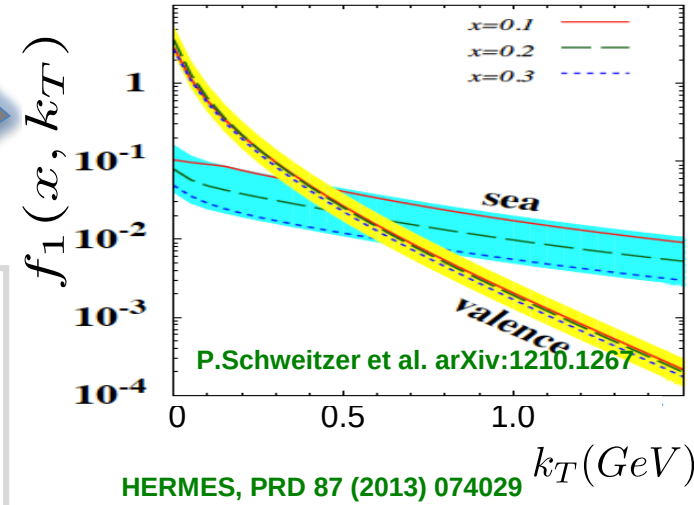
$$P_t = p_t + z\,k_t + O(k_t^2/Q^2)$$

Probing the flavor-dependence of k_T-distributions



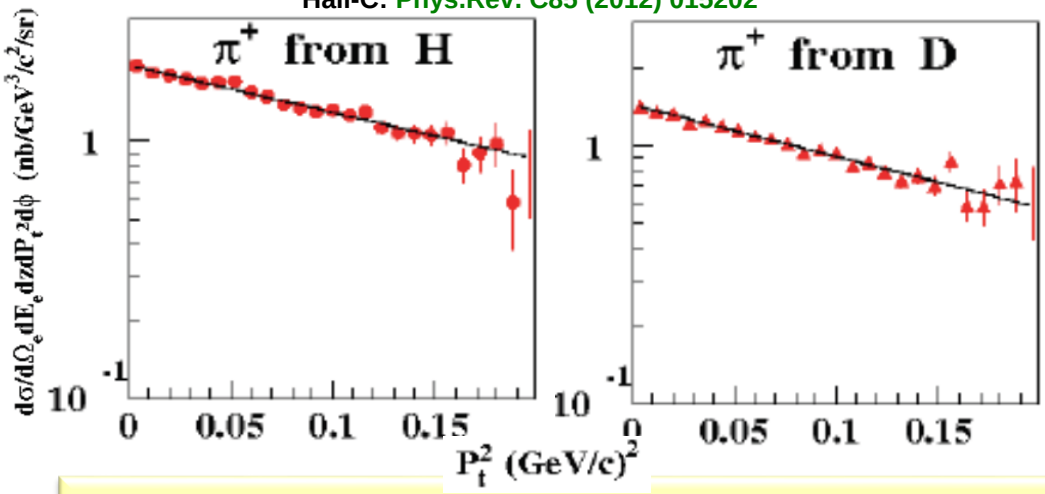
Higher probability to find more sea & d-quarks at **large k_T**

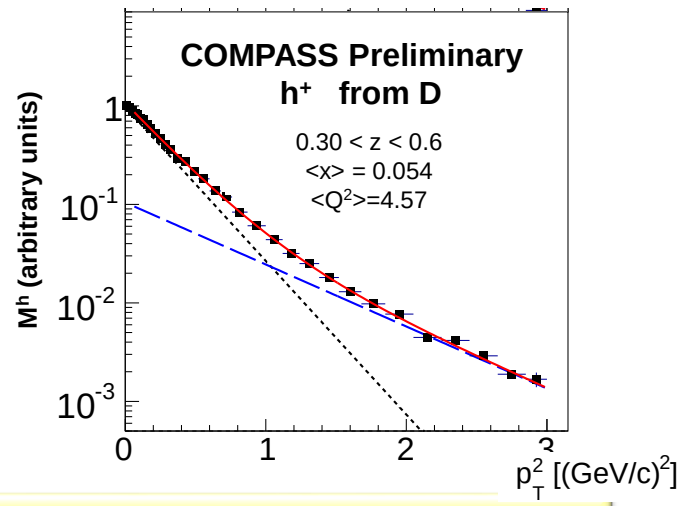
Measurements of hadronic multiplicities provide a crucial input for studies of **k_T** dependence of spin independent distributions



HERMES, PRD 87 (2013) 074029
COMPASS, EPJC 73 (2013) 2531

Hall-C: Phys.Rev. C85 (2012) 015202





There are indications from both theory (lattice, chiral constituent quark model) and experimental data of the k_T dependence of quark flavor distribution.

Hall C SIDIS Program (typ. x/Q^2 ~ constant)

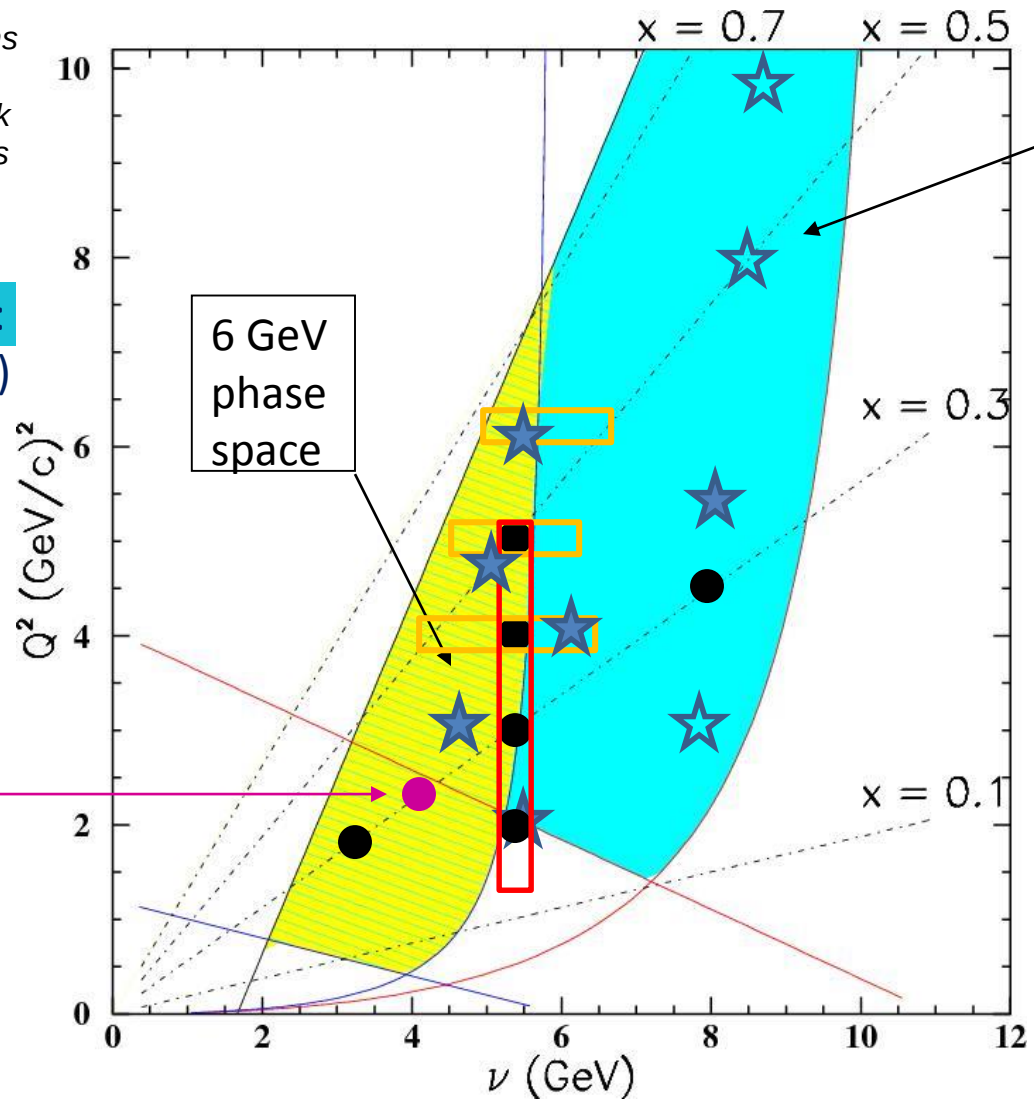
HMS + SHMS (or NPS) Accessible Phase Space for SIDIS

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 & E12-09-002

Parasitic with E12-13-010

E00-108 (6 GeV)



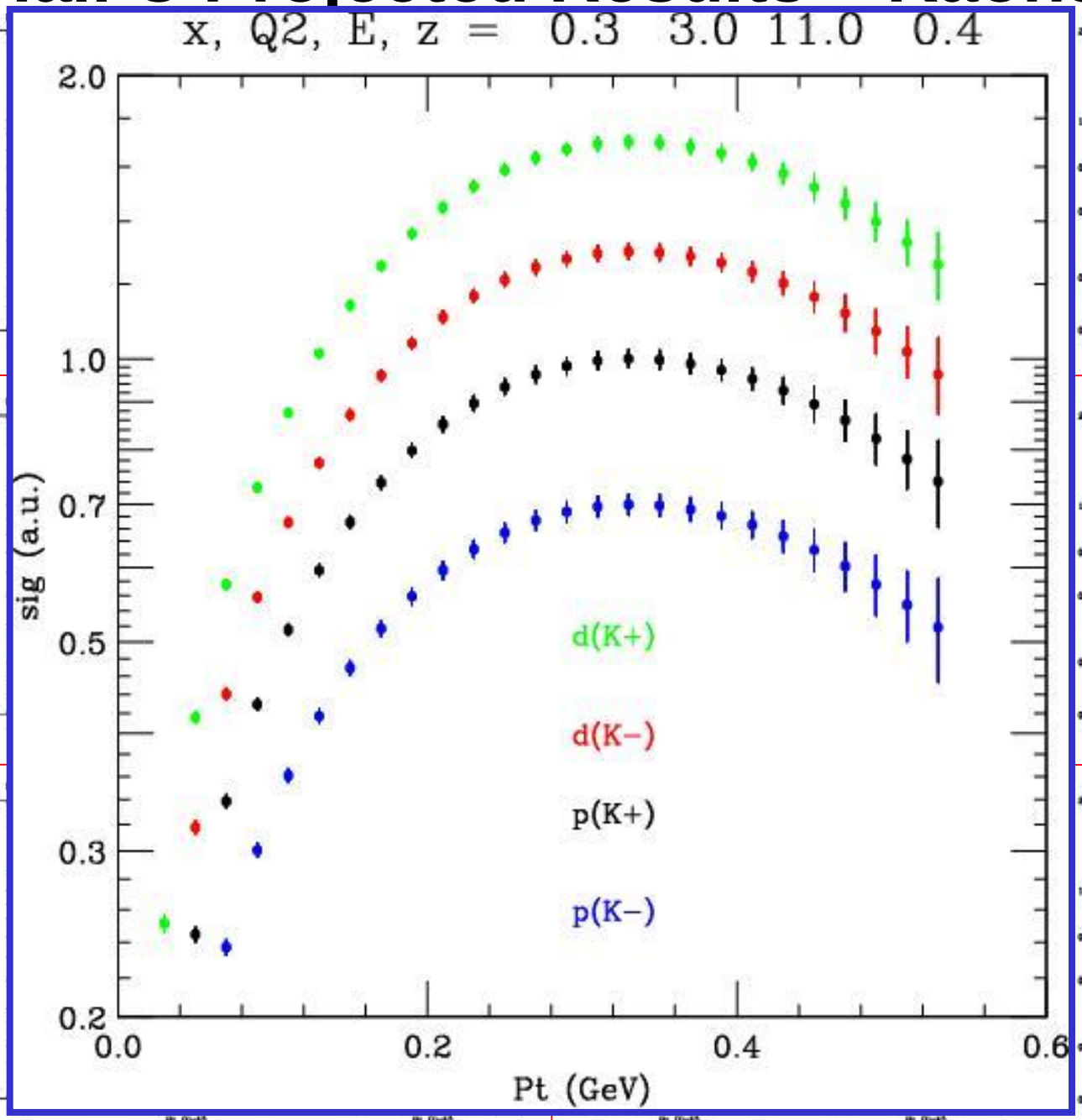
Charged pions:

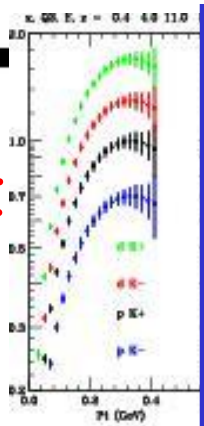
E12-06-104
L/T scan in (z,P_T)
No scan in Q^2 at fixed x: $R_{DIS}(Q^2)$ known

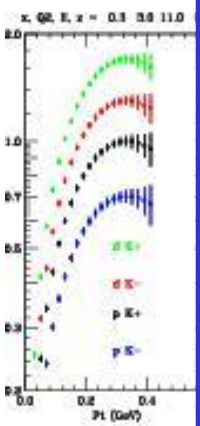
E12-09-017
Scan in (x,z,P_T)
+ scan in Q^2 at fixed x

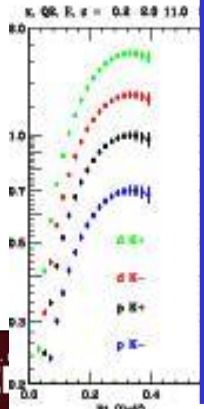
E12-09-002
+ scans in z

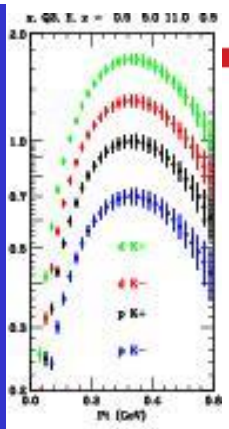
Hall C Projected Results – Kaons

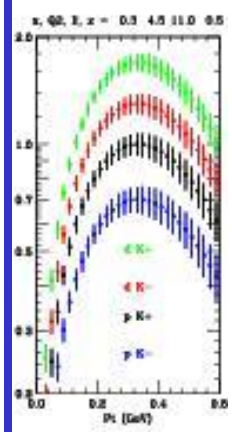


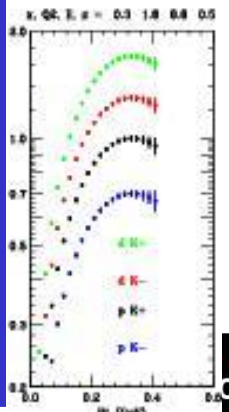












III

II

I

IV

VI

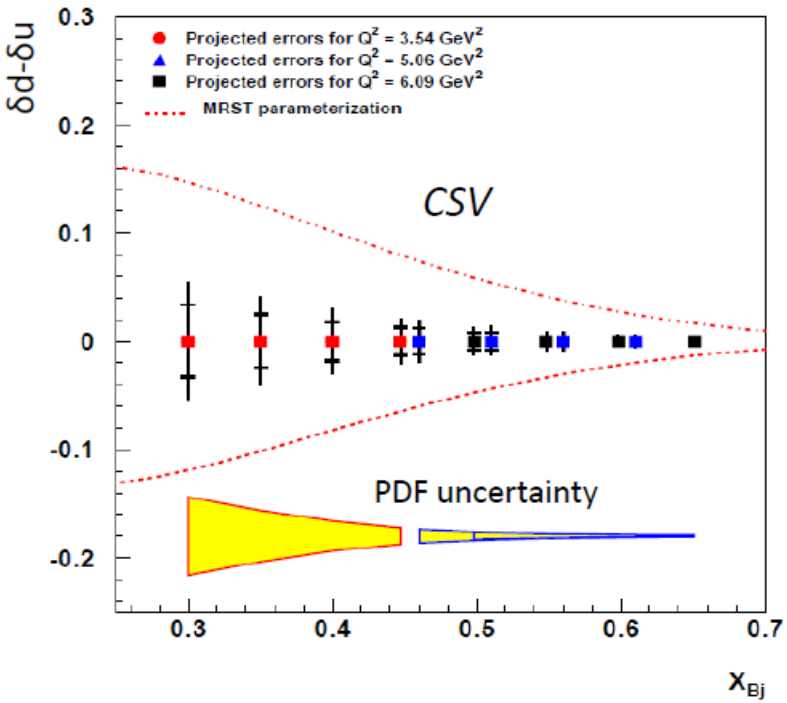
V

Hall C E12-09-002: The Hunt for CSV

- Charge symmetry (CS) is an approximate symmetry in the nuclear world, respected to better than 1%: $M_p \approx M_n$, energy levels in mirror nuclei (after Coulomb corrections), …
- At the quark level CS implies $u^p(x,Q^2) = d^n(x,Q^2)$, $d^p(x,Q^2) = u^n(x,Q^2)$. *This is widely assumed but never thoroughly checked by experiment!*
- In QCD charge symmetry violation (CSV) originates from EM interactions (small at high energies) and $\delta m = m_d - m_u$.
- Naively, CSV ~ $(m_d - m_u)/\langle M \rangle$, where $\langle M \rangle$ ~ 0.5 – 1 GeV from the strong Hamiltonian → one expects an ~1% effect

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

Experiment aims, assuming a thorough understanding of the SIDIS reaction mechanism is validated, to extract CSV info from the charged-pion yield ratio on a D target.



Hall C SIDIS Program – basic (e,e'π) cross sections

(Hall C's basic SIDIS cross section data at a 6-GeV JLab showed agreement with partonic expectations laying the foundation for a vigorous 12-GeV SIDIS program. PRL 98 (2007) 022001; PL B665 (2008) 20; PRC 85 (2012) 015202. At a 12-GeV JLab, Hall C's role will be again to provide basis SIDIS cross sections, furthering our understanding.)

Low-energy (x,z) factorization, or possible *convolution in terms of quark distribution and fragmentation functions*, at JLab-12 GeV must be well validated to substantiate the SIDIS science output. Many questions remain at intermediate-large z (~0.2-1) and low-intermediate Q^2 (~2-10 GeV^2).

Why need for $(e,e'\pi^0)$ beyond $(e,e'\pi^{+/-})$?

$(e,e'\pi^0)$ experimental advantages:

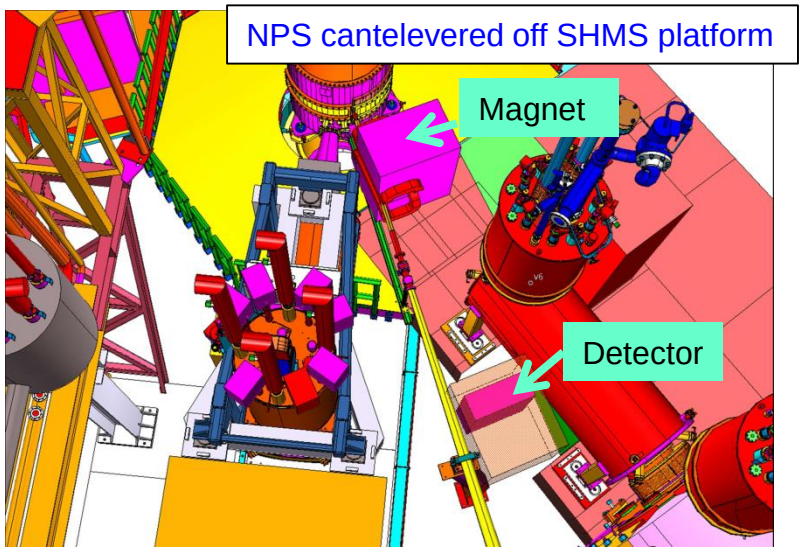
☺ no diffractive ρ contributions
☺ no exclusive pole contributions
☺ reduced resonance contributions
☺ proportional to average D

Further advantages:

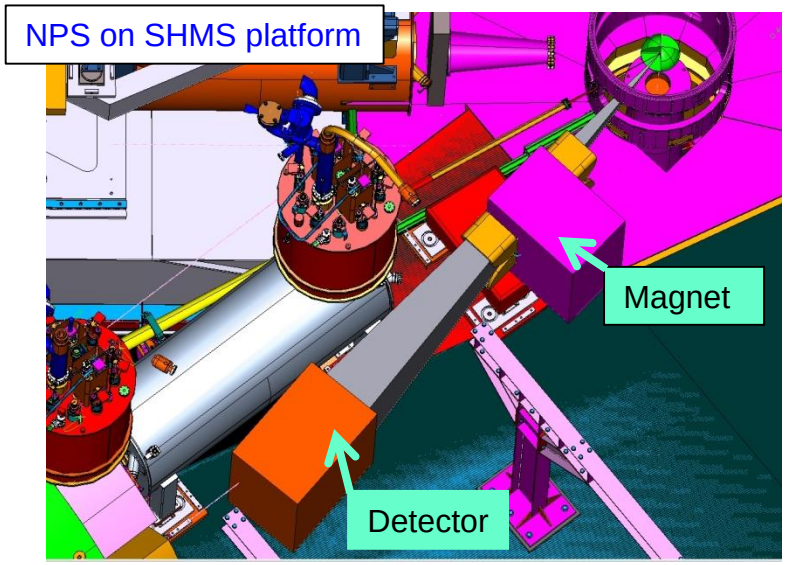
- Can verify: $\sigma^{\pi^0}(x,z) = \frac{1}{2}(\sigma^{\pi^+}(x,z) + \sigma^{\pi^-}(x,z))$
- Confirms understanding of flavor decomposition & of k_T dependence

The Neutral-Particle Spectrometer (NPS)

The NPS is envisioned as a facility in Hall C, utilizing the well-understood HMS and the SHMS infrastructure, to allow for precision (coincidence) cross section measurements of neutral particles (γ and π^0). The NPS will be remotely rotatable off the SHMS platform.



NPS angle range: 5.5 – 30 degrees



NPS angle range: 25 – 60 degrees

The large interest for such a device can be exemplified by the PAC-approved science program:

E12-13-007 – Measurement of Semi-inclusive π^0 production as Validation of Factorization

E12-13-010 – Exclusive Deeply Virtual Compton and
Neutral Pion Cross Section Measurements in Hall C

(E12-13-007 & E12-13-010 runs as one run group – first run group in Hall C)

E12-14-003 – Wide-angle Compton Scattering at 8 and 10 GeV Photon Energies

E12-14-005 – Wide Angle Exclusive Photoproduction of π^0 Mesons **(runs as run group with E12-14-003)**

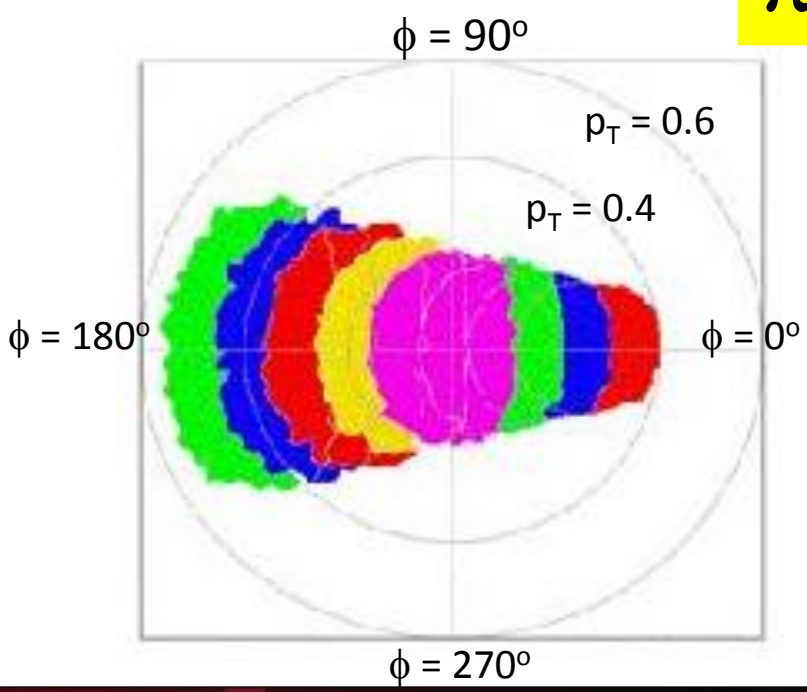
E12-14-006 – Initial State Helicity Correlation in Wide-Angle Compton Scattering

E12-09-017: P_T coverage

Can do meaningful $\pi^{+/-}$ 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 up to P_T = 0.4 GeV
  → coverage at ϕ = 0, π
- Limited up to P_T = 0.5 GeV
  → use f(ϕ) from CLAS12

$\pi^{+/-}$



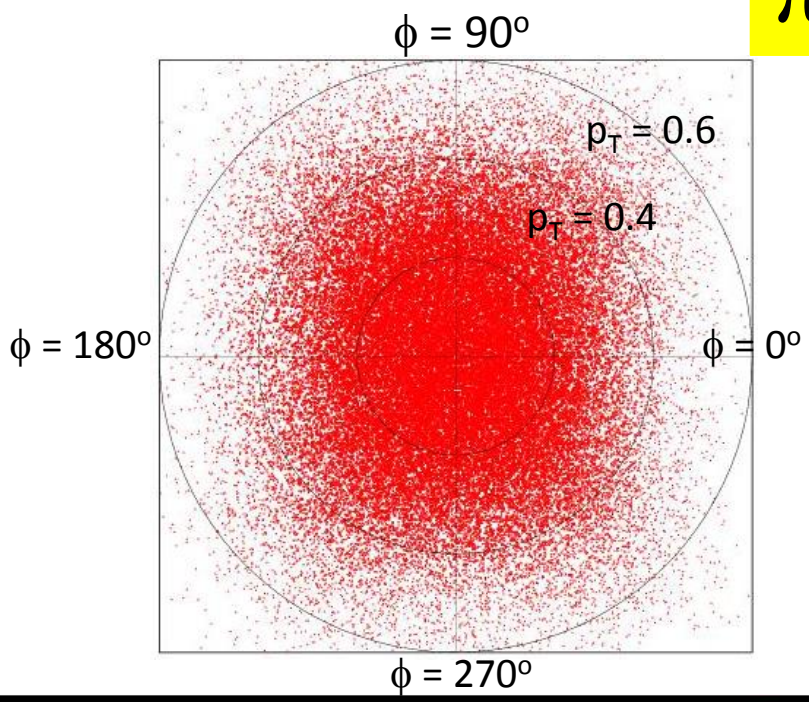
E12-13-007: P_T coverage

Basic π^0 SIDIS cross sections with excellent precision, and very good momentum and angle resolutions!

- Excellent ϕ coverage
  up to P_T = 0.3 GeV
- Good up to P_T = 0.4 GeV

- Limited up to P_T = 0.5 GeV
  → use f(ϕ) from CLAS12

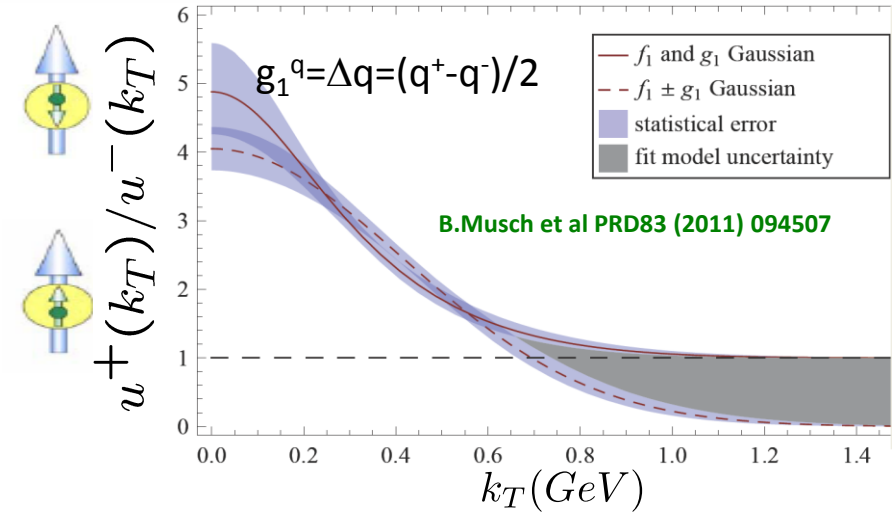
π^0

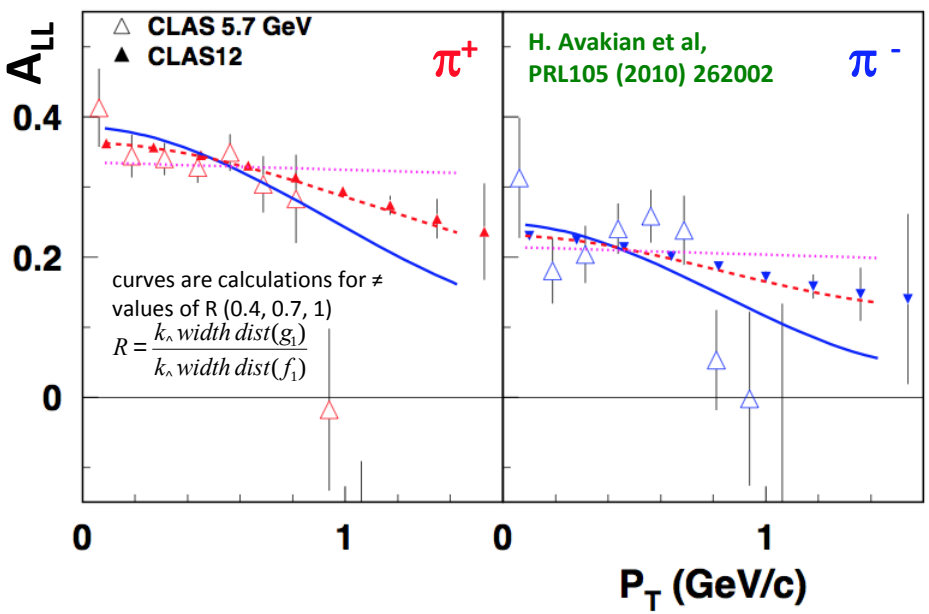


spin and flavor dependence of quark transverse momentum distributions

Distributions of PDFs may depend on flavor and spin
(lower fraction aligned with proton spin, and less u-quarks at large k_T,b_T)

CLAS12: K_T Helicity Dependence





- Higher probability to find a quark anti-aligned with proton spin at **large k_T**
- Important to have q^+ and q^- **k_T** -dependent distribution separately
- q^- sensitive to orbital motion:

$$q^-_{L=1} \sim (1-x)^5 log^2(1-x)$$

H. Avakian et al. PRL 99 (2007) 082001

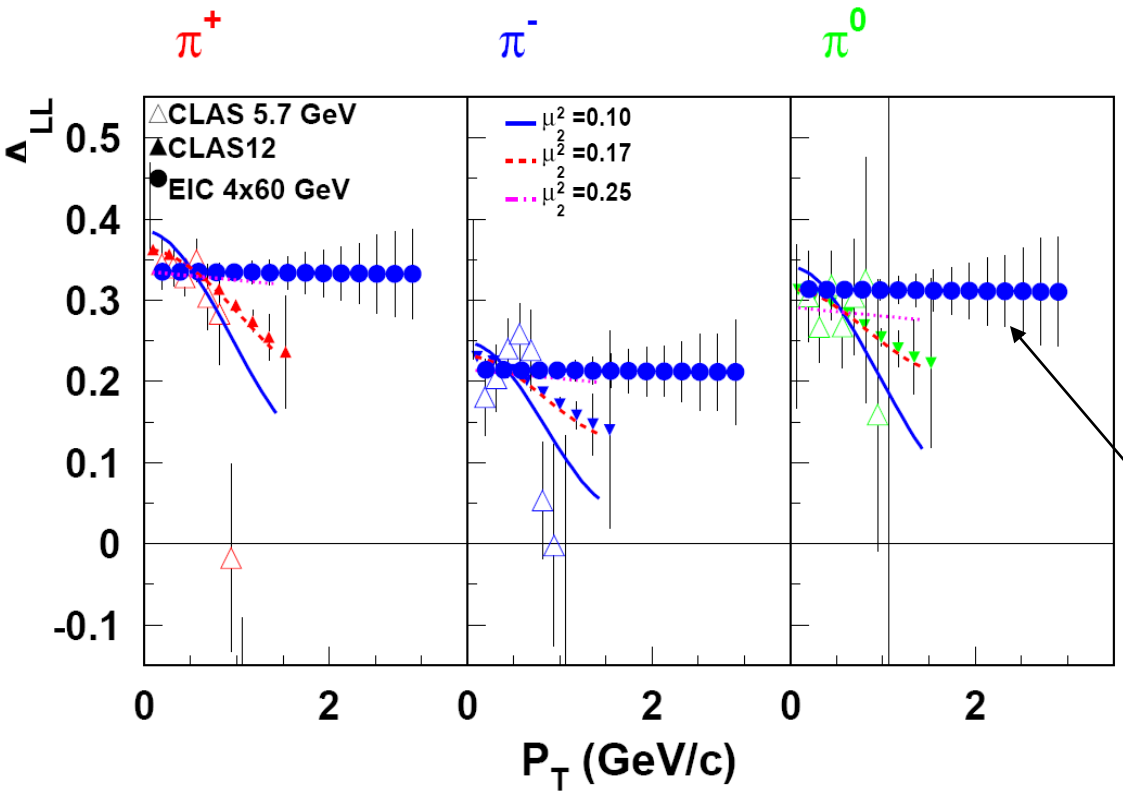
- Double spin asymmetries from CLAS@JLab consistent with wider **k_T** distributions for f_1 than for g_1
- **Wider range in P_T from CLAS12 is crucial !**

Measurements of the P_T-dependence of A_{LL} ($\propto g_1/f_1$) provide access to transverse momentum distributions of quarks anti-aligned with the proton spin.

A_1 P_T-dependence in SIDIS

$$A_1(\pi) \propto \frac{\sum_q e_q^2 g_1^q(x) D_1^{q\to\pi}(z)}{\sum_q e_q^2 f_1^q(x) D_1^{q\to\pi}(z)} \; e^{-z^2 P_T^2 \frac{(\mu_0^2-\mu_2^2)}{(\mu_D^2+z^2\mu_0^2)(\mu_D^2+z^2\mu_2^2)}}$$

M.Anselmino et al
hep-ph/0608048



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

$$g_1^q(x,k_T) = g_1(x)\frac{1}{\pi\mu_2^2}\exp\left(-\frac{k_T^2}{\mu_2^2}\right)$$

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

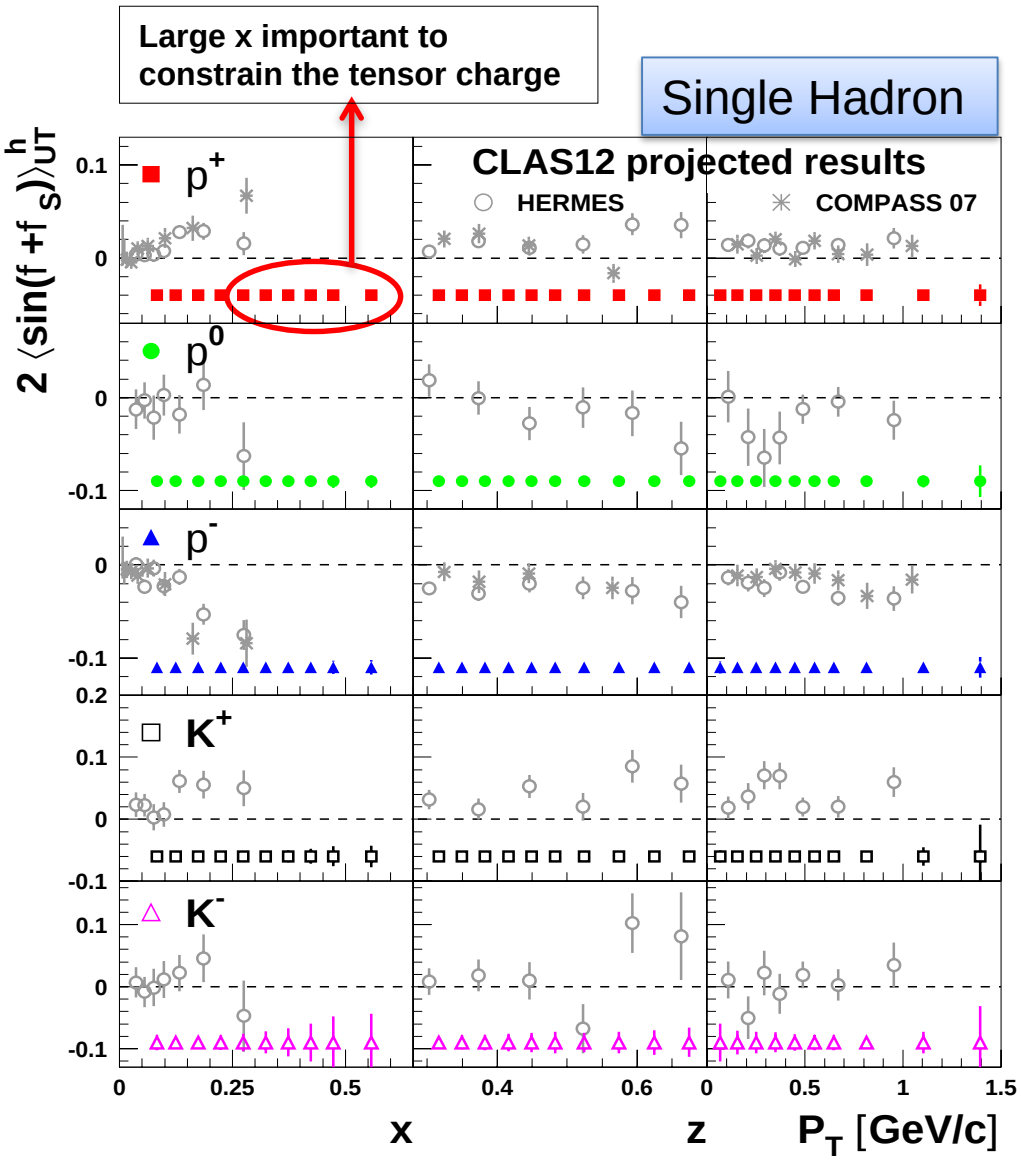
μ_0^2=0.25GeV^2
μ_D^2=0.2GeV^2

Perturbative limit calculations available for $g_1^q(x,k_T), f_1(x,k_T)$

J.Zhou, F.Yuan, Z Liang: arXiv:0909.2238

- **A_{LL} (π) sensitive to difference in k_T distributions for f_1 and g_1**
- **Wide range in P_T allows studies of transition from TMD to perturbative approach**

Transversity with CLAS12



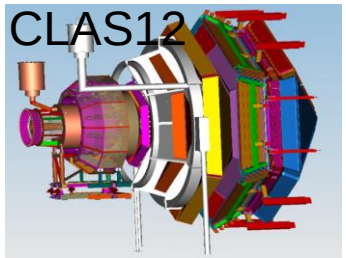
High Impact Exp. From PAC41 (C12-11-111 + C12-12-009)

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

- HD-transversely polarized target and CLAS12

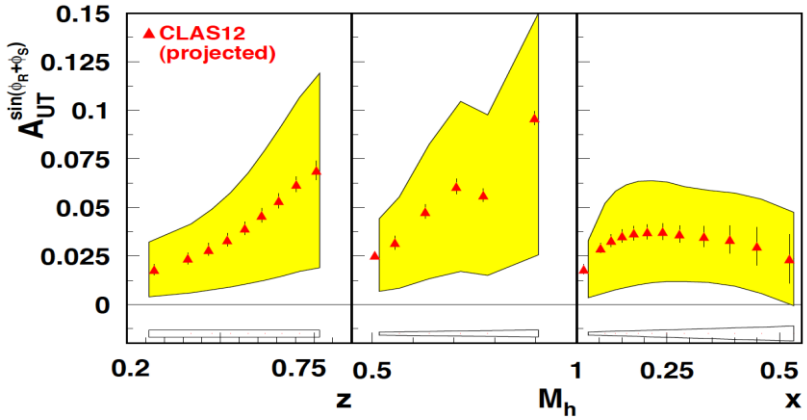
Accessing transversity in dihadron production

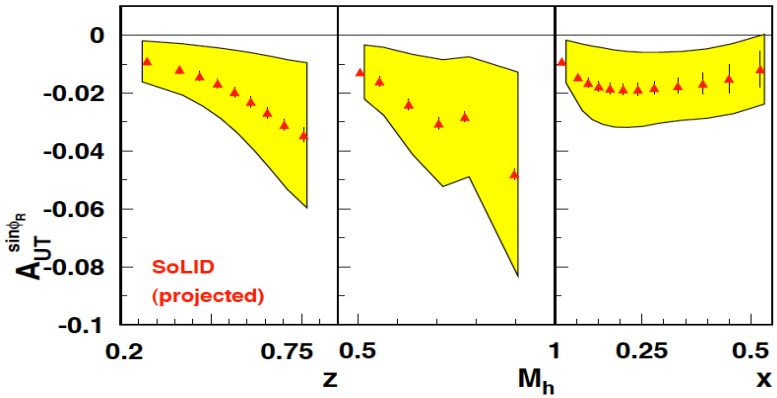
Measurements with polarized protons



$$A_{UT}(\phi_R,\theta) = \frac{1}{fP_t}\frac{(N^+ - N^-)}{(N^+ + N^-)}$$

Measurements with polarized neutrons

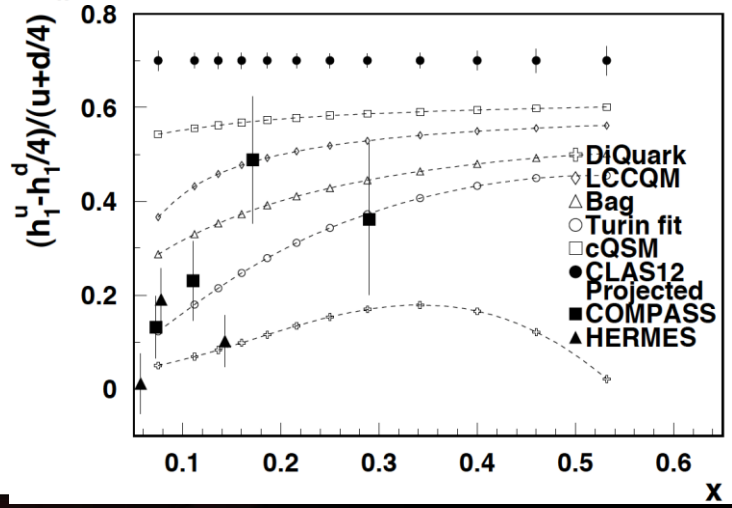




Di-hadron

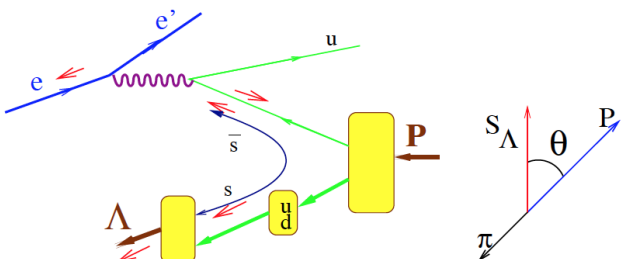
$$\frac{H_{1,sp}^{\sphericalangle,u}(z,M_h)[4h_1^u - h_1^d(x)]}{D_1^u(4f_1^u + f_1^d)}$$

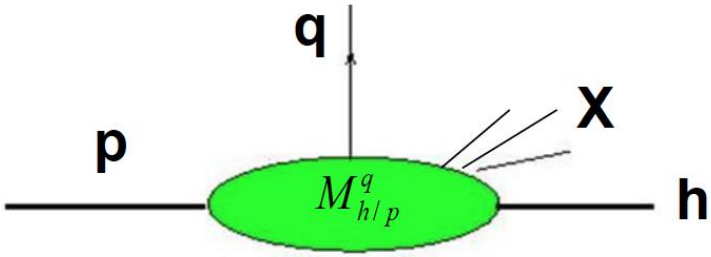
(Chiral-odd interference fragmentation function)



$$\frac{H_{1,sp}^{\sphericalangle,u}(z,M_{\pi\pi})\ (4h_1^d(x) - h_1^u(x))}{D_1^u(z,M_{\pi\pi})\ (4f_1^d(x) + f_1^u(x))}$$

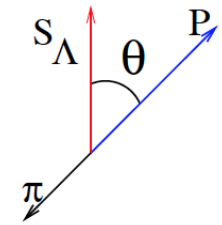
Target fragmentation region: Λ production



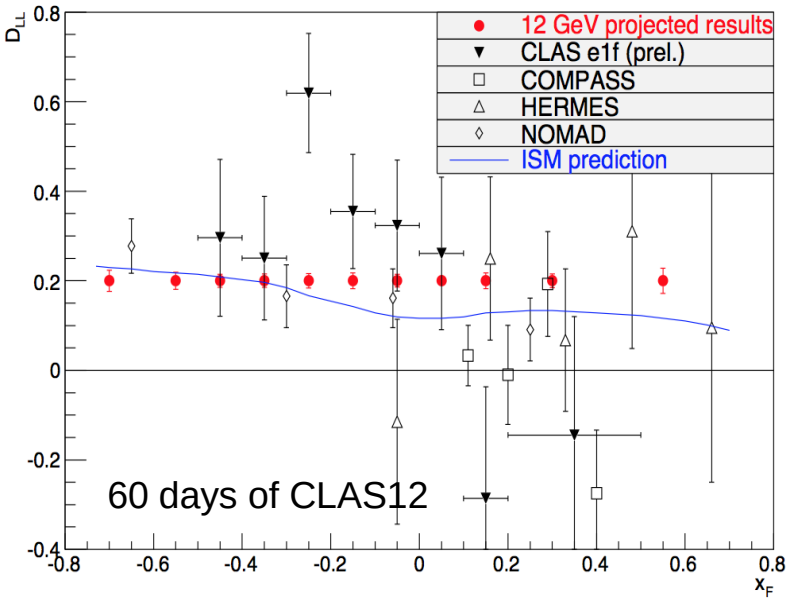


probability to produce the hadron h when a quark q is struck in a proton target

$$D^{LL} = \frac{\sum_a e_a^2 \Delta M^L}{\sum_a e_a^2 M}$$



polarization tranfer coefficient



Measurements of fracture functions opens a new avenue in studies of the structure of the nucleon in general and correlations between current and target fragmentation in particular

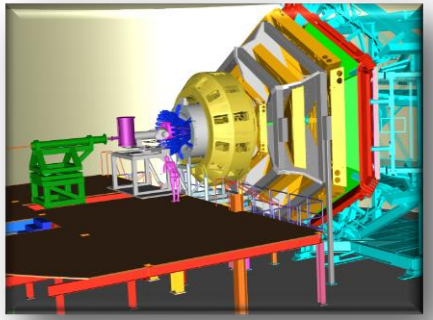
$$A_{LUL}^{TFR} = hS_{\parallel} \frac{y\left(1-\frac{y}{2}\right)\sum_a e_a^2 \Delta M^L}{\left(1-y+\frac{y^2}{2}\right)\sum_a e_a^2 M}$$

•Large acceptance of CLAS12 provides a unique possibility to study the nucleon structure in target fragmentation region and correlations of target and current fragmentation regions

Together stronger: SIDIS Studies with 12 GeV

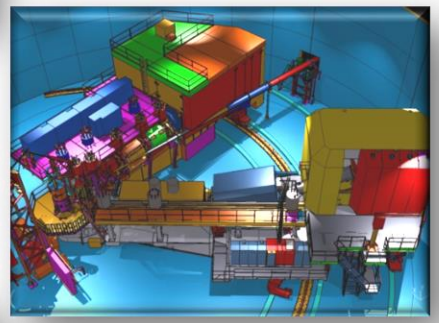
- **CLAS12 in Hall B**

  General survey, medium lumi



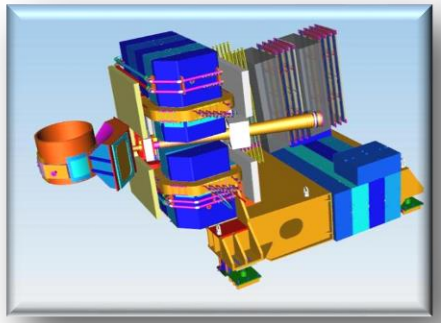
- **SHMS, HMS, NPS in Hall C**

  L-T studies, precise $\pi^+/\pi^-/\pi^0$ ratios



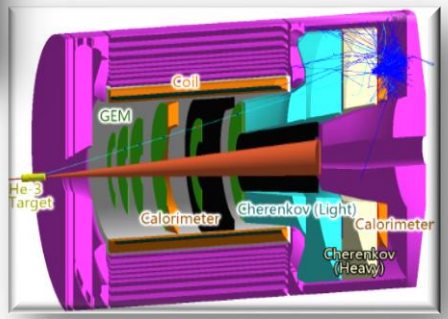
- **SBS in Hall A**

  High x, High Q^2, 2-3D

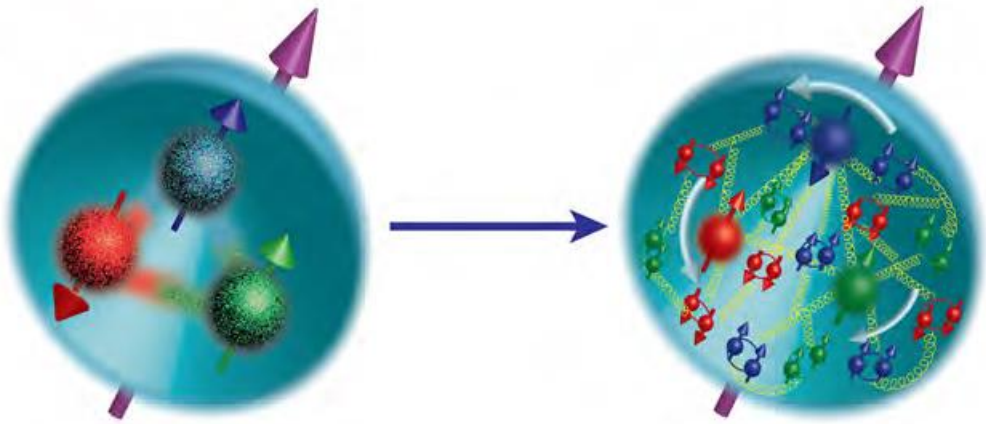


- **SOLID in Hall A**

  High lumi and acceptance – 4D



The Incomplete Nucleon: Spin Puzzle



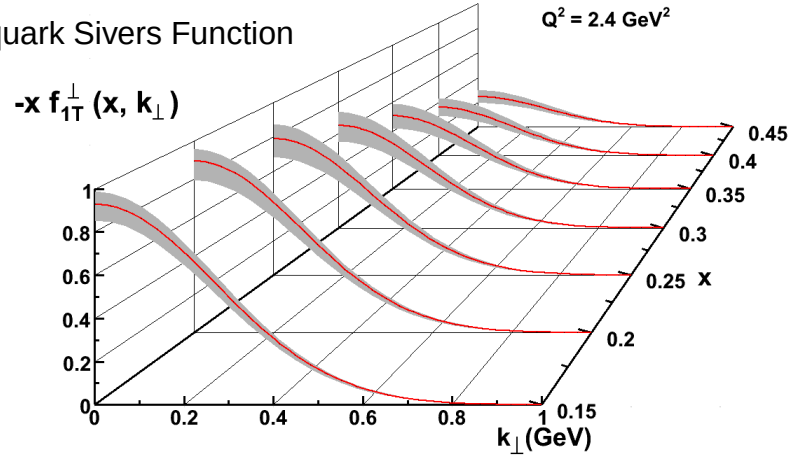
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_q + J_g$$

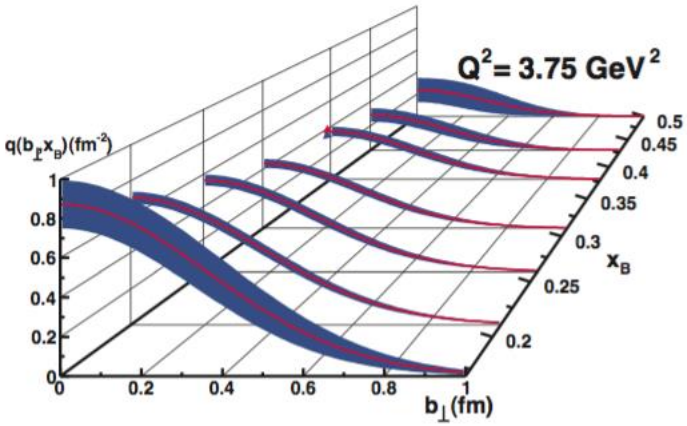
- $\Delta\Sigma \sim 0.25$ (world DIS)
- $\Delta G \sim 0.2$? (RHIC+DIS)
- L_q?

Longitudinal momentum fraction x and transverse momentum images

Longitudinal momentum fraction x and transverse spatial images

Up quark Sivers Function





12 GeV projections: valence quarks well mapped

Overall Goal of Halls B and C SIDIS Program

validate basic reaction mechanism of SIDIS at JLab energies

and then

spin and flavor dependence of quark transverse momentum distributions

There are indications from both theory (lattice, chiral constituent quark model) and experimental data of different k_T dependences of quark flavor distributions

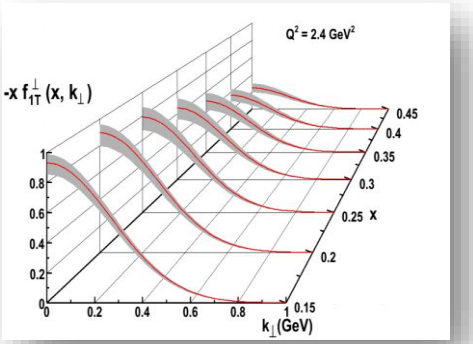
3D Mapping of the Nucleon

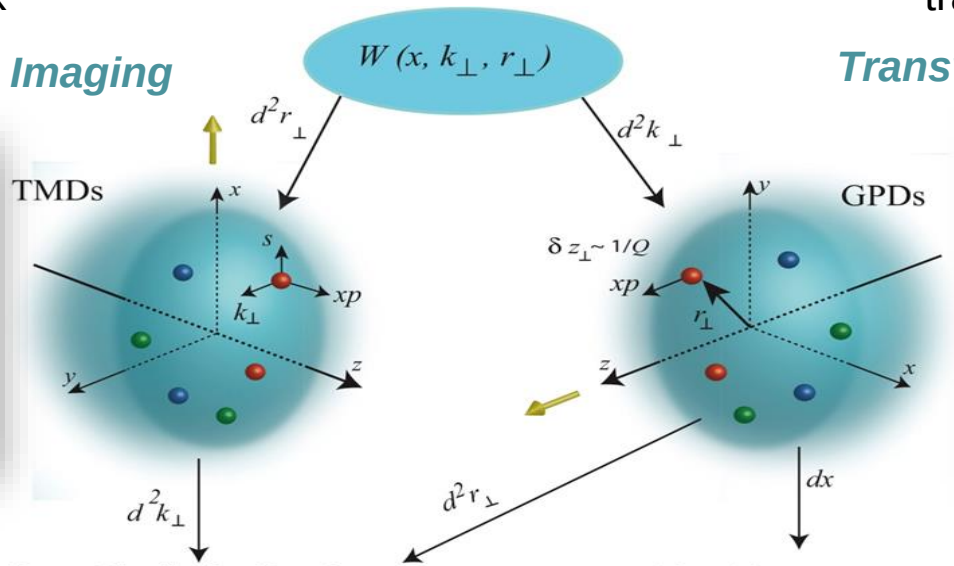
TMDs: Longitudinal momentum fraction x and transverse momentum k

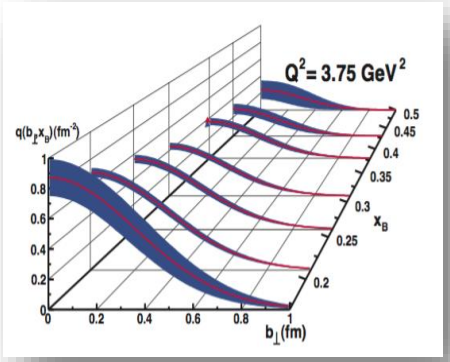
GPDs: Longitudinal momentum fraction x at transverse location b

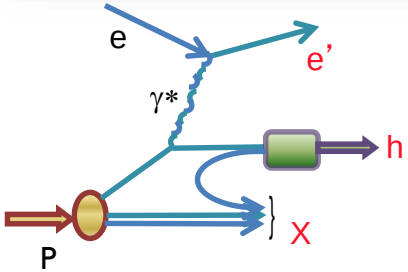
Transverse Momentum Imaging

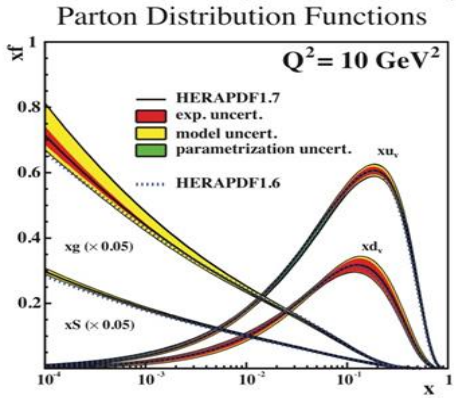
Transverse Spatial Imaging

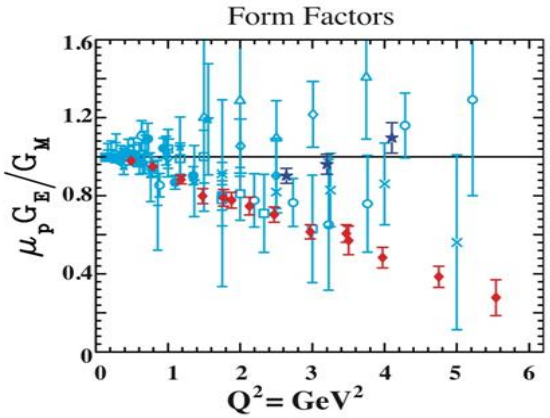


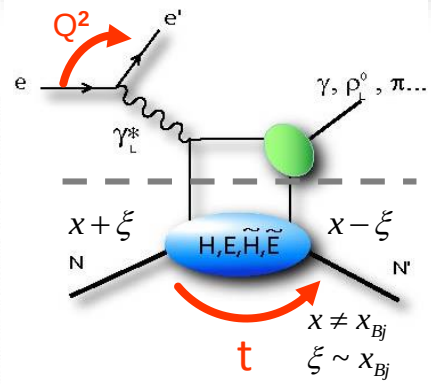








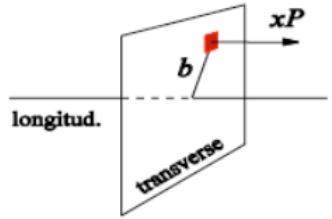


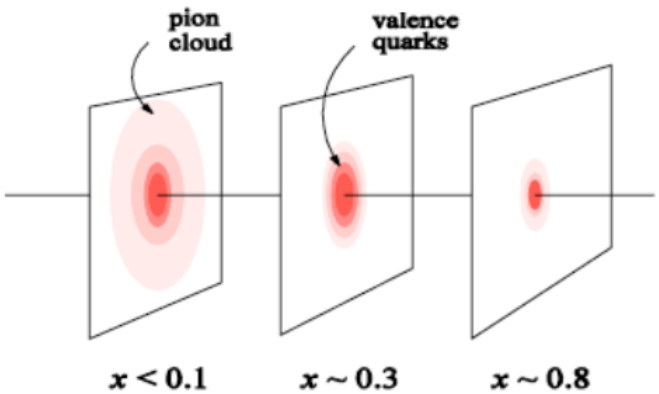


Hard Exclusive Processes → GPDs

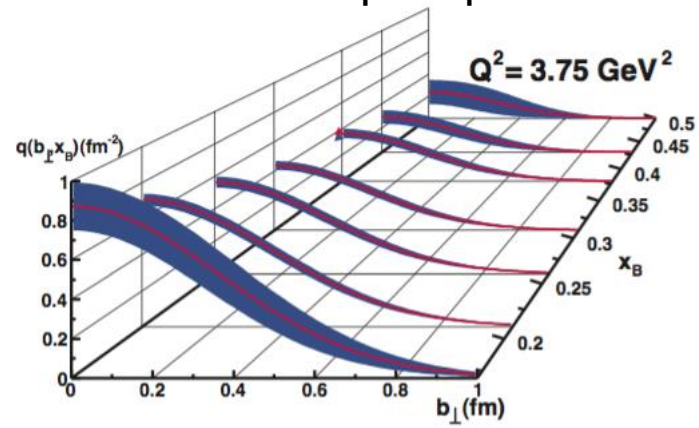
Goal 1: Transverse Imaging of Nucleon

Fourier transform of t-dependence





The proton's transverse profile as function of the impact parameter b



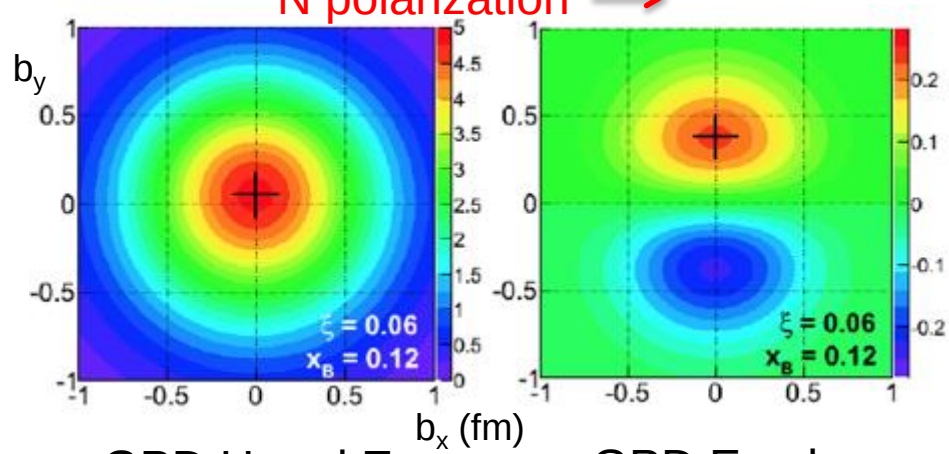
Goal 2: Orbital Angular Momentum

Ji's Sum Rule for $J^q = \frac{1}{2}\Delta\Sigma + L^q$

$$J^q = \frac{1}{2}\int_{-1}^{1} x\,dx\,[H^q(x,\xi,t=0) + E^q(x,\xi,t=0)]$$

Distortions induced by spin direction

N polarization →



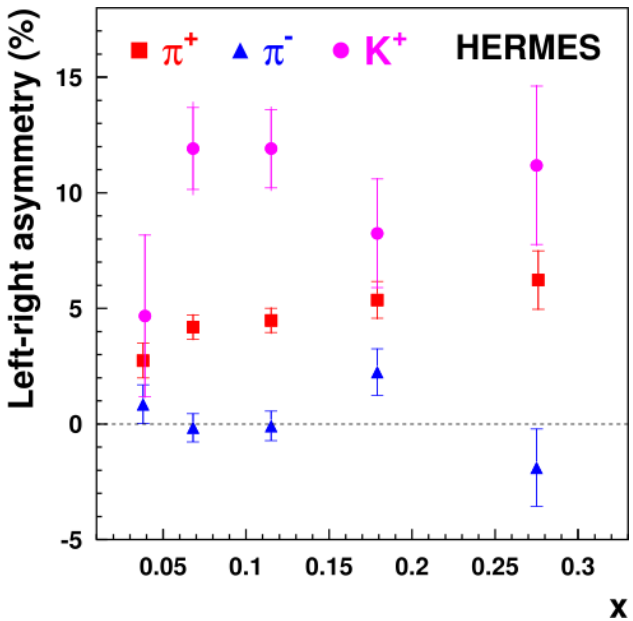
GPD H and E

GPD E only

CLAS12 with help from Halls A & C

3D Parton Distributions: TMDs

A surprise of transverse-spin experiments



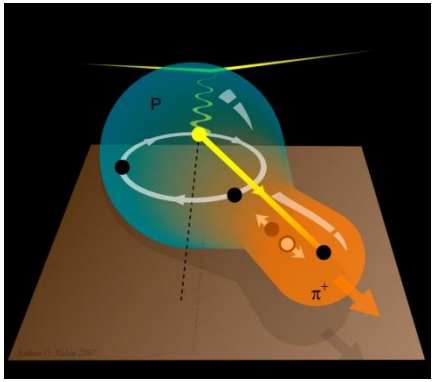
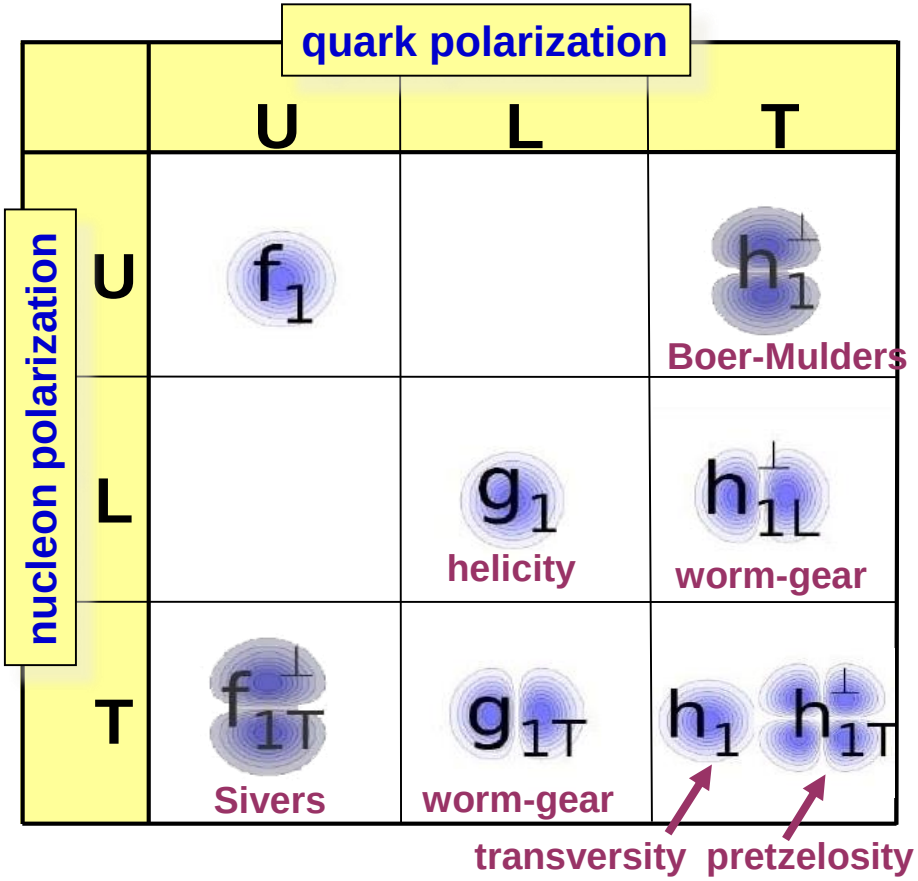
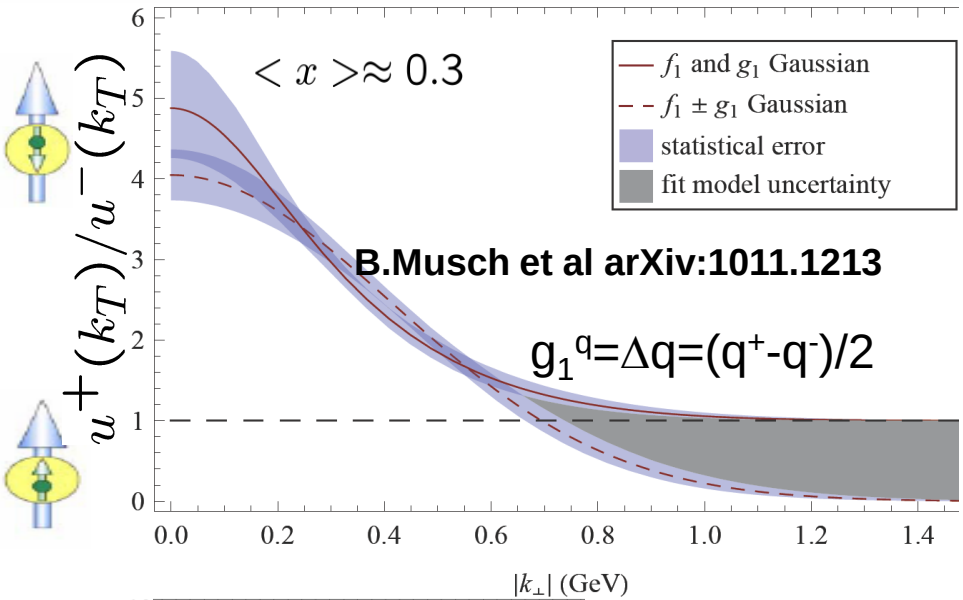


Illustration of the possible correlation between the internal motion of an up quark and the direction in which a positively-charged pion (ud) flies off.

- **Access orbital motion of quarks ➔ contribution to the proton's spin**
- Observables: Azimuthal asymmetries due to correlations of spin q/n and transverse momentum of quarks

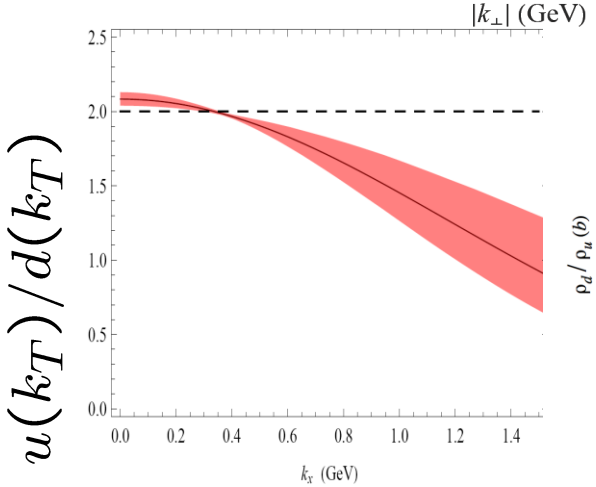


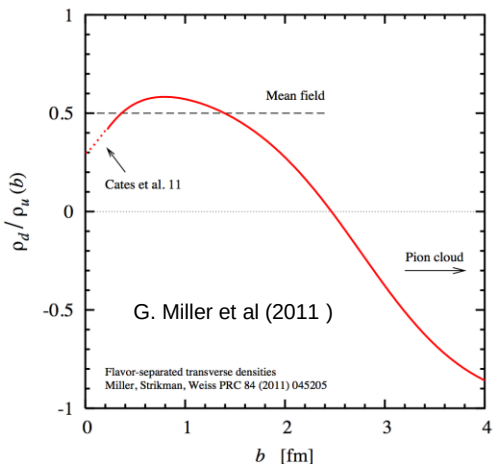
Correlations in quark distributions



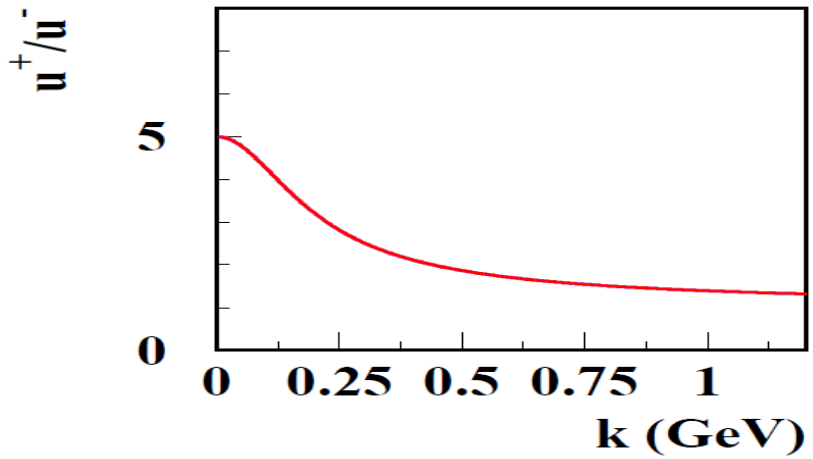
B.Musch et al arXiv:1011.1213

$g_1^q = \Delta q = (q^+ - q^-)/2$

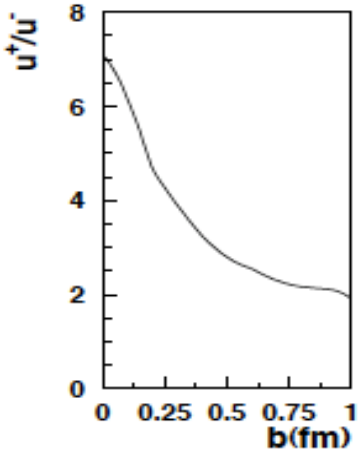


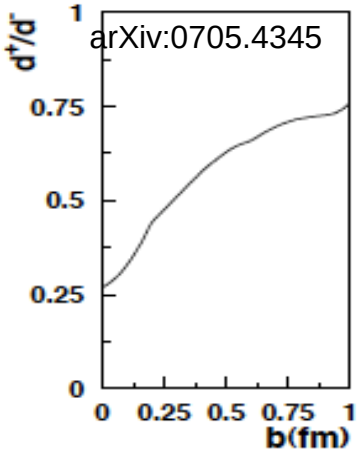


G. Miller et al (2011)



B.Pasquini et al



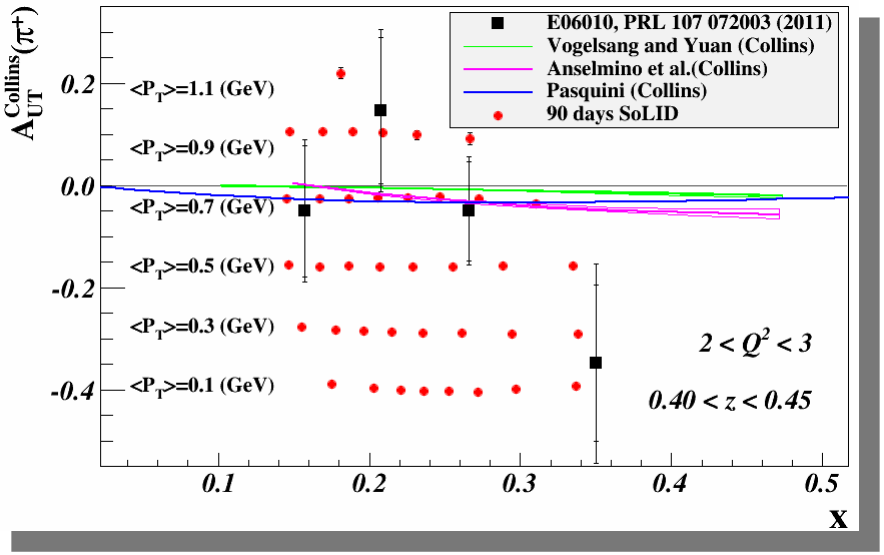


arXiv:0705.4345

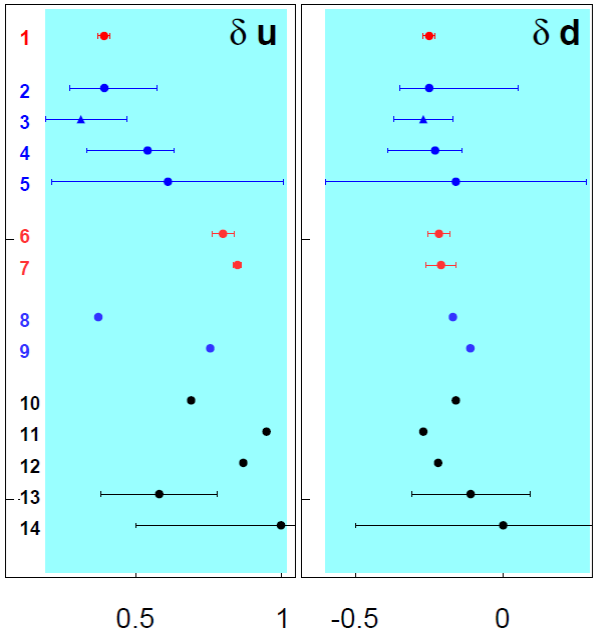
Distributions of PDFs may depend on flavor and spin (lower fraction aligned with proton spin, and less u-quarks at large k_T,b_T)

TMD Program in Hall A with SoLID & SBS

(match large acceptance devices at high luminosity to anticipated polarized 3He target performance)



Tensor Charges



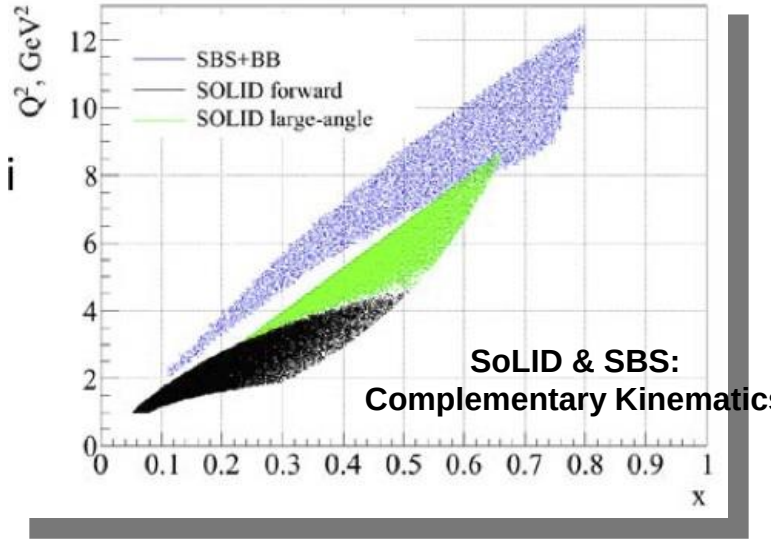
SoLID projections

Extractions from existing data

LQCD

DSE

Models

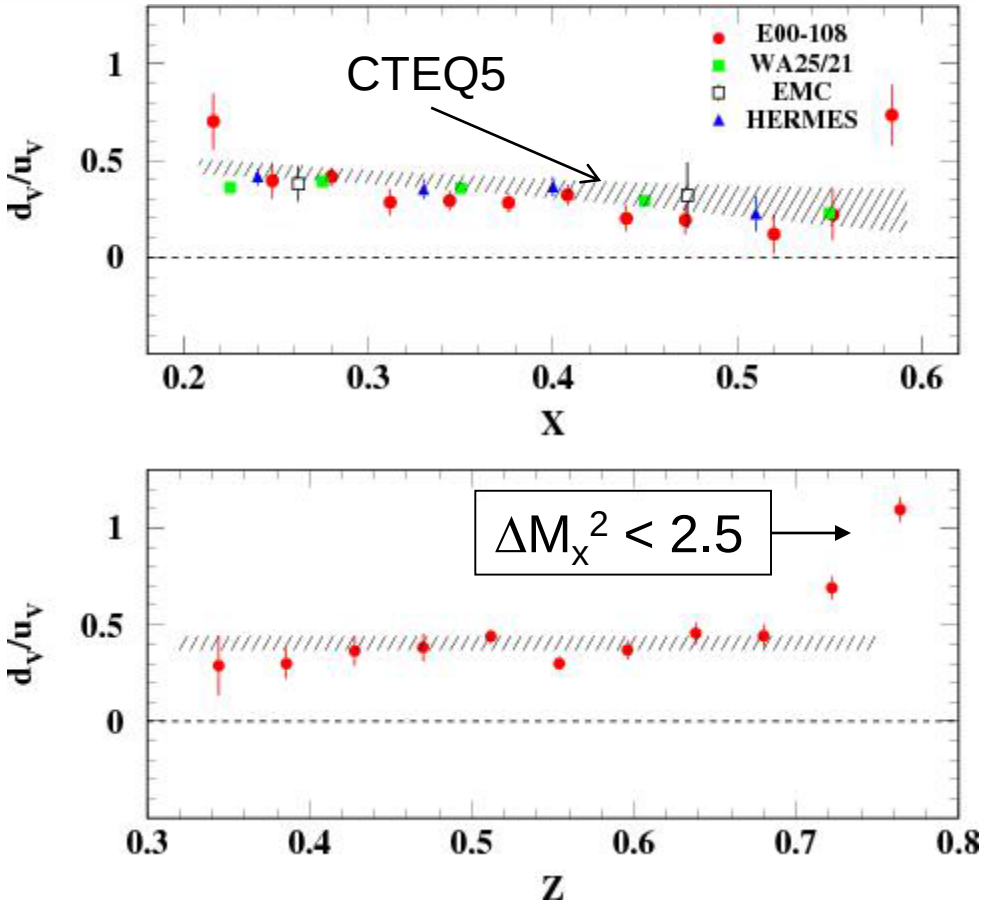


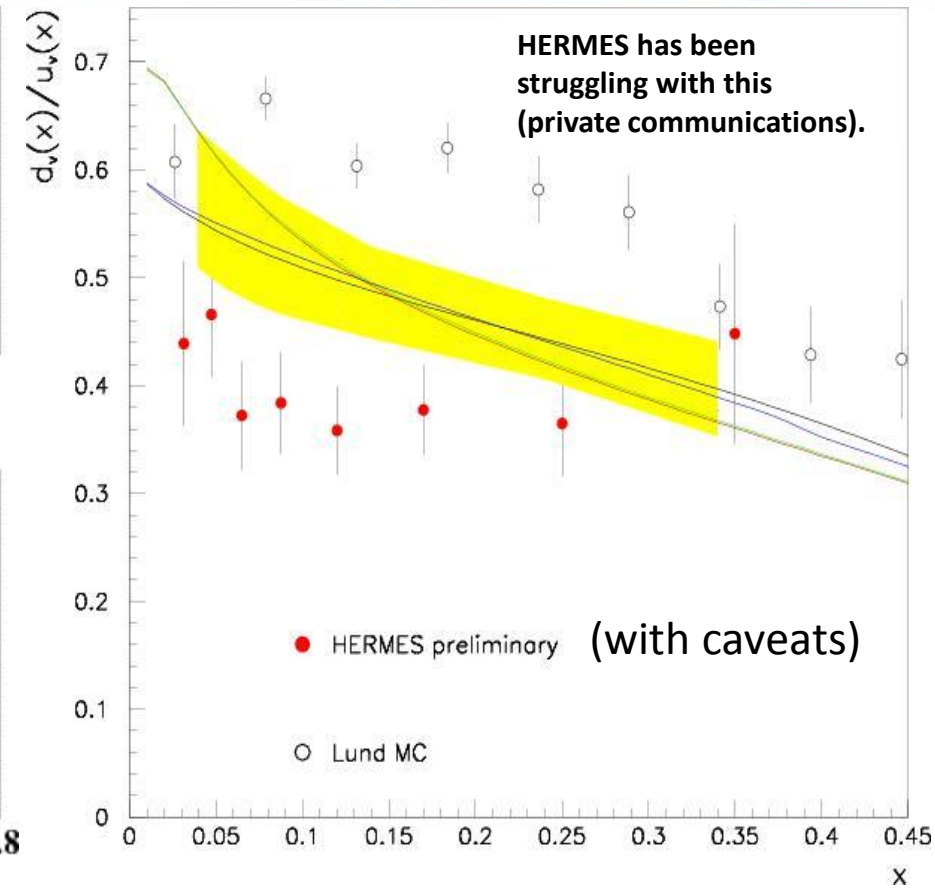
SoLID & SBS: Complementary Kinematics

SoLID projection extraction by A. Prokudin using **only** statistical errors and based on:

- a set of data with a limited range of x values
- the assumption of a negligible contribution from sea quarks
- assumption on Q^2 evolution
- model dependent assumptions on the shape of underlying TMD distributions

Example - The Problem Child: d_v/u_v





As long as we do not quantitatively understand the extraction of a basic and known quantity like d_v/u_v (at intermediate x) from SIDIS data, we should question the SIDIS analysis, and leave no stone unturned to reach final quantitative understanding.

Hall C SIDIS Program – basic (e,e'π) cross sections

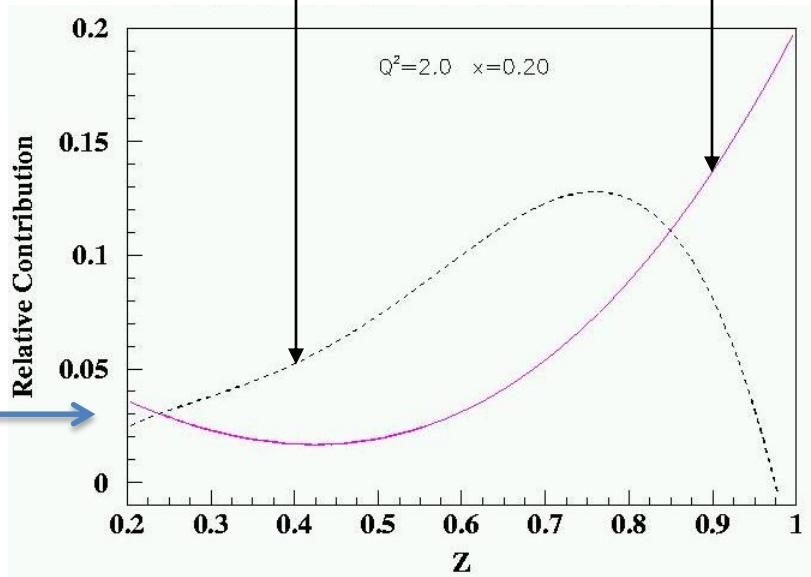
(Hall C's basic SIDIS cross section data at a 6-GeV JLab showed agreement with partonic expectations laying the foundation for a vigorous 12-GeV SIDIS program. PRL 98 (2007) 022001; PL B665 (2008) 20; PRC 85 (2012) 015202. At a 12-GeV JLab, Hall C's role will be again to provide basis SIDIS cross sections, furthering our understanding.)

Low-energy (x,z) factorization, or possible *convolution in terms of quark distribution and fragmentation functions*, at JLab-12 GeV <u>must be</u> well validated to substantiate the SIDIS science output. Many questions at intermediate-large z (~0.2-1) and low-intermediate Q^2 (~2-10 GeV^2) remain.

Further non-trivial contributions to $(e,e'\pi^+)$ Cross Sections:

Contributions from ρ

Radiation contributions, including from exclusive



<u>Why need for $(e,e'\pi^0)$ beyond $(e,e'\pi^{+/-})$?</u>

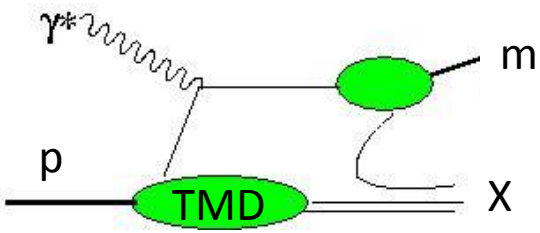
$(e,e'\pi^0)$ experimental advantages:

- ☺ no diffractive ρ contributions
- ☺ no exclusive pole contributions
- ☺ reduced resonance contributions
- ☺ proportional to average D

Hall C SIDIS Program – basic (e,e'π) cross sections

Linked to framework of *Transverse Momentum Dependent Parton Distributions*

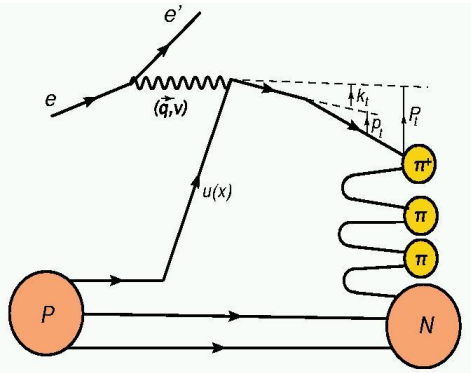
- Validation of factorization theorem needed for most future SIDIS experiments and their interpretation
- Need to constrain TMD evolution w. precision data
- Questions on target-mass corrections and ln(1-z) resummations require precision large-z data



$TMD^q(x,k_T)$

Transverse momentum widths of quarks with **different flavor (and polarization)** can be different

$P_T = p_t + z\, k_t + O(k_t^2/Q^2)$



Hall C goals: Measure the basic SIDIS cross sections of π^+, π^-, π^0 production off the proton, including a map of the P_T dependence ($P_T \sim \Lambda < 0.5$ GeV), to validate(*) flavor decomposition and the k_T dependence of (unpolarized) up and down quarks

(*) Can only be done using spectrometer setup capable of %-type measurements (an essential ingredient of the global SIDIS program!)

Requires SHMS and new ~25 msr Neutral-Particle Spectrometer

Advantages of (e,e'π^0) beyond (e,e'$\pi^{+/-}$)

- Many experimental and theoretical advantages to validate understanding of SIDIS with neutral pions
- Can verify: $\sigma^{\pi^0}(x,z) = \frac{1}{2}(\sigma^{\pi^+}(x,z) + \sigma^{\pi^-}(x,z))$
- Confirms understanding of flavor decomposition/k_T dependence

PAC: "the **cross sections** are **such basic tests of the understanding of SIDIS** at 11 GeV kinematics that they will play a **critical role** in establishing the entire SIDIS program of studying the partonic structure of the nucleon."