Overview of the Jefferson Lab 12 GeV Experimental Program in Halls A, B, and C

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Jefferson Lab

GHP – February 3, 2017

Outline
1. JLab at 12 GeV
2. Semi-inclusive and Deep-exclusive processes
3. Form factors
4. Nuclear Effects
5. …and more

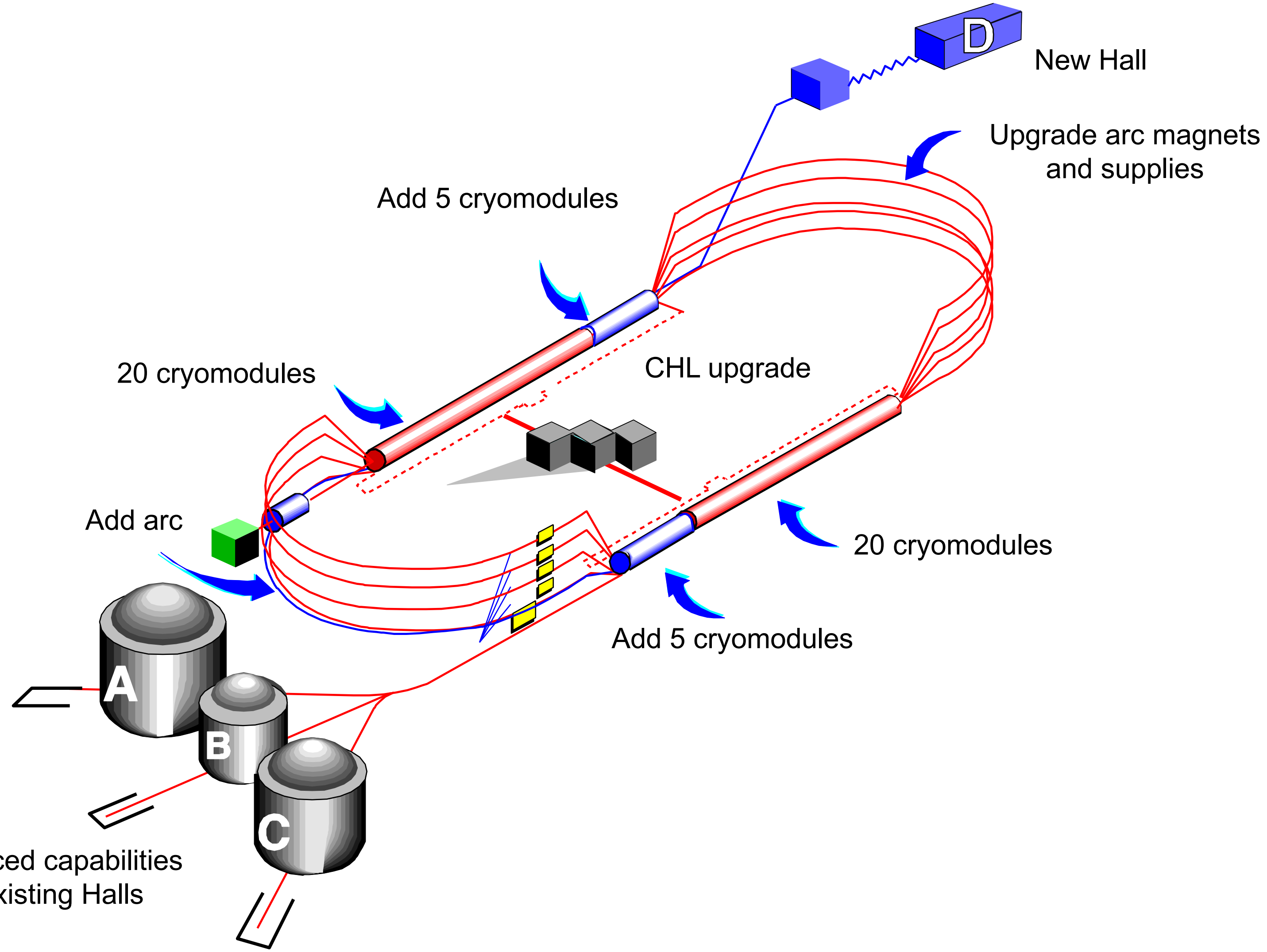
Jefferson Lab 12 GeV Upgrade

JLab 12 GeV Upgrade expands physics reach by doubling maximum available beam energy:

6 GeV → *12 GeV*

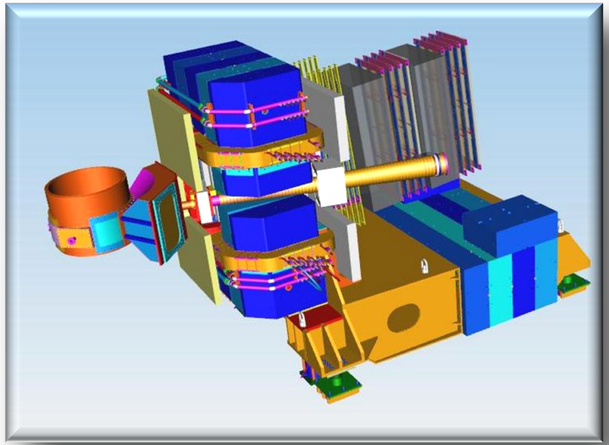
→ **New** experimental Hall D – experiments with (polarized) photons – gluonic excitations in meson spectrum

→ **Halls A, B, and C** will build on their rich 6 GeV program to provide new insight into hadronic structure

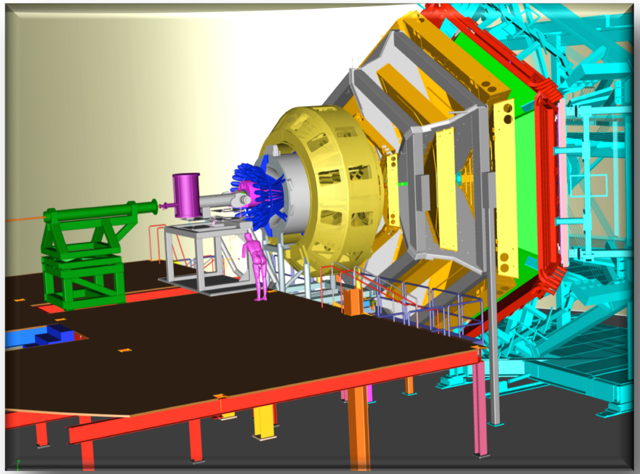


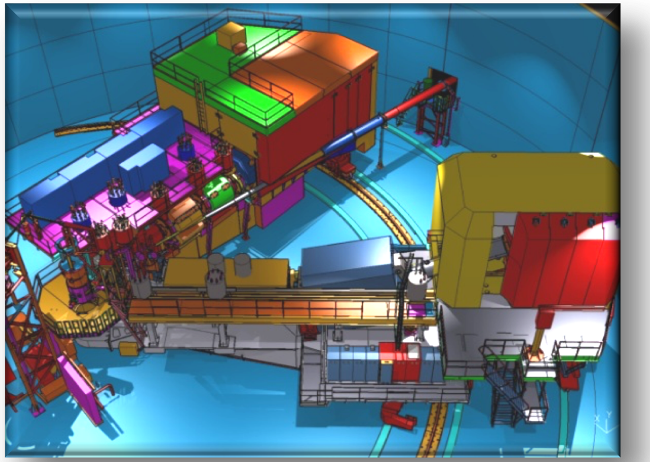
Experimental Capabilities

Hall A
Existing HRS magnetic focusing spectrometers + Big Bite + new, large acceptance Super Big Bite

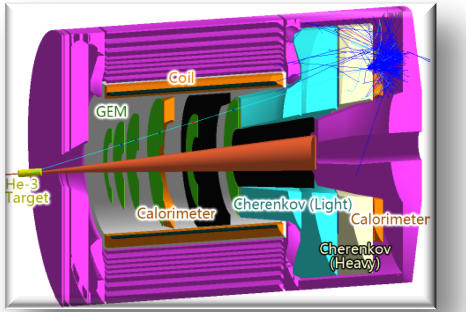


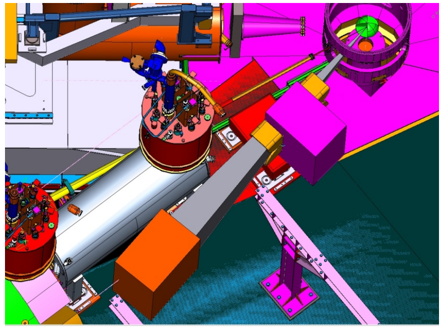
Hall B
New CLAS12, large acceptance spectrometer
→ Good hadron PID
→ Simultaneous measurement of broad phase space

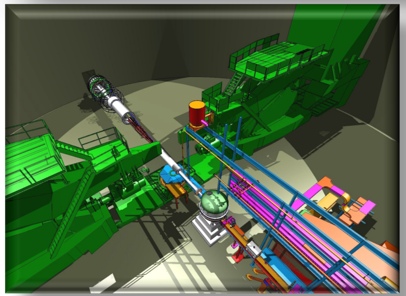




Hall C
HMS + new SHMS magnetic focusing spectrometers
→ Precision cross sections, LT separations





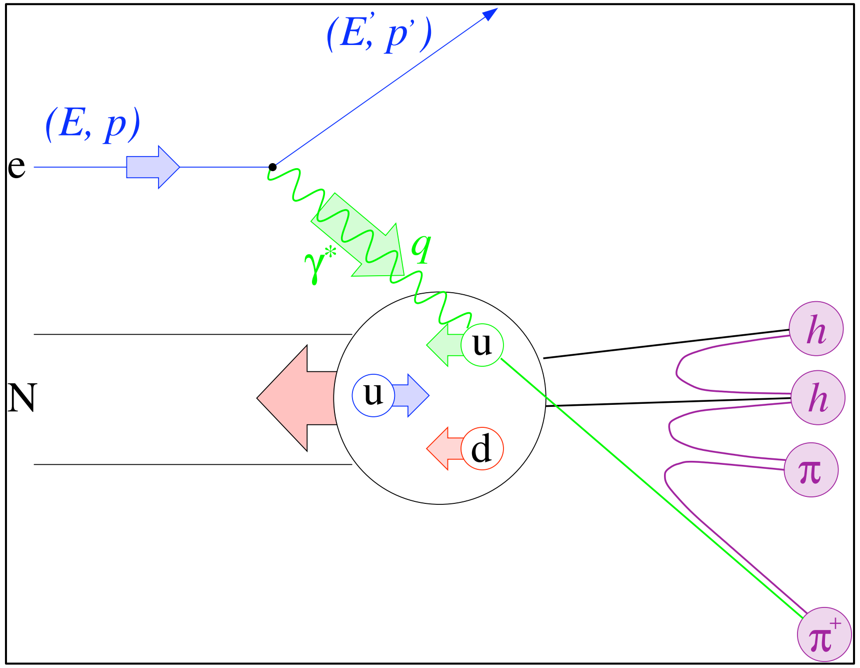


More new equipment in future
→ Hall A: SOLID spectrometer, MOLLER
→ Hall C: Neutral Particle Spectrometer

Semi-inclusive Processes

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

Transverse degrees of freedom allow us to explore k_T dependence of quarks – access to orbital angular momentum
→ Transversity distribution
→ Transverse Momentum Distributions (TMDs)



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

↓

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

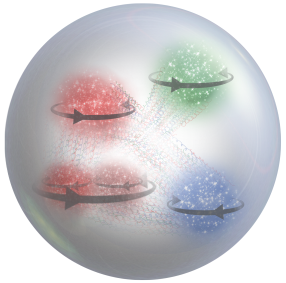
Jefferson Lab

Partonic Structure of Nucleons in 3D

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

quark

nucleon



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

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

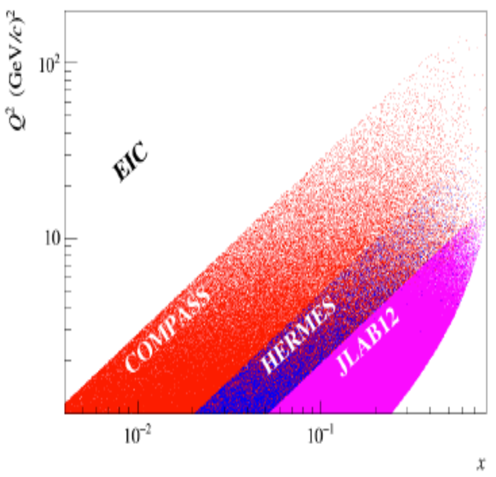
U=unpolarized
L=long. polarized
T=trans. polarized

→ Transverse position and momentum of partons are correlated with the spin of the parent hadron and the spin of the parton itself
→Transverse position and momentum of partons depend on flavor
→Transverse position and momentum of partons correlated with longitudinal momentum

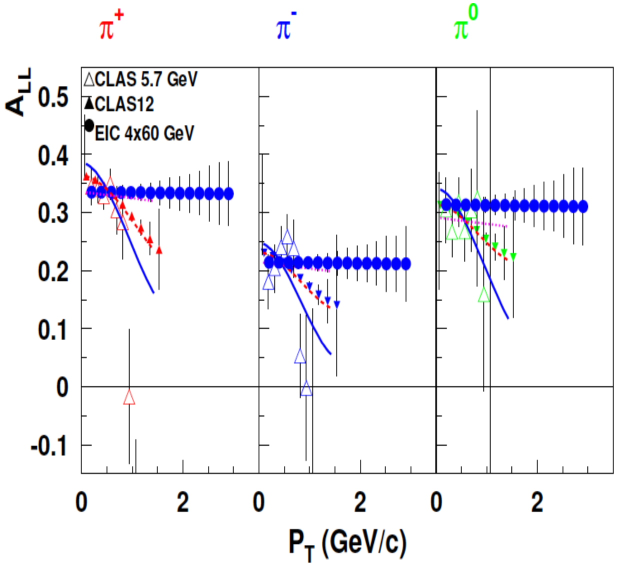
$f_{1T}^{\perp}$ → Sivers function, describes unpolarized quark in trans. pol. nucleon

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

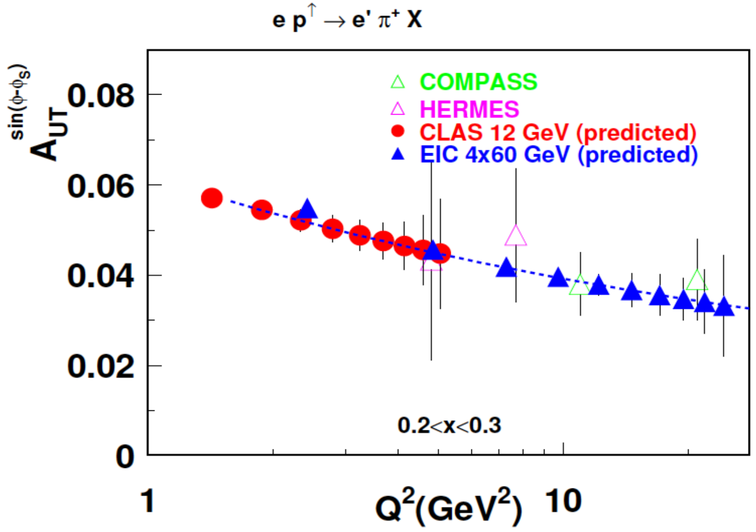
CLAS12: Evolution and k_T-dependence of TMDs



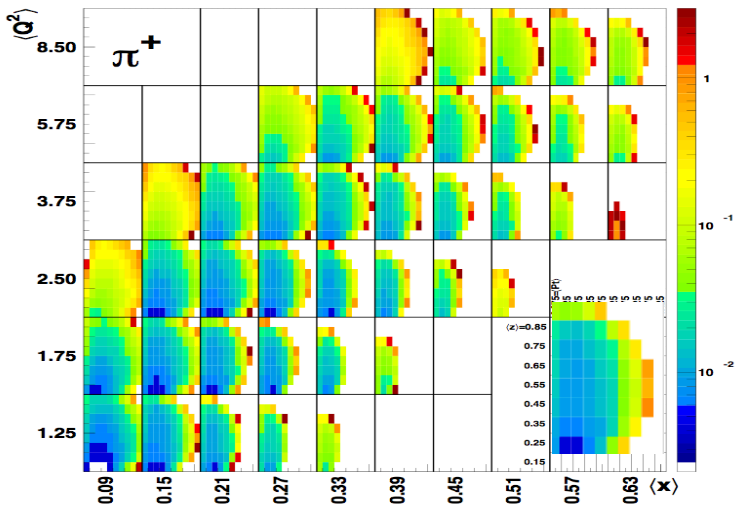
CLAS12 kinematical coverage



k_T-dependence of $g_1(x, k_T)$



Q^2-dependence of Sivers, $f_1^{\perp}(x, k_T)$



- Large acceptance of CLAS12 allows studies of P_T and Q^2-dependence of SSAs in a wide kinematic range
- Comparison of JLab12 data with HERMES, COMPASS (and EIC) will pin down transverse momentum dependence and the non-trivial Q^2 evolution of TMD PDFs in general, and Sivers function in particular.

Hall C – Cross Sections in SIDIS

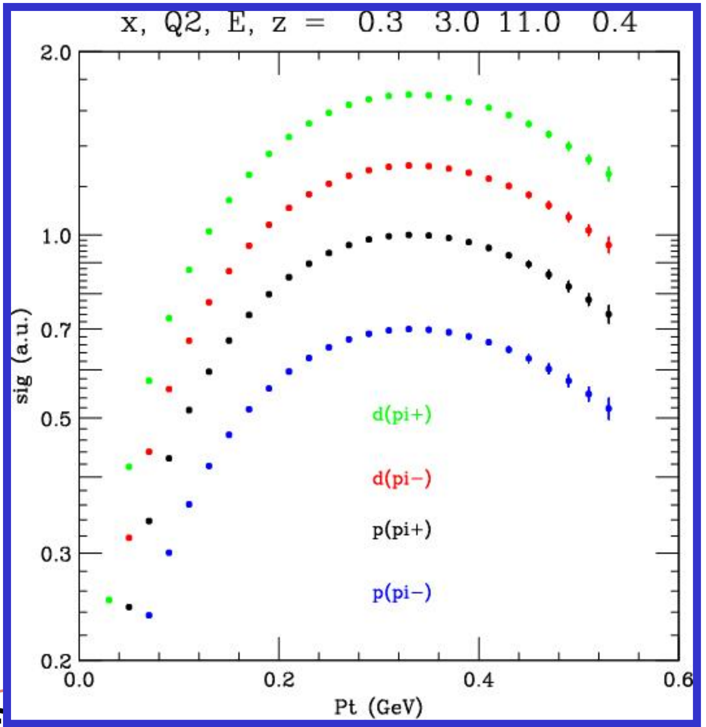
$$\sigma = \sum_q e_q^2 f(x) \otimes D(z)$$

Cross section measurements with magnetic focusing spectrometers (HMS/SHMS) will play important role in JLab SIDIS program

→ Demonstrate understanding of reaction mechanism, test factorization

→ Able to carry out precise comparisons of charge states, $\pi+/\pi-$

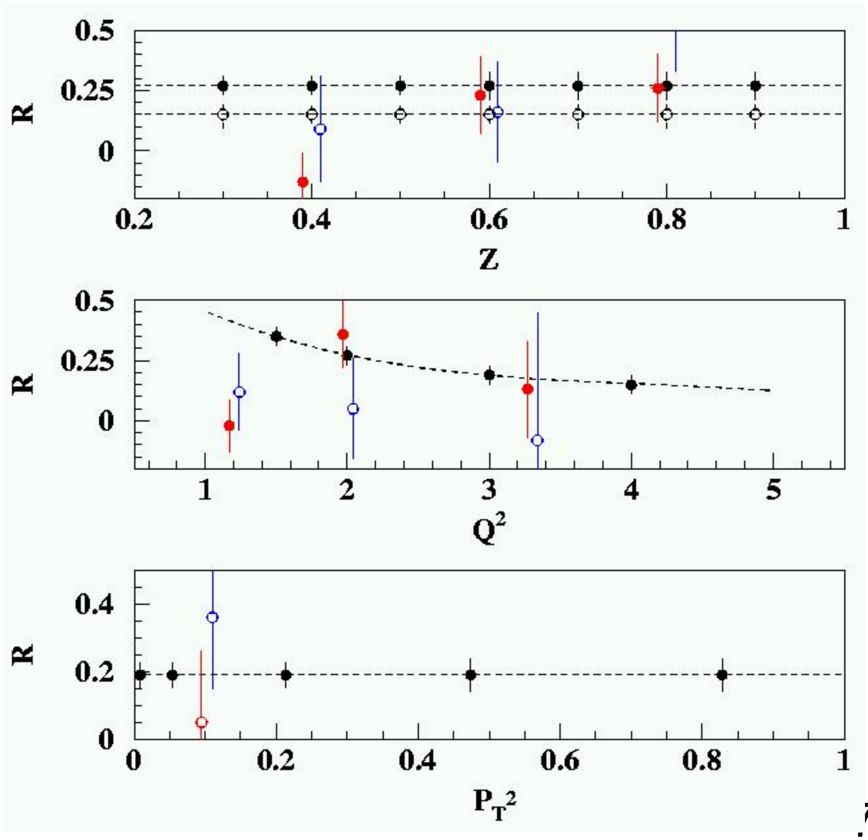
→ Complete ϕ dependence at small P_T, access to large P_T at fixed ϕ



SHMS/HMS will allow precise L-T separations
→ Does $R_{DIS} = R_{SIDIS}$?

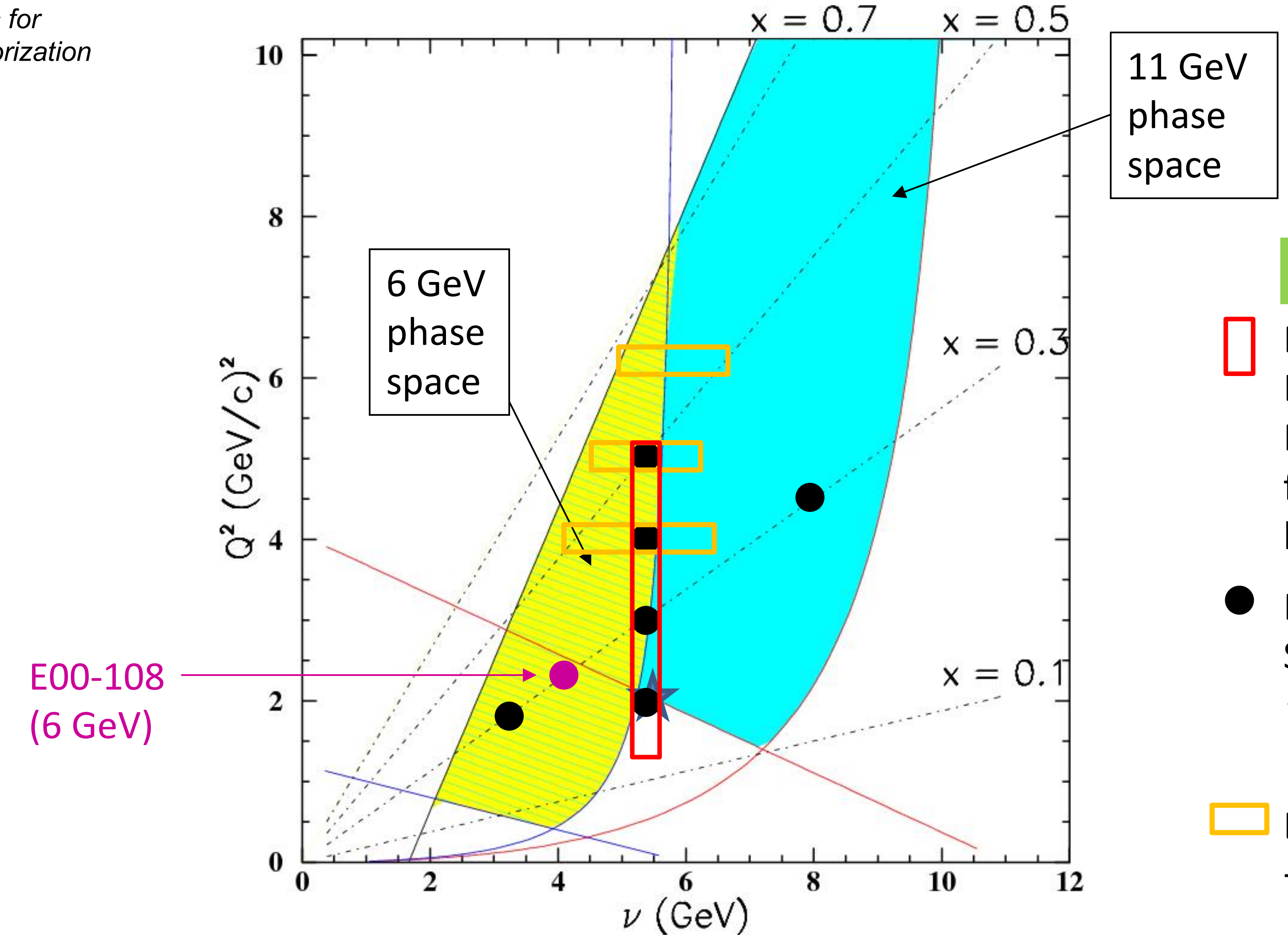
Measure P_T dependence to access k_T depedence of parton distributions

R = σ_L/σ_T in SIDIS (ep → e'$\pi^{+/-}$X)



Hall C SIDIS Program – HMS+SHMS

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



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

Courtesy R. Ent

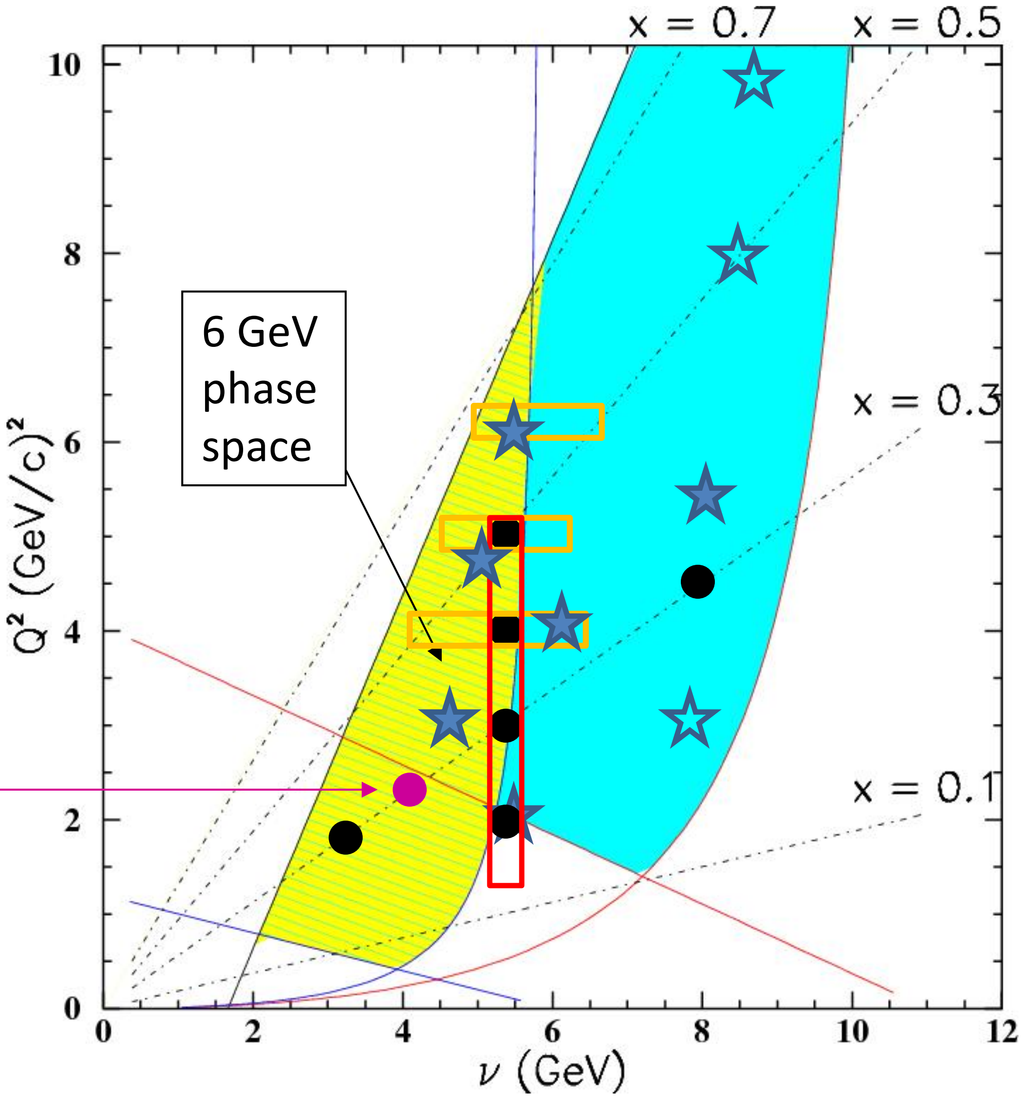
Hall C SIDIS Program – HMS+SHMS+NPS

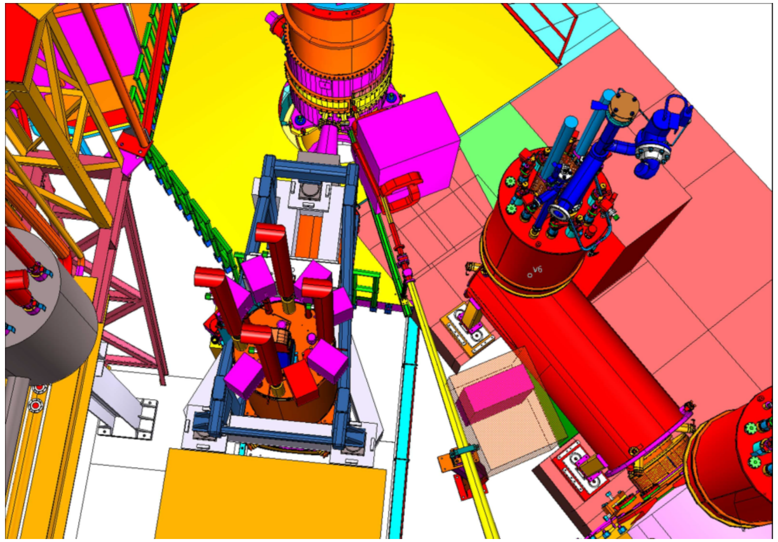
Accurate cross sections for validation of SIDIS factorization framework and for L/T separations

★ 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)

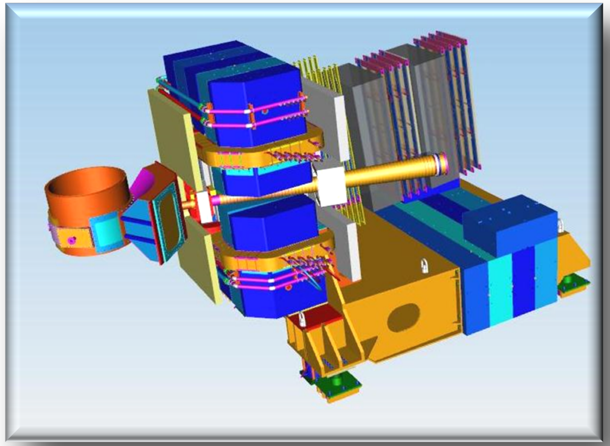




Calorimeter + sweeper magnet adds capability to detect neutral particles (γ and π^0)
→ In addition to broadening SIDIS program, enables DVCS, DVMP (π^0), WACS measurements

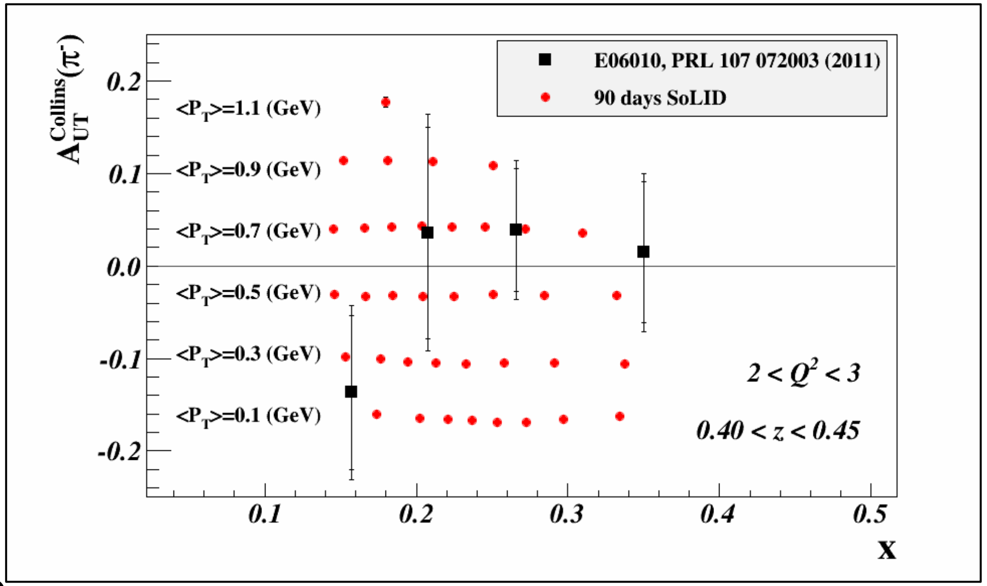
Courtesy R. Ent

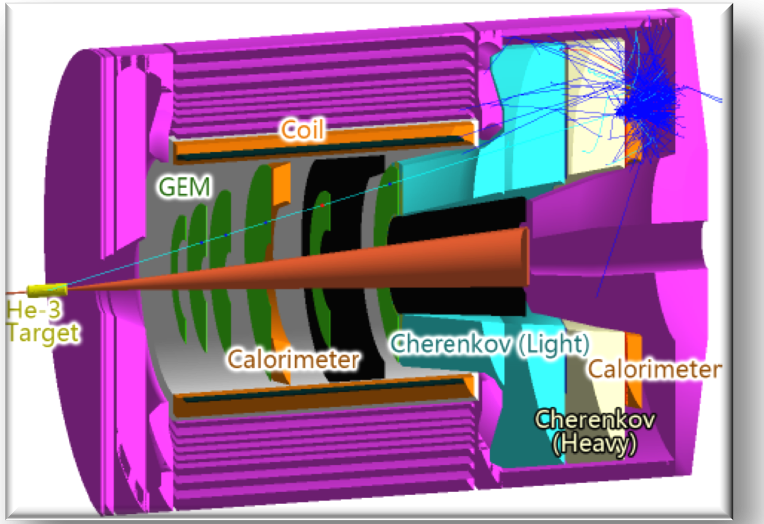
Hall A – SIDIS with Super Big Bite and SOLID



"Near term" – Hall A will use new Super Big Bite Spectrometer (approaching completion) with polarized ^3He target to access Sivers and Collins asymmetries

"Long term" – Solenoid Large Intensity Device (SOLID) will be used to measures SIDIS from polarized ^3He, and NH3 targets → combines large acceptance with high luminosity (10^{36}-10^{37})



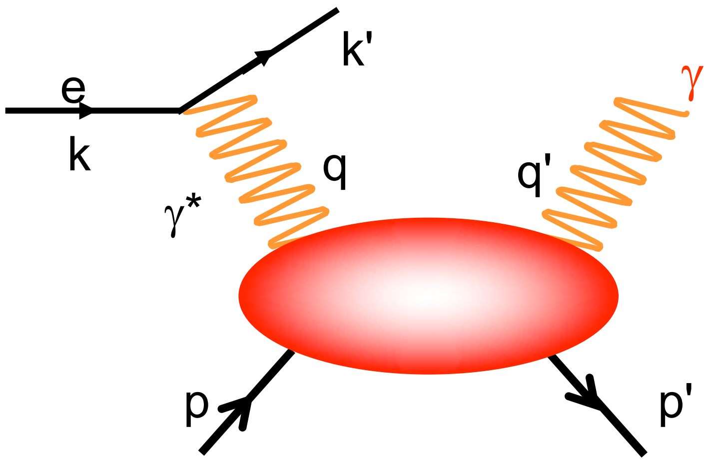


Generalized Parton Distributions

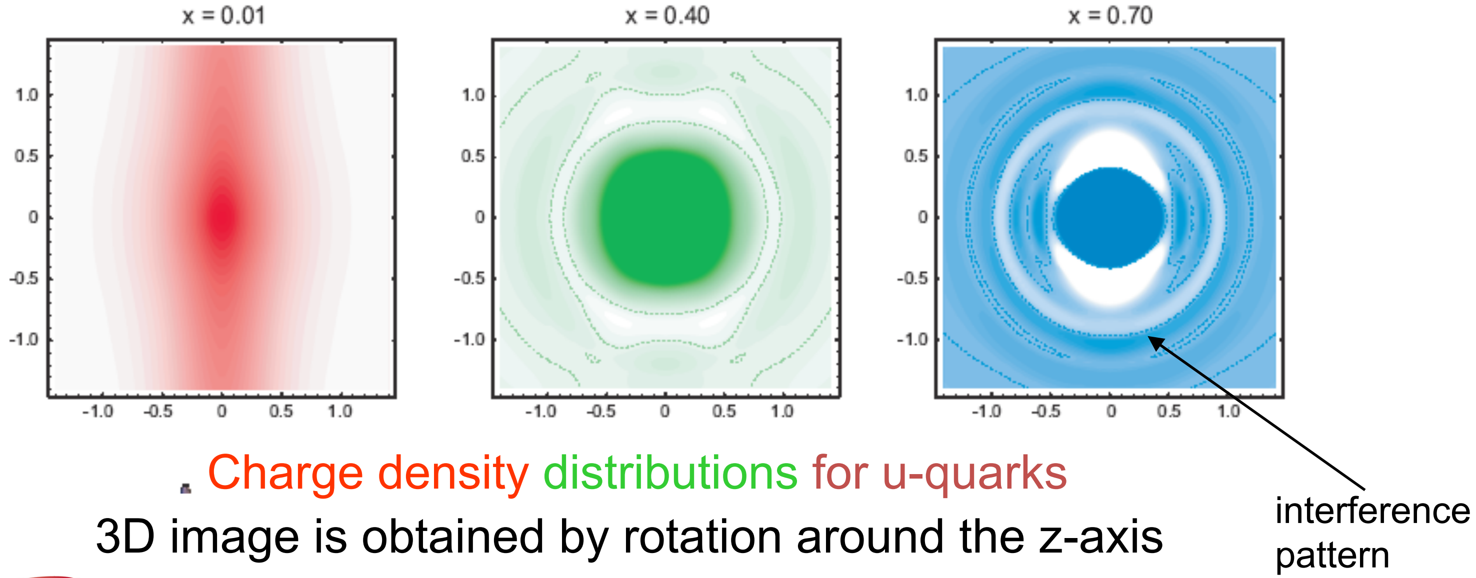
GPDs provide another handle for 3-D mapping of the quark structure of the nucleon.

→ JLab 6 GeV began the first stages of a program of exclusive reactions to access GPDs

→ 12 GeV program will allow a comprehensive GPD program



x = Longitudinal momentum fraction



Charge density distributions for u-quarks

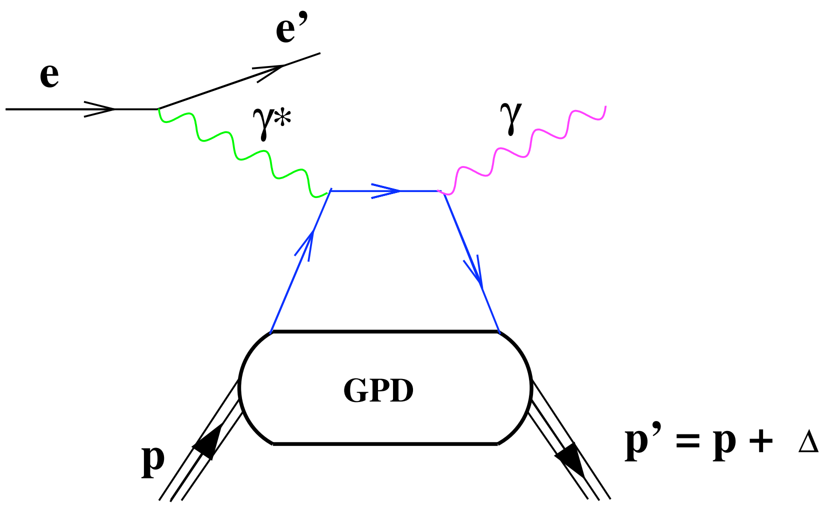
3D image is obtained by rotation around the z-axis

GPD program experimental requirements

→ Need to isolate exclusive channel via missing mass resolution or recoil detector

→ Measure Q^2 dependence at fixed x, access –t dependence

Exclusive Reactions – Leading Twist GPDs



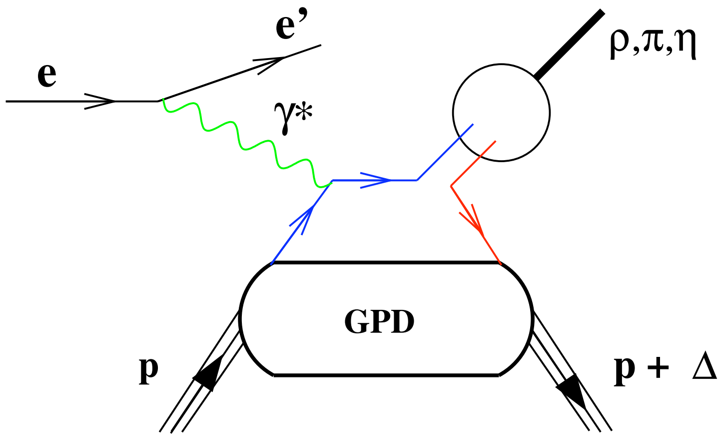
DVCS:

$$H, E, \tilde{H}, \tilde{E}$$

Beam-spin asymmetry → H

Long. target asymmetry → $H, \tilde{H}$

Trans. target asymmetry → E



Meson production:

pseudoscalar mesons (π,η):

$$\tilde{H}, \tilde{E}$$

vector mesons (ρ,ω):

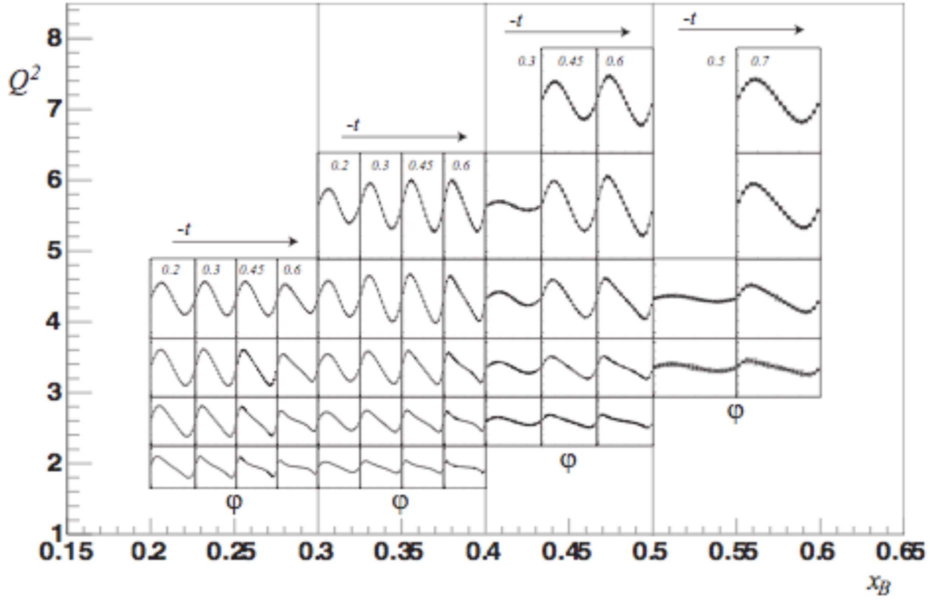
$$H, E$$

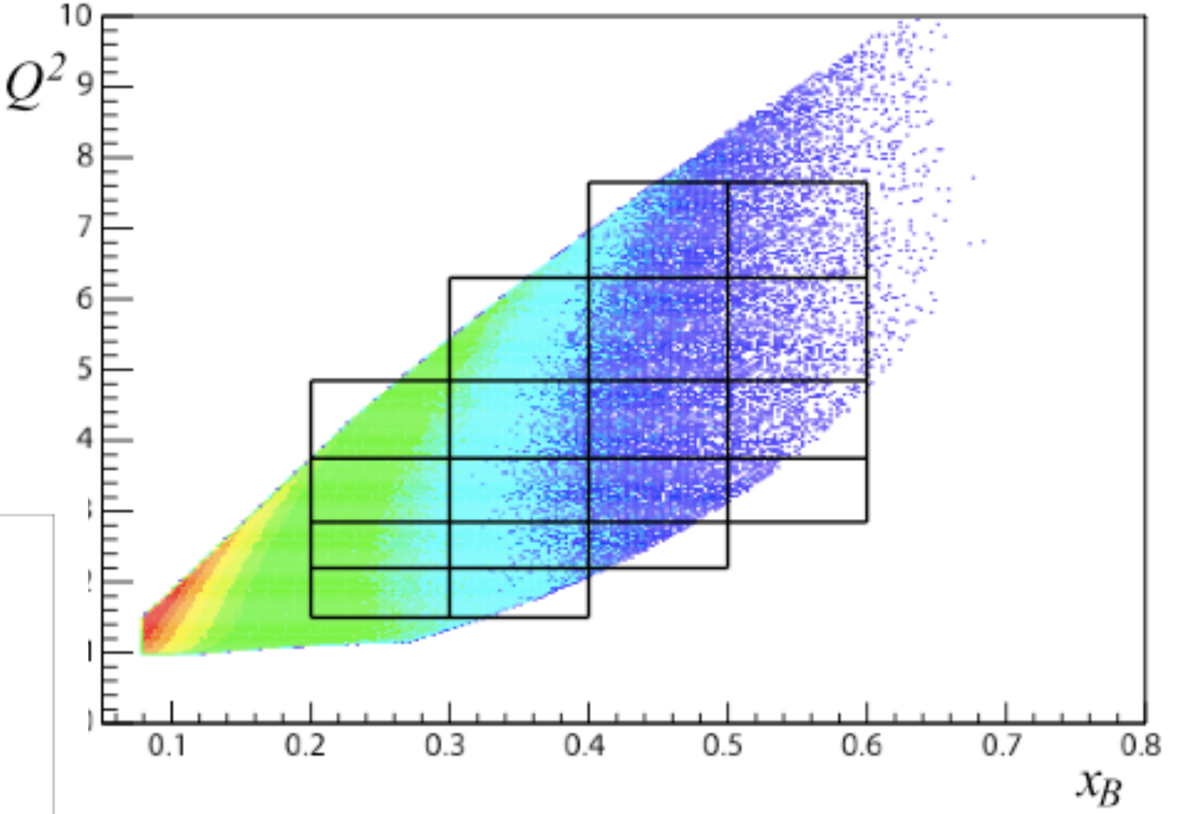
Note: need σ_L

DVCS with CLAS12

12 GeV Hall B DVCS program builds on 6 GeV program → expanded Q^2 and x range

Max Q^2: 4 GeV^2 → 6 GeV^2
Max x: 0.4 → 0.6

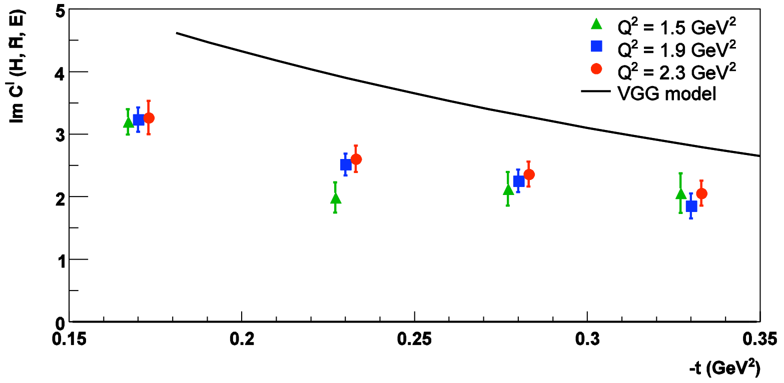




Variety of measurements planned with unpolarized, longitudinally polarized, and transversely polarized targets

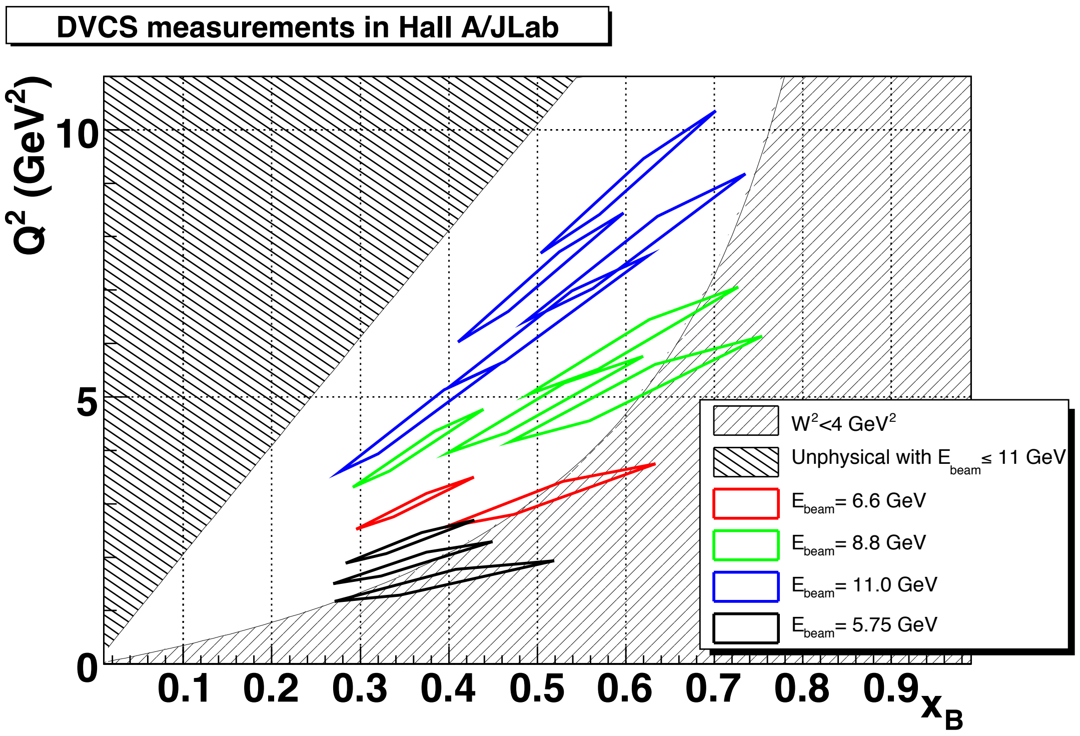
DVCS in Hall A

$$F_1(t)\mathcal{H} + \frac{x_B}{2-x_B}[F_1(t)+F_2(t)]\tilde{\mathcal{H}} - \frac{t}{4M^2}F_2(t)\mathcal{E}$$



[C. Muñoz Camacho et al., PRL**97**, 262002 (2006)]

6 GeV measurements looked at Q^2 dependence of cross sections and asymmetries → test factorization



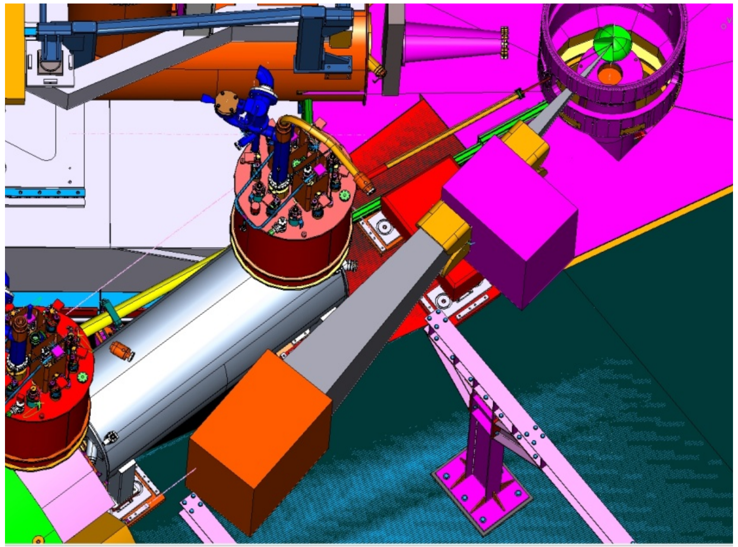
12 GeV experiment greatly increases Q^2 range at fixed x, and –t

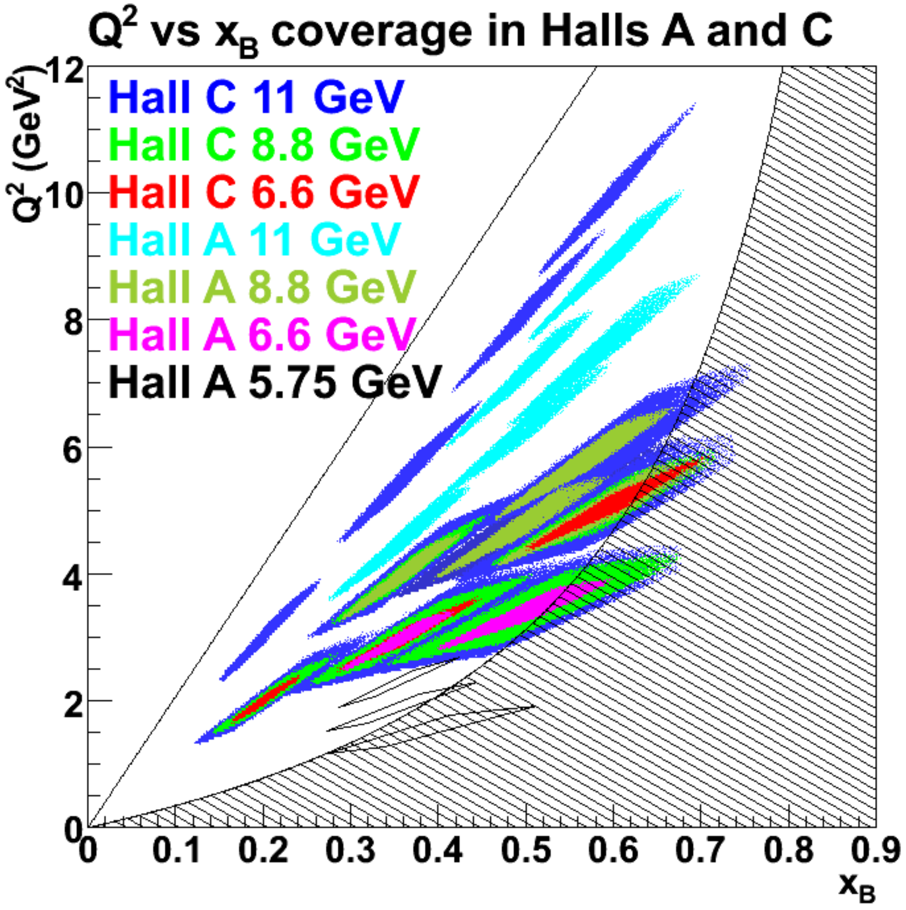
→ Initial running in Hall A recently completed!

Hall A-C DVCS Program

HMS + new NPS in Hall C will allow
→ Measurement of DVCS cross sections to even larger Q^2
→ Energy dependence of DVCS cross at fixed x and Q^2 - allow full deconvolution exclusive photon cross section

In addition – can also access π^0 cross sections.
→ Rosenbluth separation to access σ_L and σ_T separately





Deep Exclusive π^0

σ_L → access to leading twist GPDs (non-pole backgrounds!)

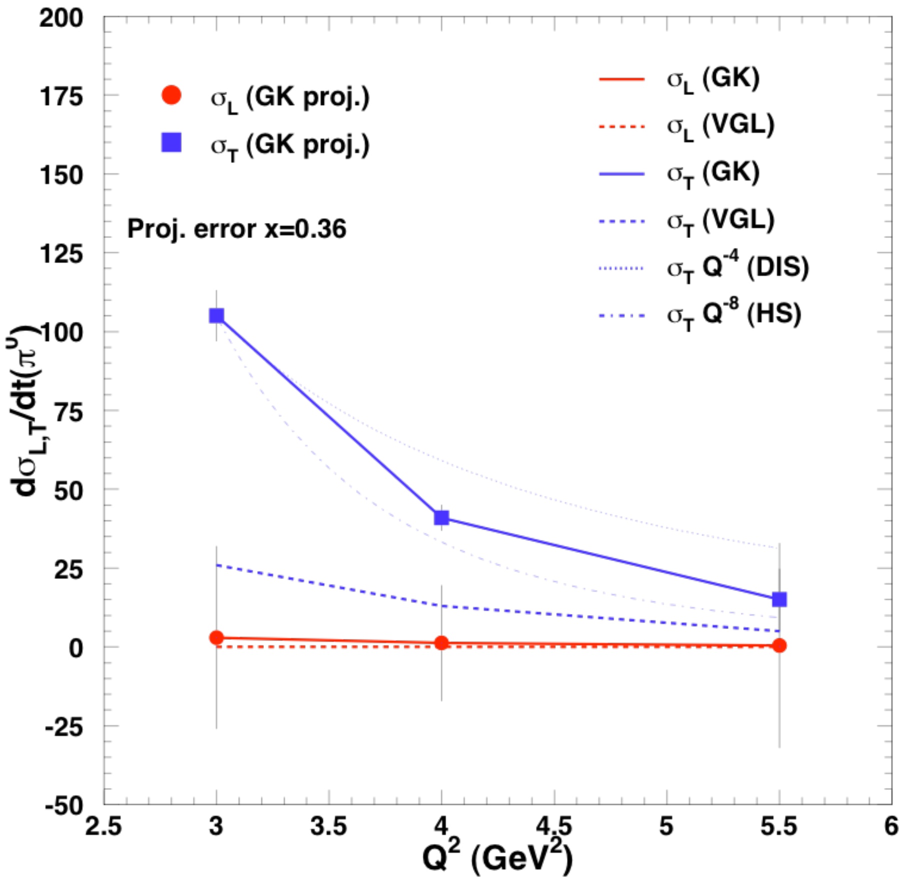
σ_T → access to transversity GPD, H_T

L-T separation required to see if σ_T dominates – if so, can access H_T without LT separation over wide kinematic range → CLAS12

Neutral particle spectrometer in Hall C will allow targeted studies of L/T cross sections

Little existing L-T separated data above resonance region

x=0.36, Q^2=3-5.5 GeV^2
x=0.5, Q^2=3.4, 4.8 GeV^2
x=0.6, Q^2=5.1, 6.0 GeV^2

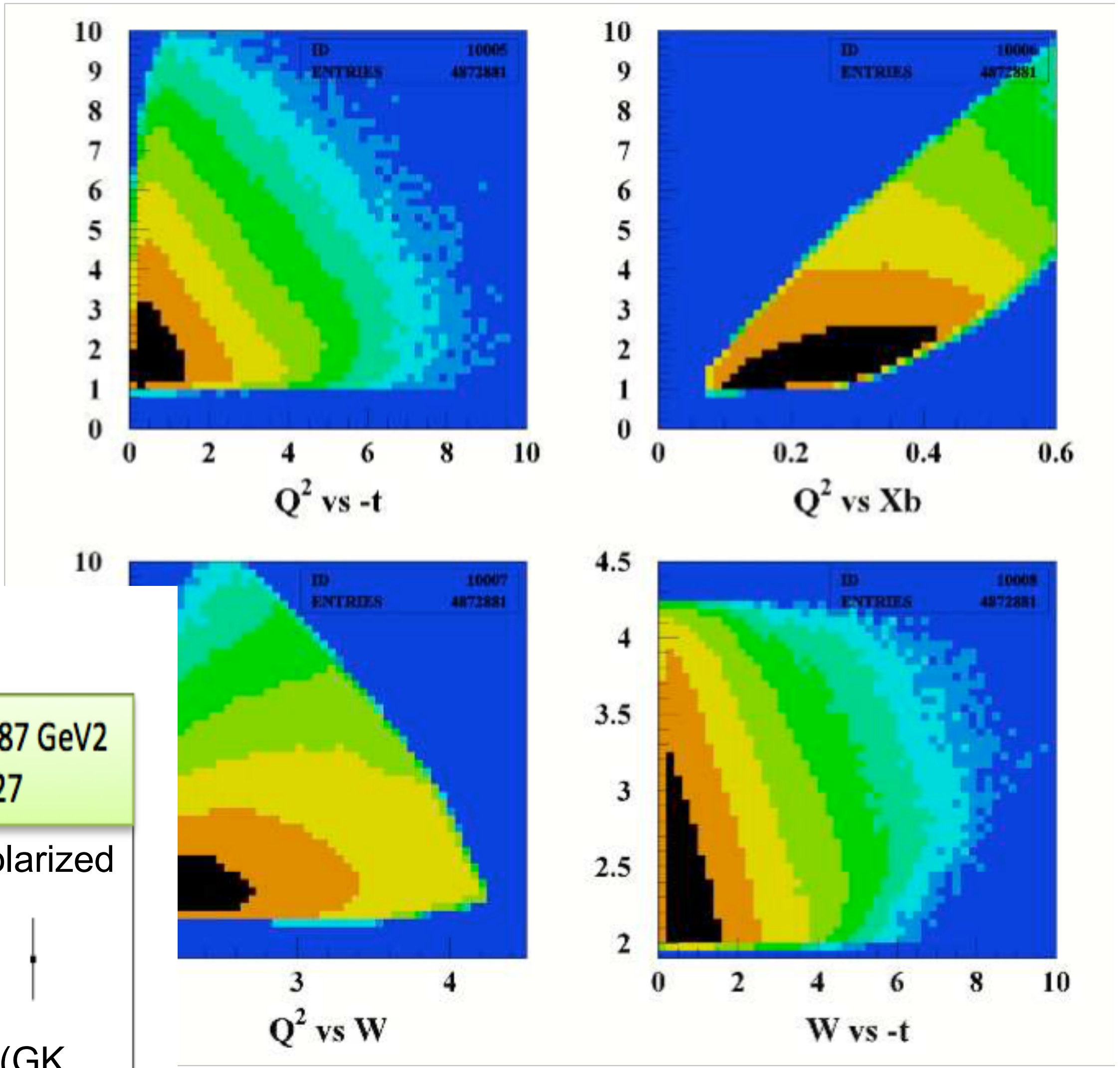


E12-13-10: C. Munoz Camacho, T. Horn, C. Hyde, R. Paremuzyan, J. Roche

Meson Production with CLAS12

Measure cross sections and asymmetries for π^0 and η electroproduction
→ Vector mesons also accessible
→ $\sigma_T + \varepsilon\sigma_L$
→ σ_{TT}, σ_{LT}, $\sigma_{LT'}$

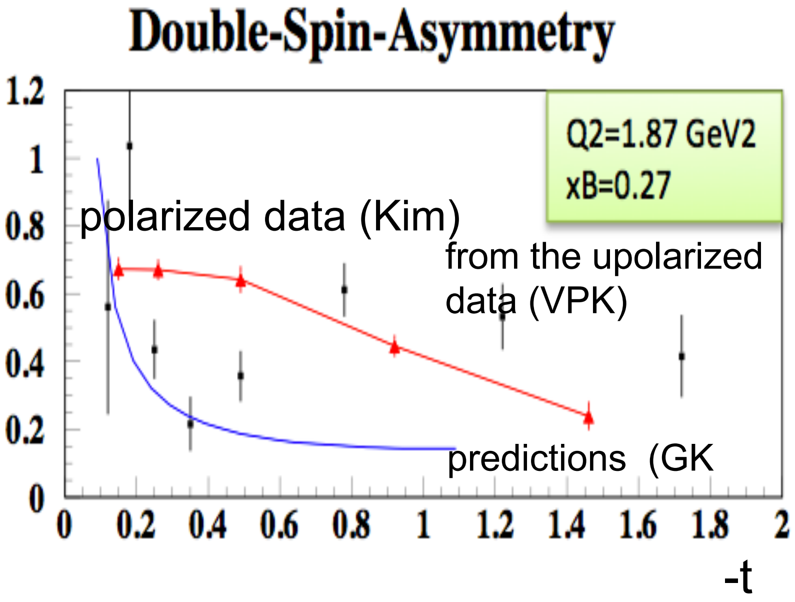
Study Q^2 (at low $-t$) dependence of all to look for evidence of factorization



$$\sigma_{LL}^{const} = \frac{4\pi\alpha}{2k}\frac{\mu_\pi^2}{Q^8}(1-\xi^2)\,|\langle H_T\rangle|^2$$

$$A_{LL}^{const} = \frac{\sqrt{1-\epsilon^2}\,\sigma_{LL}^{const}}{\sigma_T + \epsilon\sigma_L}$$

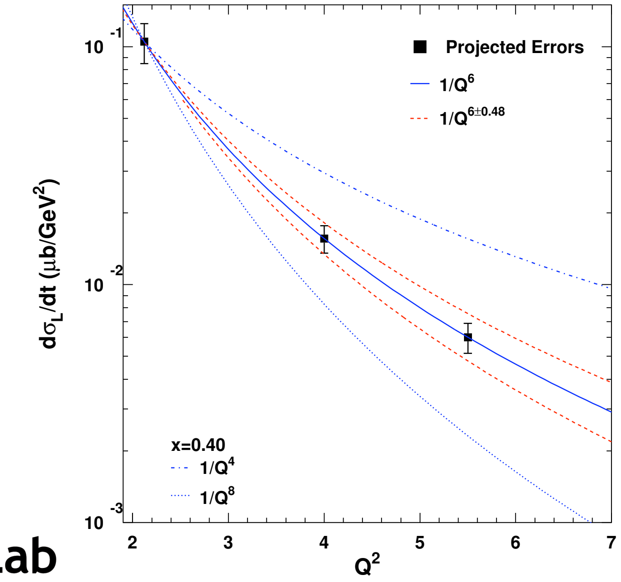
Access Q^2 dependence of H_T via double spin asymmetry

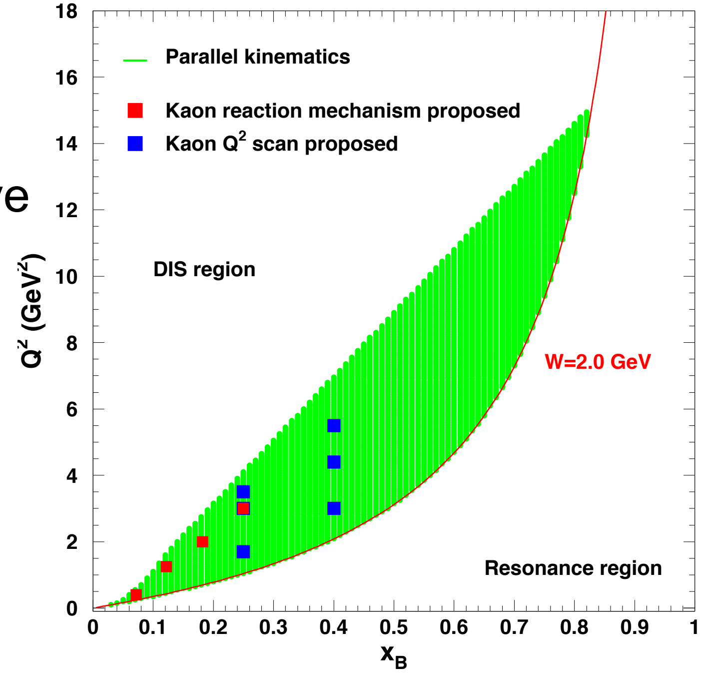


Exclusive π⁺ and K⁺ Production at Large Q^2

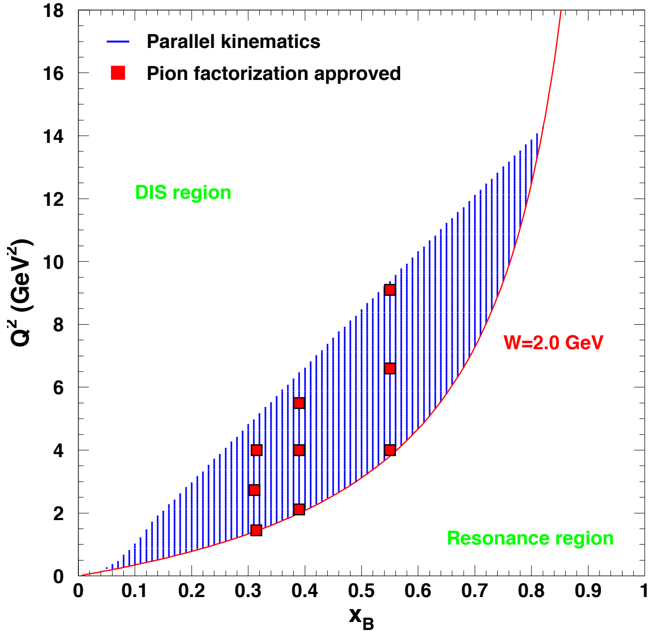
Access to GPDs requires factorization
→ Can be checked using L-T separated cross sections for charged pions and kaons

E12-07-105 and E12-09-011 (Hall C)
Deep exclusive π+ and K+ production:
→ Look for scaling in long. cross section
→ Study reaction mechanism
→ Almost no L-T separated kaon data above resonance region





E12-09-011: T. Horn, G. Huber, P. Markowitz



E12-07-105: T. Horn, G. Huber

Factorization theorem predicts:
$\sigma_L \sim 1/Q^6$
$\sigma_T/\sigma_L \sim 1/Q^2$

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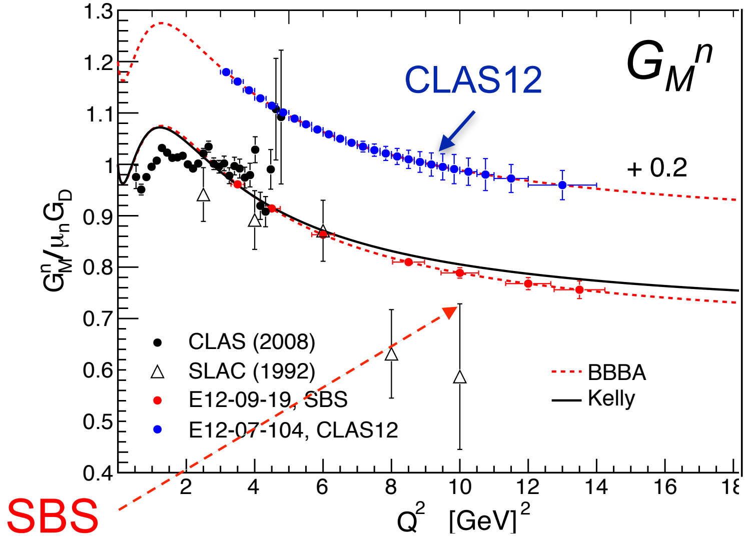
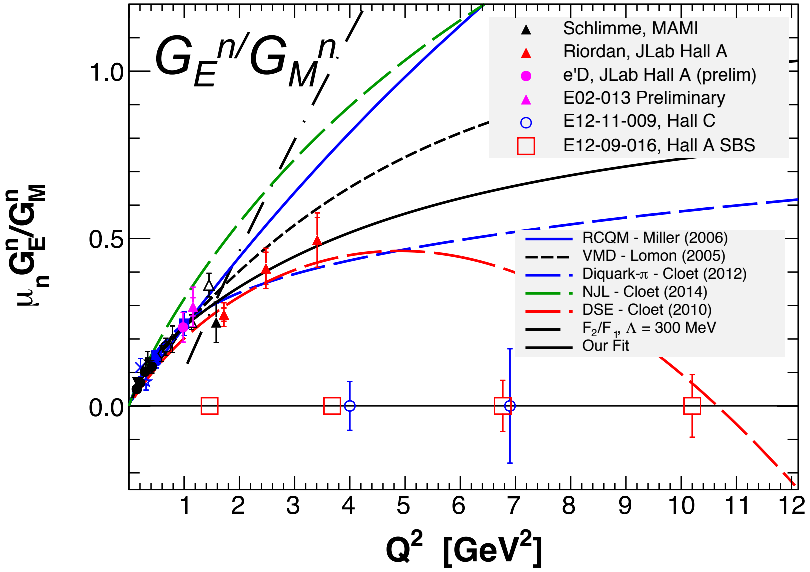
Nucleon Elastic Form Factors

Measurements of nucleon elastic form factors provide still more information with which to test models of quark structure of nucleons → "simplest" reaction (?)

→ 12 GeV program will increase reach and precision for proton and neutron form factors



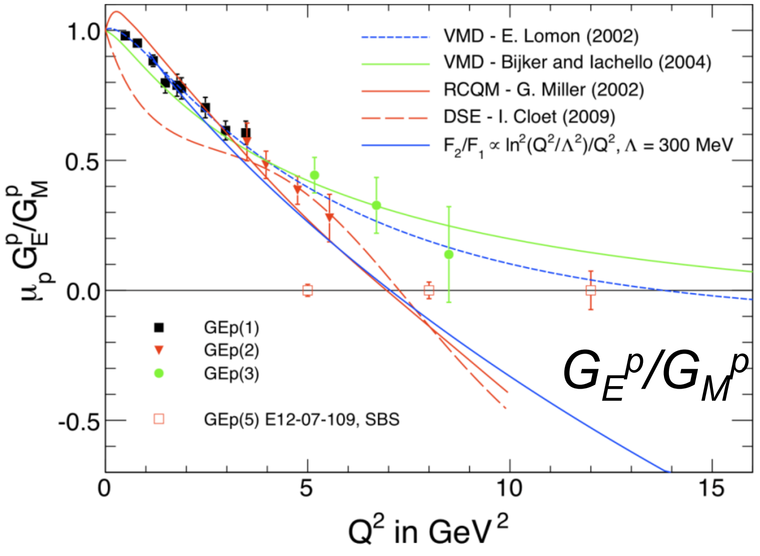
CLAS12 (Hall B)
SBS + BigBite (Hall A)



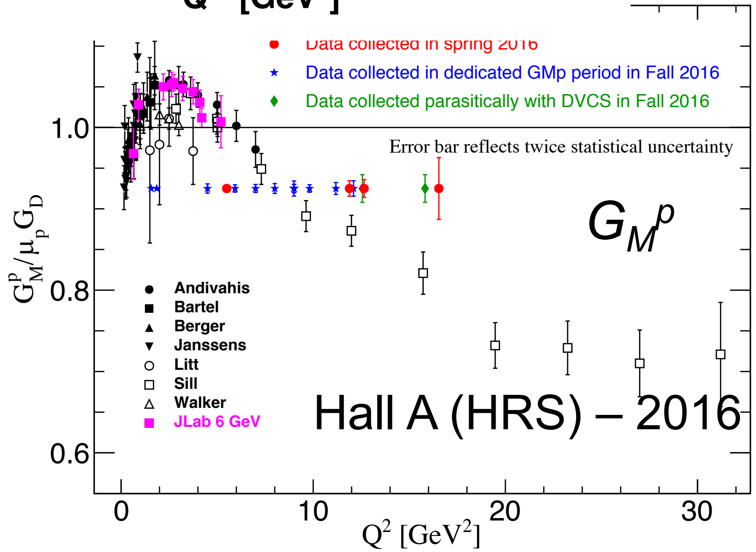
SBS + polarized ^{3}He (Hall A)

Recoil polarization in Hall C

Proton recoil polarization using SBS (Hall A)



Elastic (e,p) cross sections in HRS (Hall A)



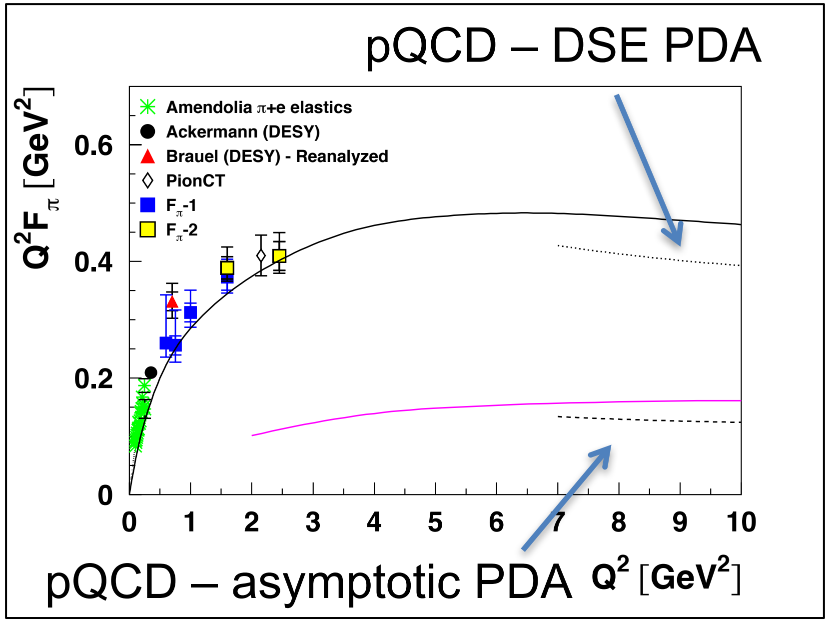
Meson Form Factors: $F_\pi(Q^2)$

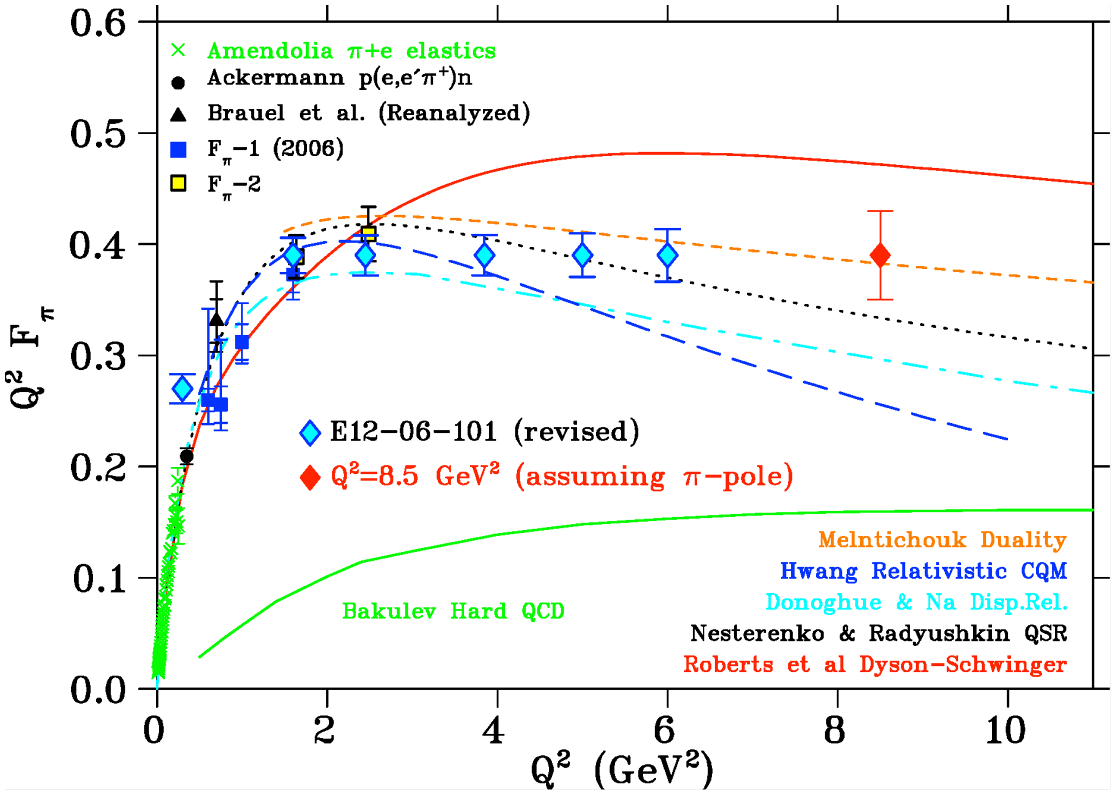
$$F_\pi(Q^2) \xrightarrow[Q^2\to\infty]{} \frac{16\pi\alpha_s(Q^2)f_\pi^2}{Q^2}$$

Is it possible to apply pQCD at experimentally accessible Q^2?

→ Use pion DA derived using DSE formalism

→ DSE-based result consistent with DA derived using constraints from lattice





Projected precision using *R* from VR model

JLab 12 GeV upgrade + HMS/SHMS will allow measurement up to Q^2=*8.5* GeV^2

Tanja Horn's talk (yesterday)

Meson Form Factors: $F_\pi(Q^2)$

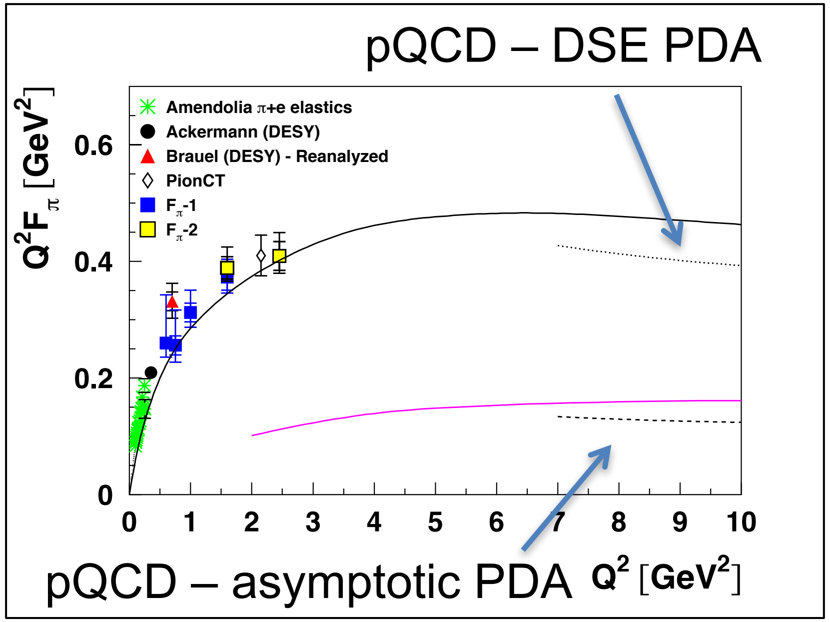
$$F_\pi(Q^2) \xrightarrow[Q^2\to\infty]{} \frac{16\pi\alpha_s(Q^2) f_\pi^2}{Q^2}$$

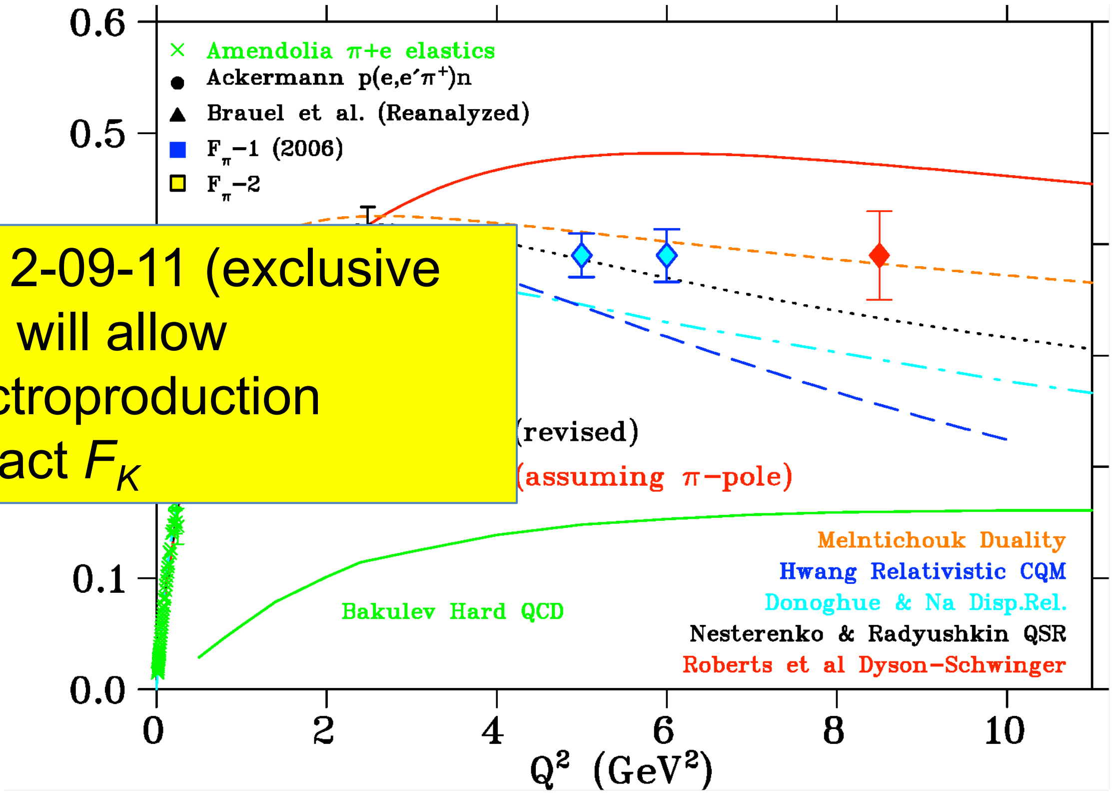
Is it possible to apply pQCD at (accessible Q^2?

→ Use pion DA derived using D

→ DSE-based result consisten derived using constraints fro

Data taken as part of E12-09-11 (exclusive Kaon electroproduction) will allow exploration of using electroproduction technique a la F_π to extract F_K





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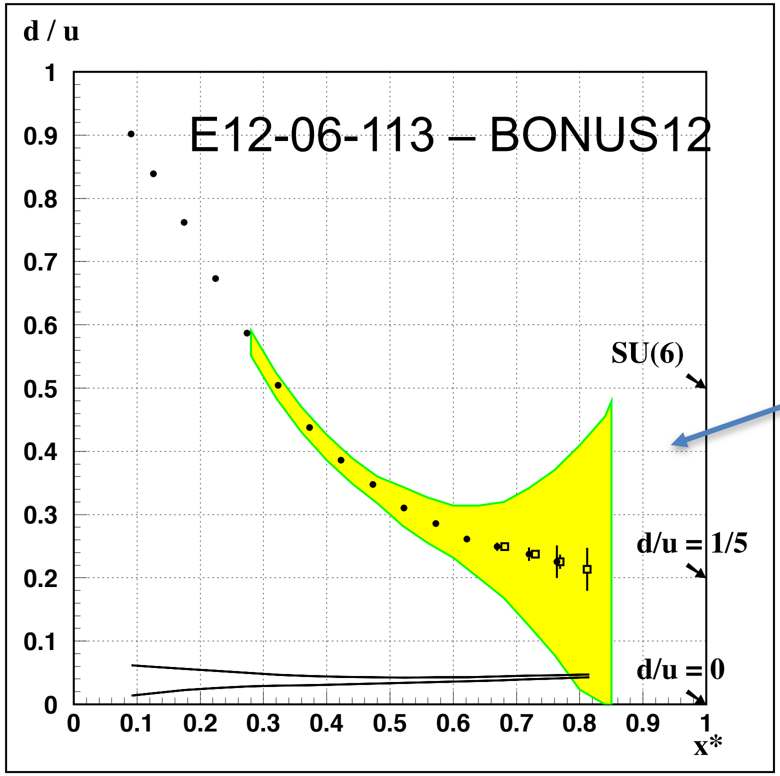
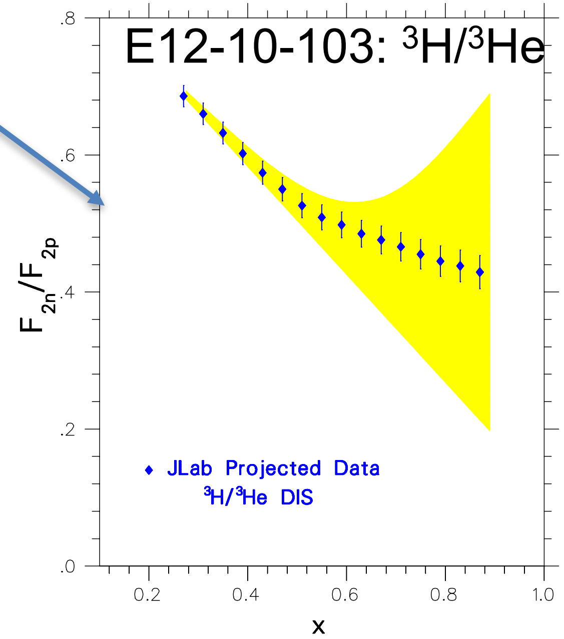
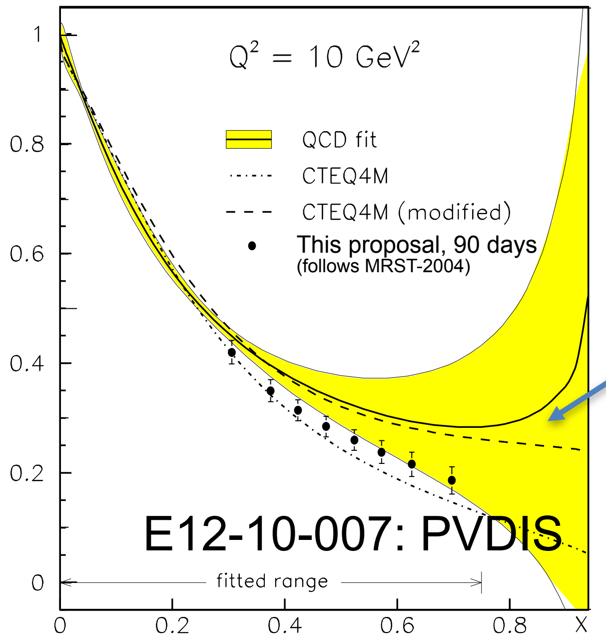
Future Measurements of $F_2^n/F_2^p \rightarrow d/u$



Hall B: CLAS12 with recoil proton detector → tag low momentum neutrons in deuterium

Hall A: Standard HRS with ^3H target



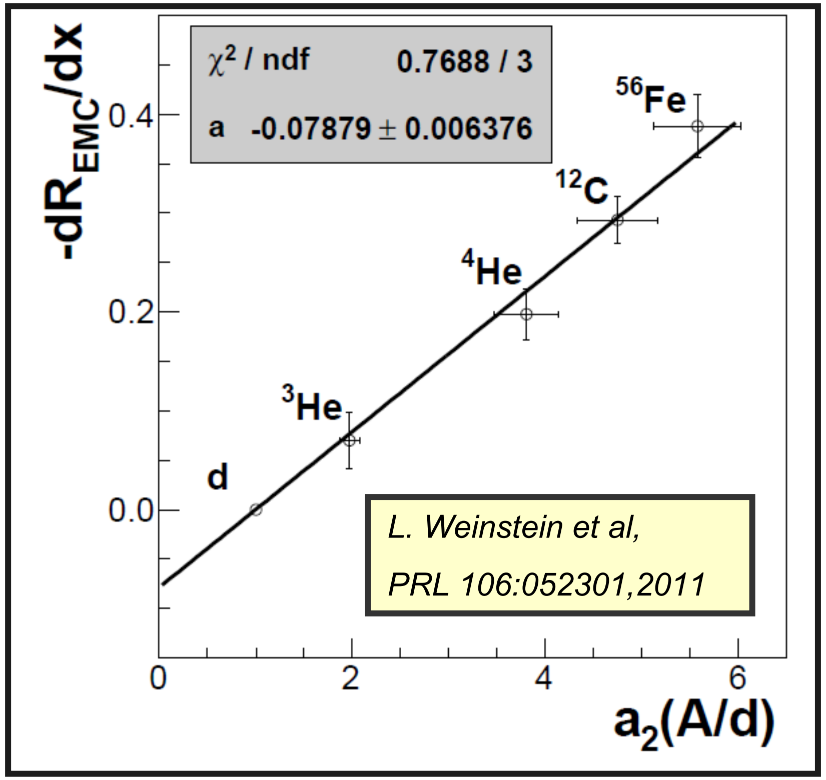


Hall A: PVDIS with SOLID

JLAB-12 GeV will allow extraction of d/u using a variety of techniques

1. Spectator tagging (BONUS)
2. PVDIS
3. Mirror nuclei $^3H/^3He$

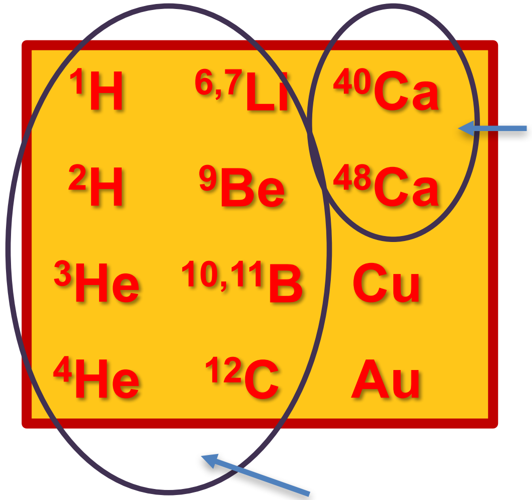
Hadrons in Nuclei - EMC Effect and SRCs



A major result for the Jlab 6 GeV program was the observed linear correlation between size of EMC effect and Short Range Correlation "plateau"

→Observing Short Range Correlations requires measurements at *x*>1

→ Reaction dynamics very different – DIS vs. QE scattering, why the same nuclear dependence?



Examine isospin dependence

A dependence in light nuclei, some with significant cluster structure

Additional information from ^{3}H/^{3}He from **Hall A** experiments using special tritium target
→E12-10-103 (DIS)
→E12-11-112 (x>1)

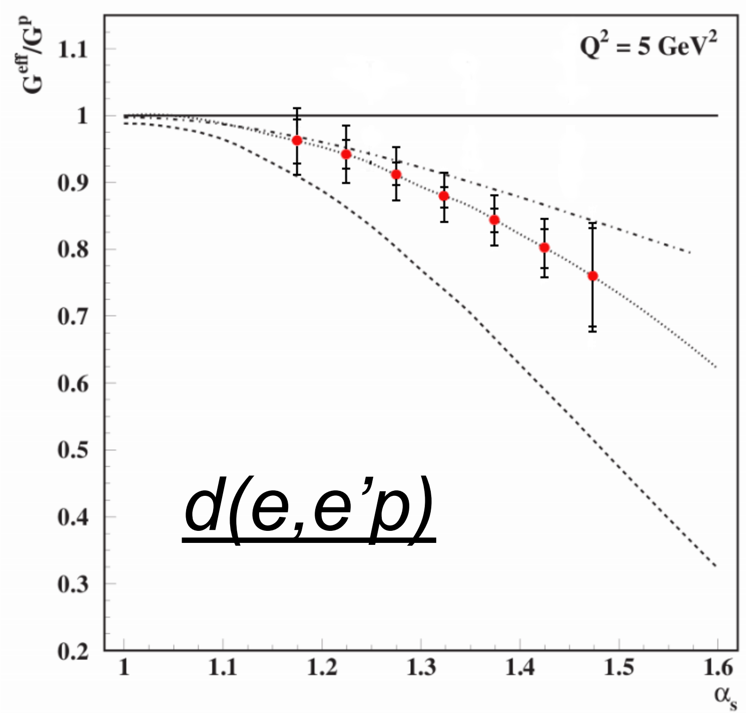
Two 12 GeV Hall C experiments will join forces to further explore this connection w/more nuclei
→E12-06-105 x>1
→E12-10-008 EMC Effect

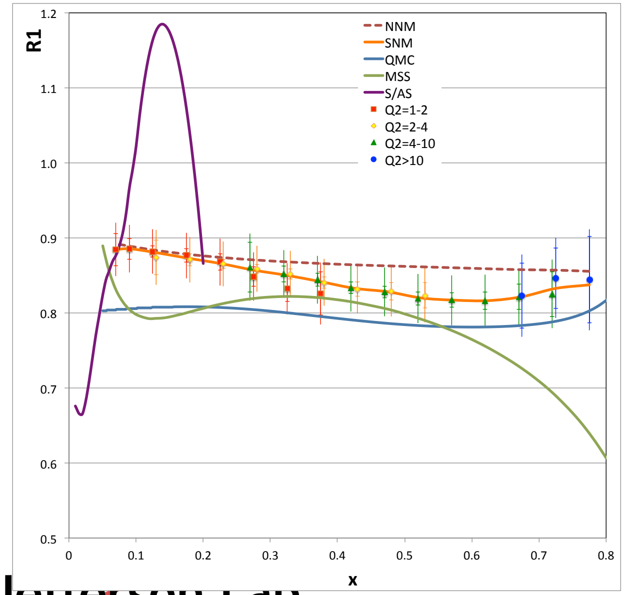
In-Medium Structure Functions

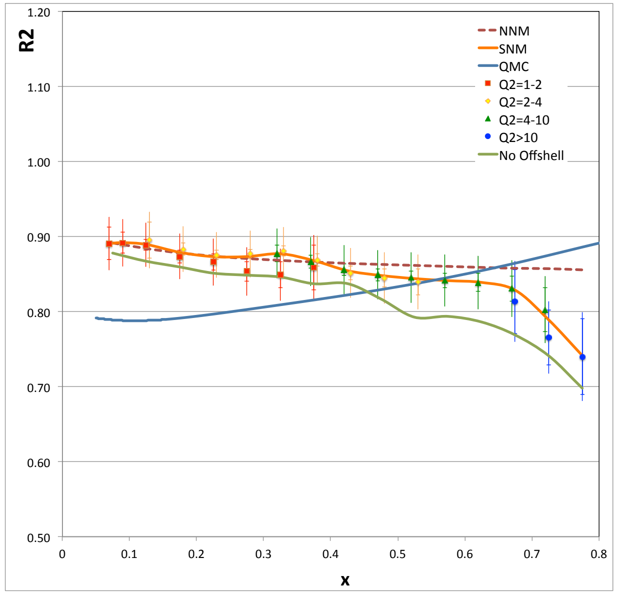
Measure structure function of high momentum nucleon in deuterium by tagging the spectator
→Final state interactions cancelled by taking double ratios
→Requires new, large acceptance proton/neutron detector at back angles

Tagged protons measured in Hall C with LAD E12-11-107, tagged neutrons with BAND in Hall B as part of E12-11-003a

Spokespersons: O. Hen, L. Weinstein, S. Gilad, S. Wood, H. Hakobyan





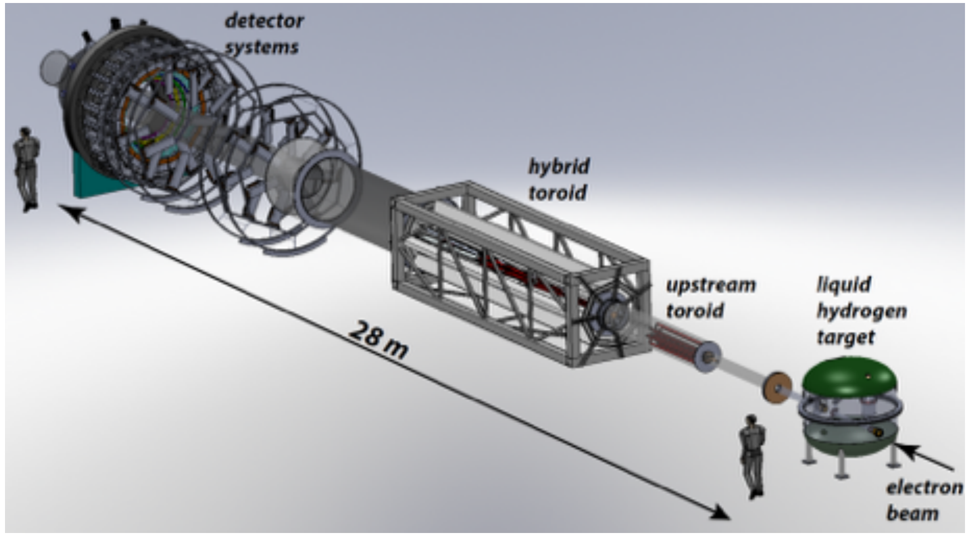


EMC effect in polarized structure functions
→ CLAS12 using ^{7}Li target
→ E12-14-001, W. Brooks and S. Kuhn

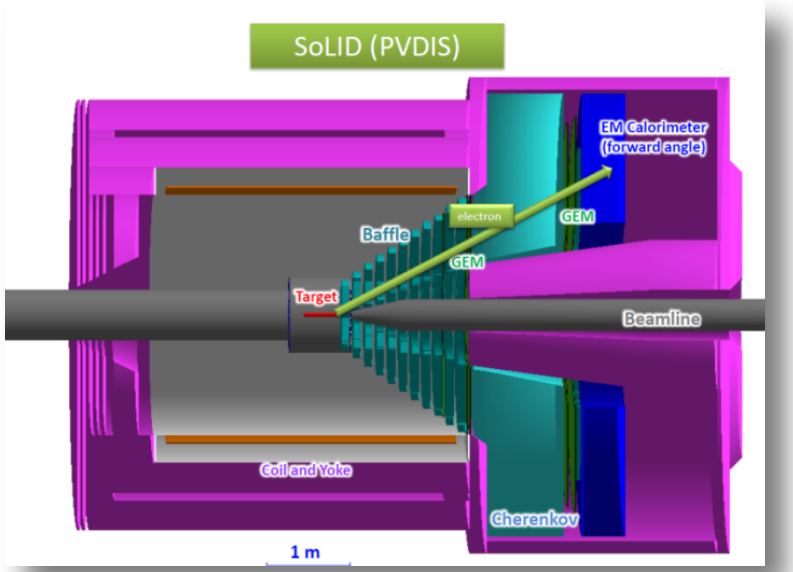
For polarized EMC effect, SRCs would play a smaller role (I. Cloet)

New Physics - BSM

MOLLER: Elastic *e*-*e* scattering



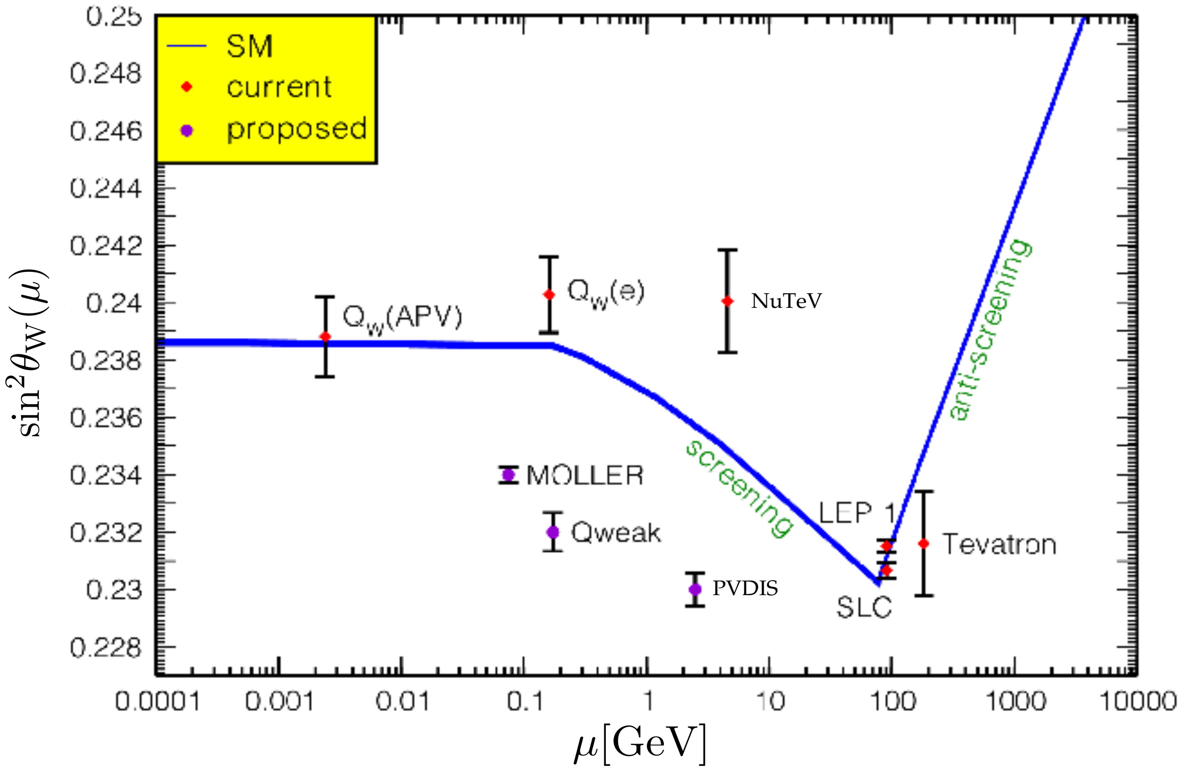
SOLID: parity violating DIS



Building on JLab 6 GeV parity program

→ Dedicated measurements in Hall A will measure Moller scattering and PVDIS

→ Sensitive to running of weak mixing → new physics at TeV scales



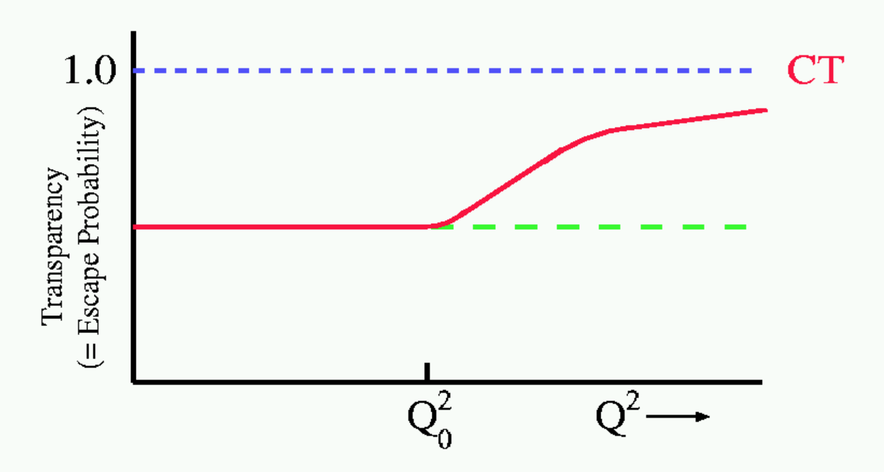
Summary

- JLab 12 GeV program will provide a rich body of data aimed at exploring the quark structure of hadrons
- Equipment in Halls A,B, C provide complementary capabilities and information
  - CLAS12 (Hall B) → Large phase space in single measurement for exploring multi-dimensional measurements, azimuthal asymmetries
  - HMS+SHMS (Hall C) → Magnetic focusing spectrometers for precision cross sections, L-T separations, ratios
  - HRS+SBS (Hall A) → Measurements requiring high luminosity, large acceptance at particular kinematics
- Planned future equipment will augment these capabilities
  - Neutral particle spectrometer in Hall C → SIDIS and exclusive π^0, DVCS, wide-angle Compton scattering
  - SOLID spectrometer in Hall A → Large acceptance at high luminosity for SIDIS, PVDIS
  - MOLLER spectrometer/experiment in Hall A → weak mixing angle

EXTRA

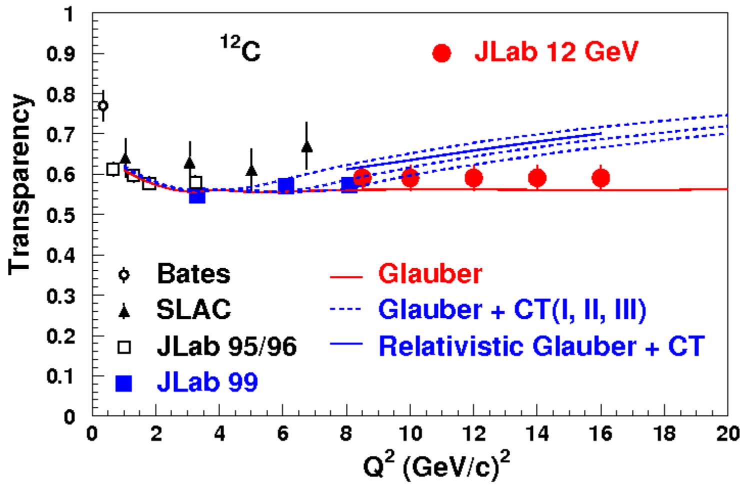
Color Transparency

From fundamental considerations (quantum mechanics, relativity, nature of the strong interaction) it is predicted (Brodsky, Mueller) that fast protons scattered from the nucleus will have decreased final state interactions

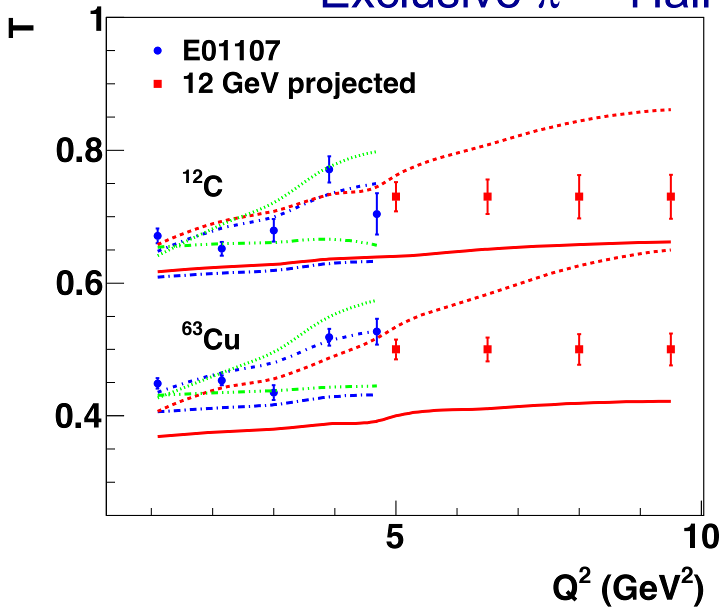


Color Transparency is closely intertwined with the notion of soft-hard factorization in exclusive processes

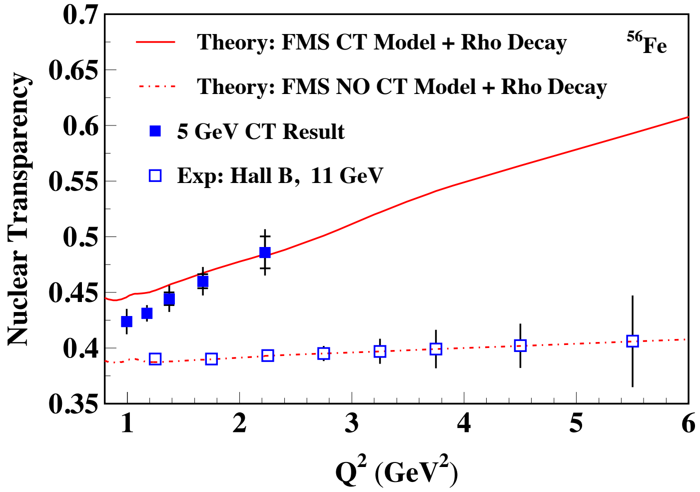
Protons – Hall C



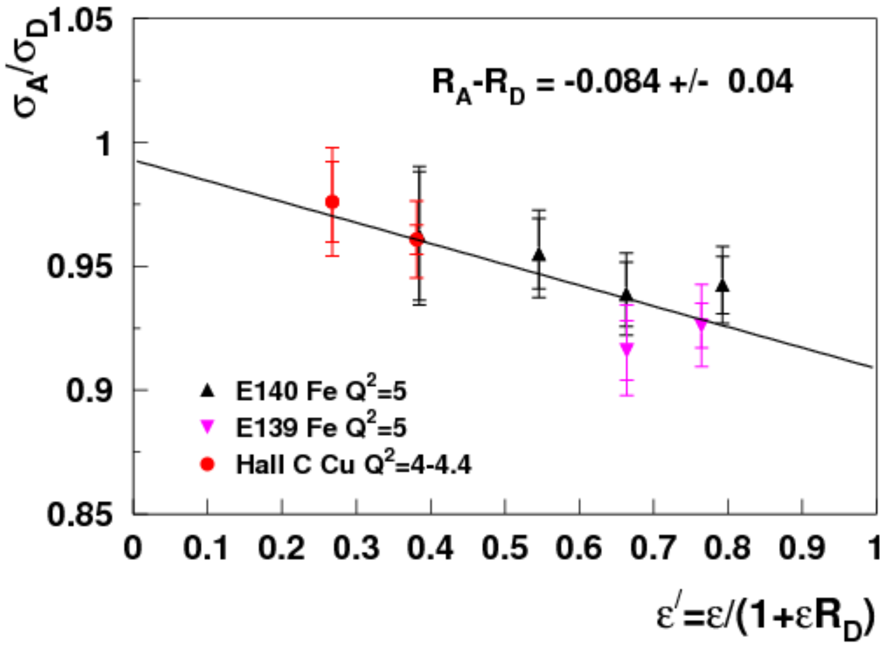
Exclusive π^+ – Hall C



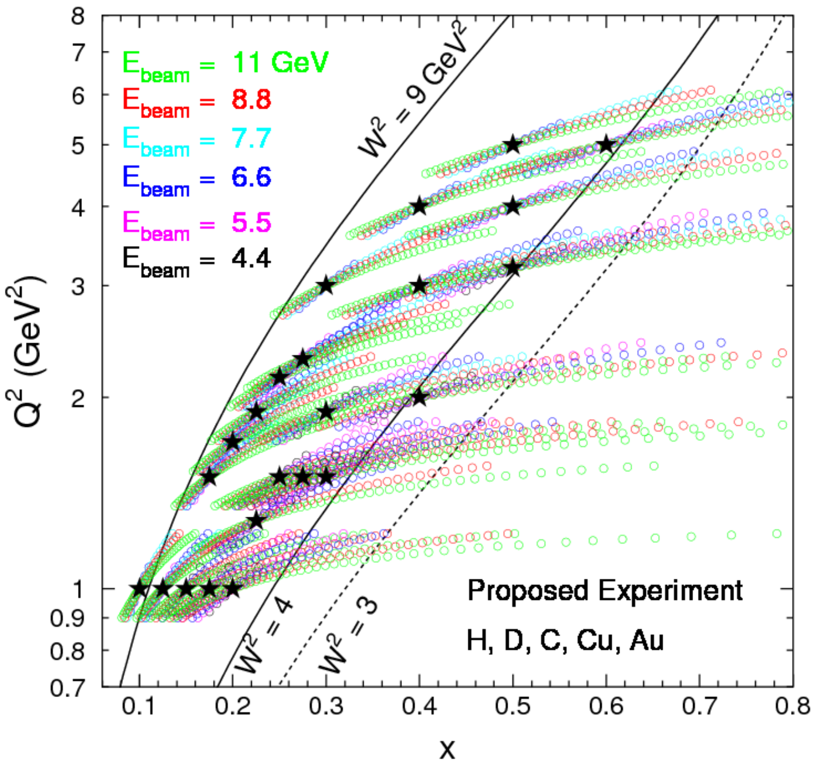
Exclusive ρ^0 – CLAS12



Nuclear Dependence of $R=\sigma_L/\sigma_T$



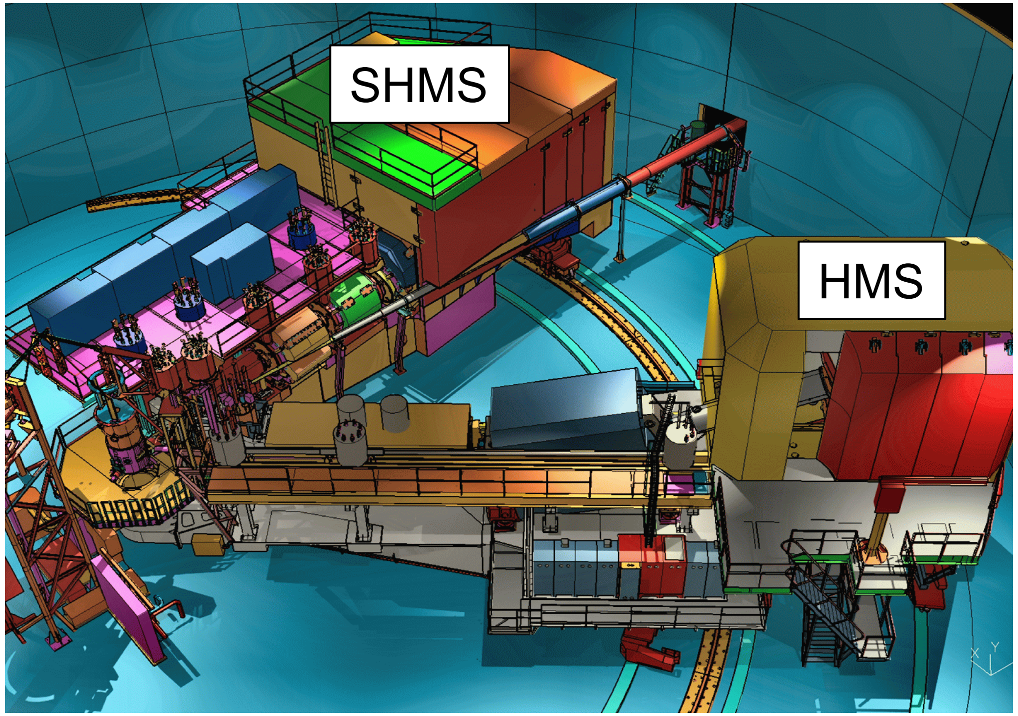
SLAC + 6 GeV JLab data provides hints of nuclear dependence of $R=\sigma_L/\sigma_T$ at large x



E12-14-002: S. Malace et al

Measurement in Hall C will provide new, high precision measurements of R_A-R_D

SHMS and HMS in Experimental Hall C



Excellent control of point-to-point systematic uncertainties required for precise L-T separations

→ Ideally suited for focusing spectrometers

→ One of the drivers for SHMS design

Spectrometer properties

HMS: Electron arm

Nominal capabilities:

dΩ ~ *6* msr, P_0= *0.5 – 7 GeV/c*

ϑ_0=*10.5 to 80 degrees*

e ID via calorimeter and gas Cerenkov

SHMS: Pion arm

Nominal capabilities:

dΩ ~ *4* msr, P_0= *1 – 11 GeV/c*

ϑ_0=*5.5 to 40 degrees*

π:K:p separation via heavy gas Cerenkov and aerogel detectors