# Experimental Perspectives on Electromagnetic Hadron Physics

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Jefferson Lab

*EINN – October 29-November 2, 2019*

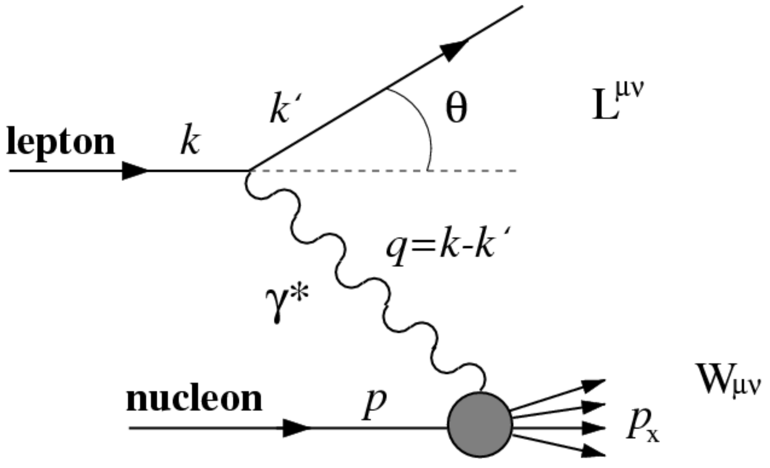
- Facilities and Programs
- JLab 12 GeV Program
  - 12 GeV Upgrade
  - Experimental Program
  - Recent experiments and Results

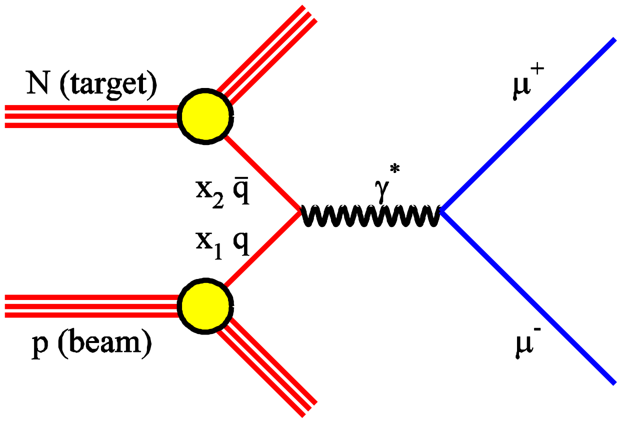
# Facilities and Programs for Hadronic Physics

- Lepton scattering has historically been the "workhorse" of hadronic physics
  - Plethora of data from EMC, NMC, SLAC, HERA, JLab (6 GeV), COMPASS

- Recently, increasing focus on the Drell-Yan reaction
  - E866 → E906 (SeaQuest) at Fermilab. Future polarized target program (SpinQuest)
  - COMPASS pion Drell-Yan polarized target program in progress → *Michela Chiosso, Friday*

- Polarized proton-proton program at RHIC will continue with planned detector upgrades → *Renee Fatemi*



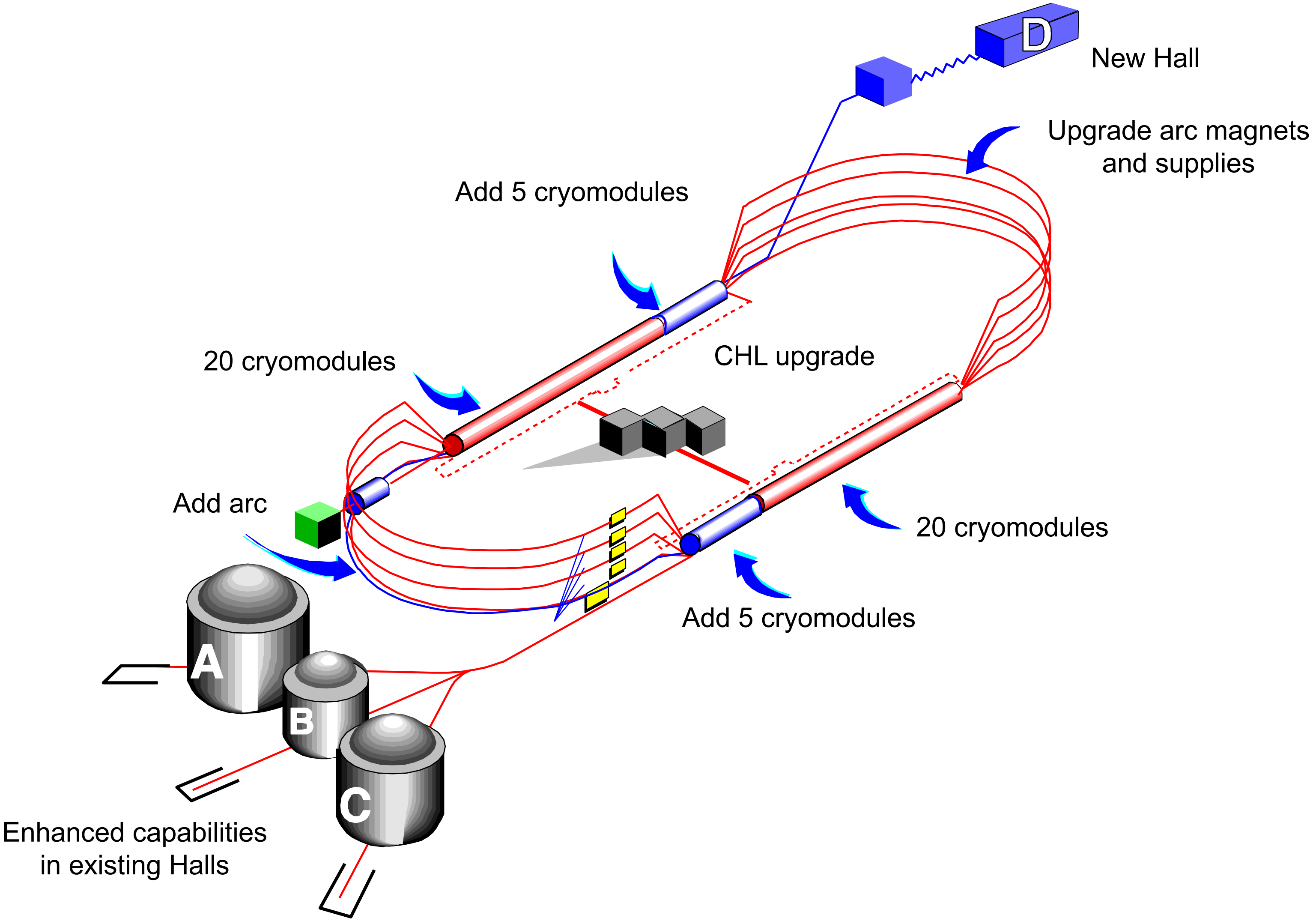
# Jefferson Lab 12 GeV Upgrade

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

***6 GeV* → *12 GeV***

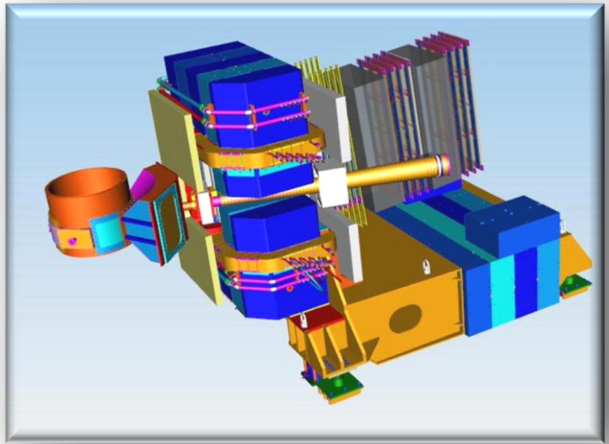
→ **New** experimental Hall D – experiments with (polarized) photons – gluonic excitations in meson spectrum

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

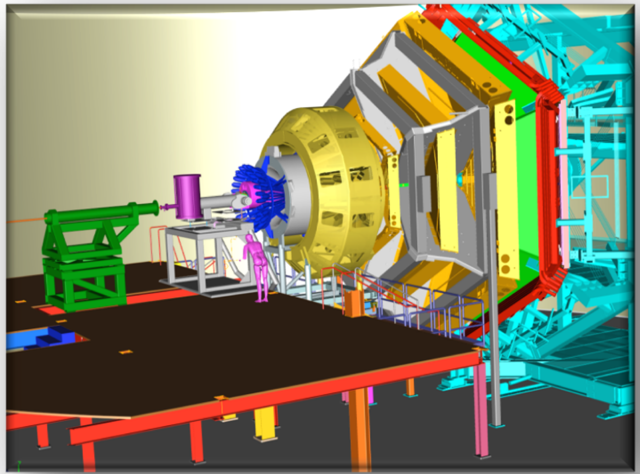


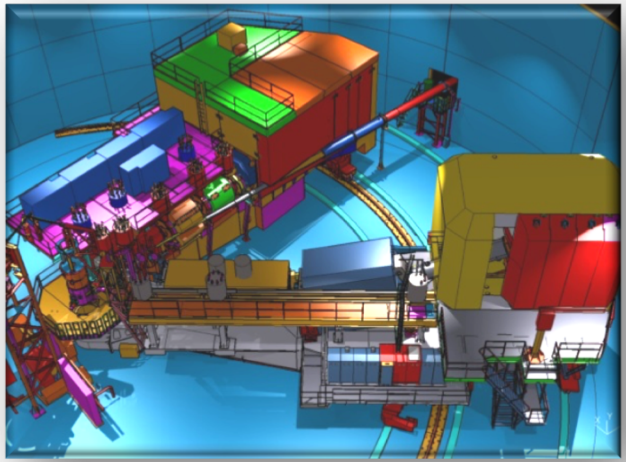
# Experimental Capabilities

<u>Hall A</u>
Existing HRS magnetic focusing spectrometers + Big Bite + new, large acceptance Super Big Bite

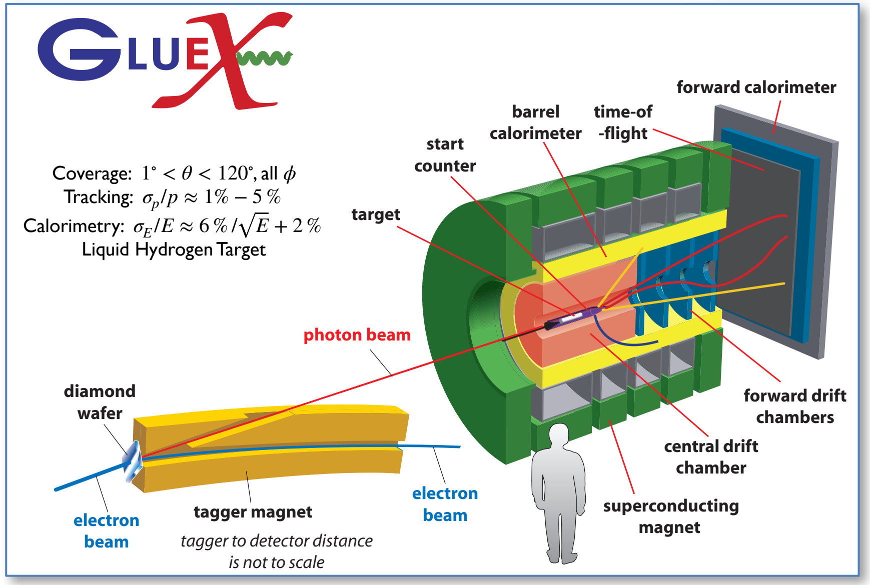


<u>Hall B</u>
New CLAS12, large acceptance spectrometer
→ Good hadron PID
→ Simultaneous measurement of broad phase space



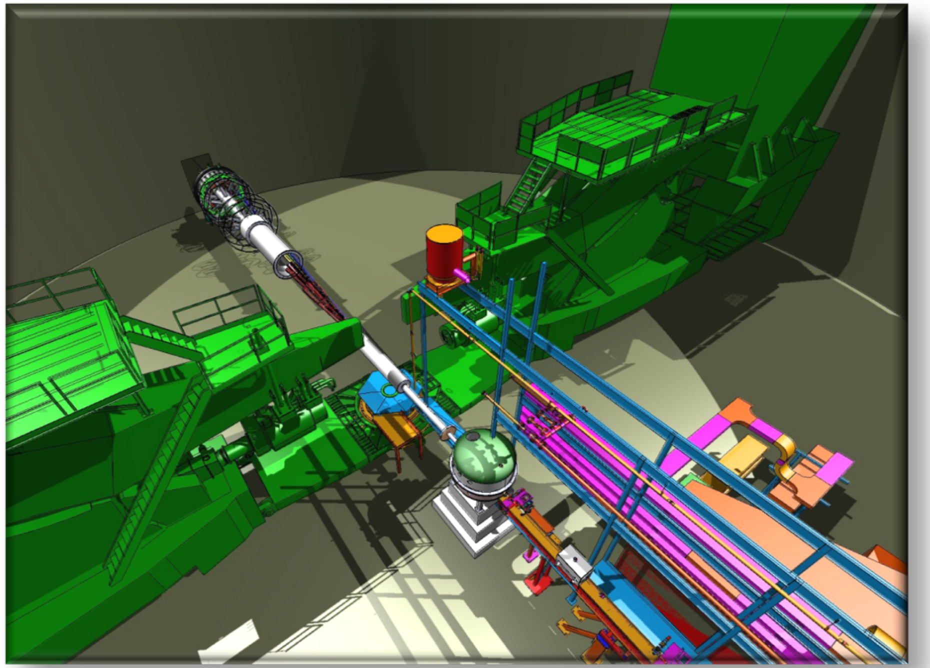


<u>Hall C</u>
HMS + new SHMS magnetic focusing spectrometers
→ Precision cross sections, LT separations



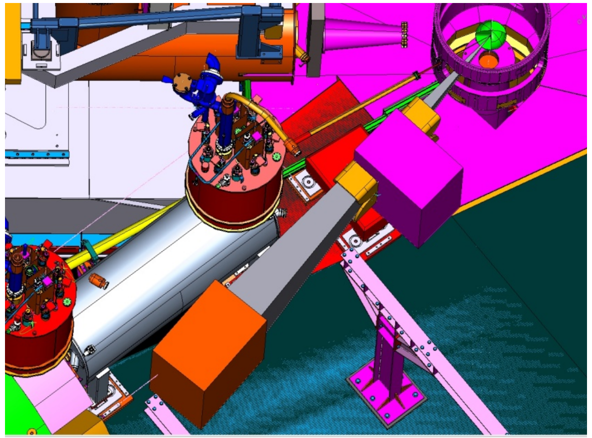

<u>Hall D</u>
GlueX large acceptance spectrometer
→ Total event reconstruction for meson spectroscopy

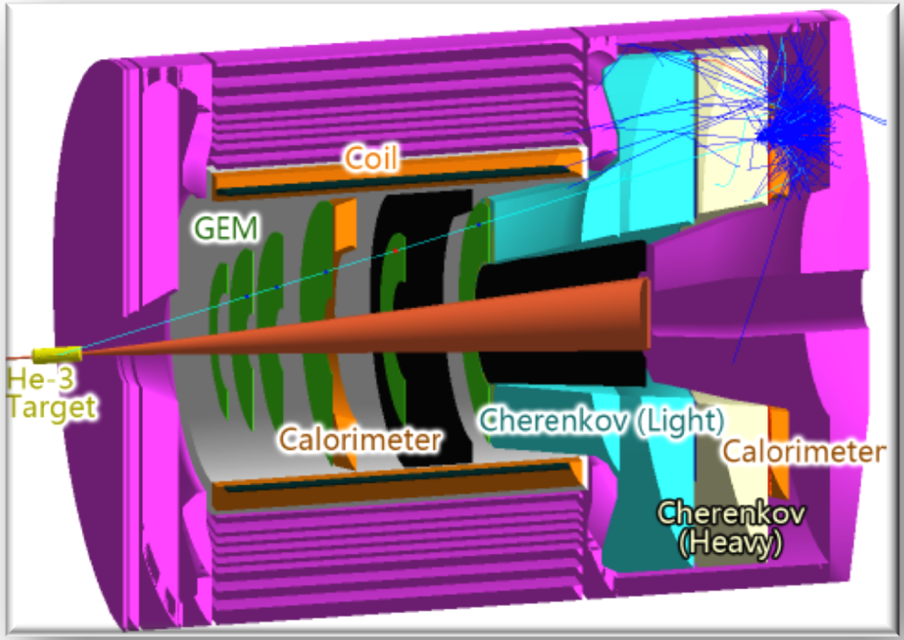
# Future Facilities and Upgrades



MOLLER spectrometer (Hall A)
→ Measurement of PV in *ee* scattering

Solenoidal Large Intensity Device (SoLID)
→ Parity violation in DIS
→ SIDIS with unpolarized/polarized targets



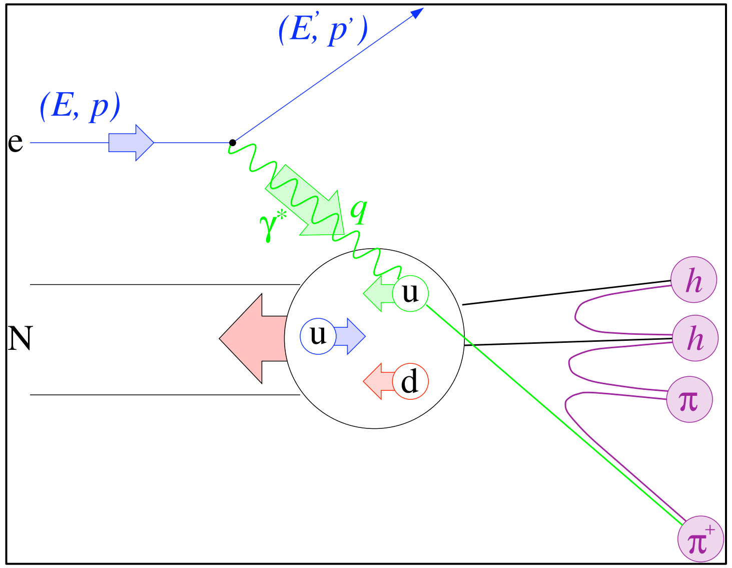



Neutral Particle Spectrometer (Hall C)
→ DVCS
→ $\pi^0$ in exclusive, SIDIS reactions
→ Wide angle Compton scattering

# Partonic Structure of Nucleons in 3D via SIDIS

Interest in semi-inclusive processes originally dominated by potential use in “flavor tagging” 1D quark PDFs
→ 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)




quark

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

nucleon

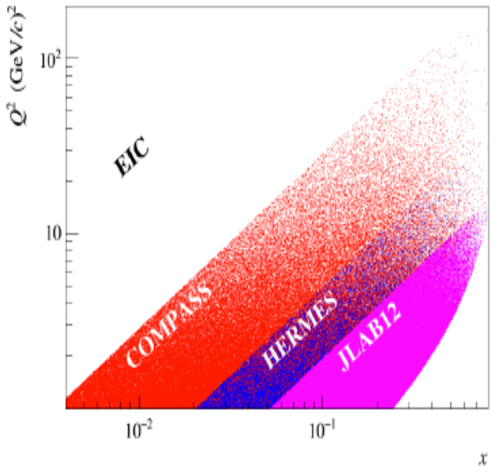
$$f^a(x, k_T^2; Q^2)$$

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

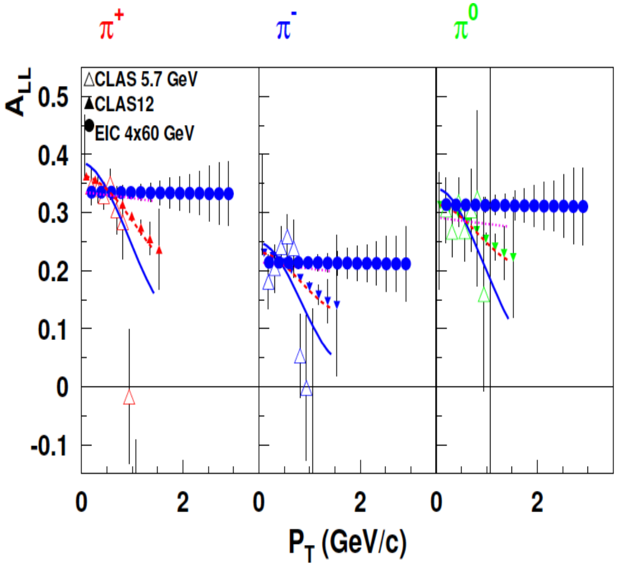
$h_1^{\perp}, h_{1L}^{\perp}, h_{1T}^{\perp}$ → Boer-Mulders functions describe transversely polarized quarks in un/long./trans./polarized nucleon

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

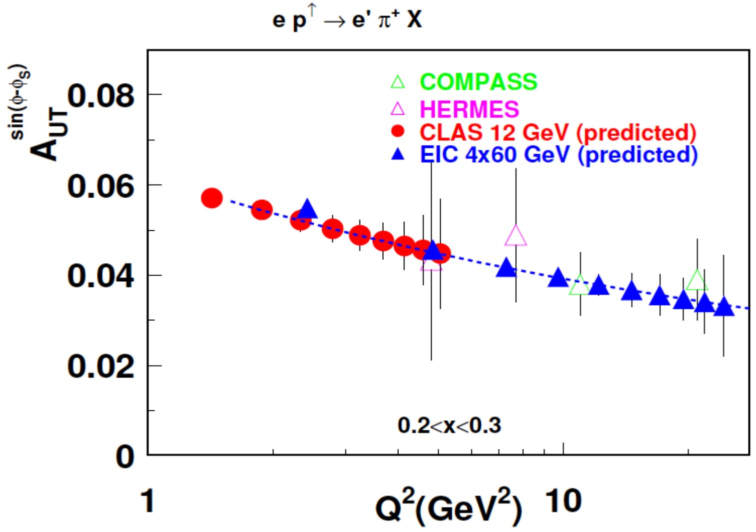
# CLAS12: Evolution and $k_T$-dependence of TMDs



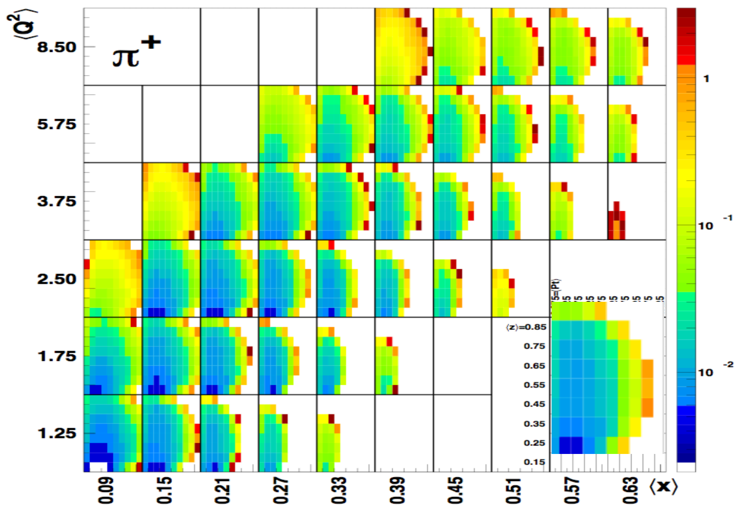

CLAS12 kinematical coverage




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



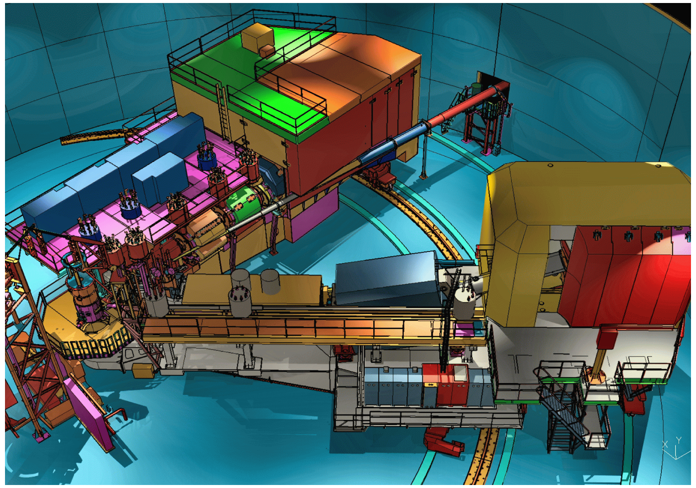

$Q^2$-dependence of Sivers, $f_1^{\perp}(x, k_T)$

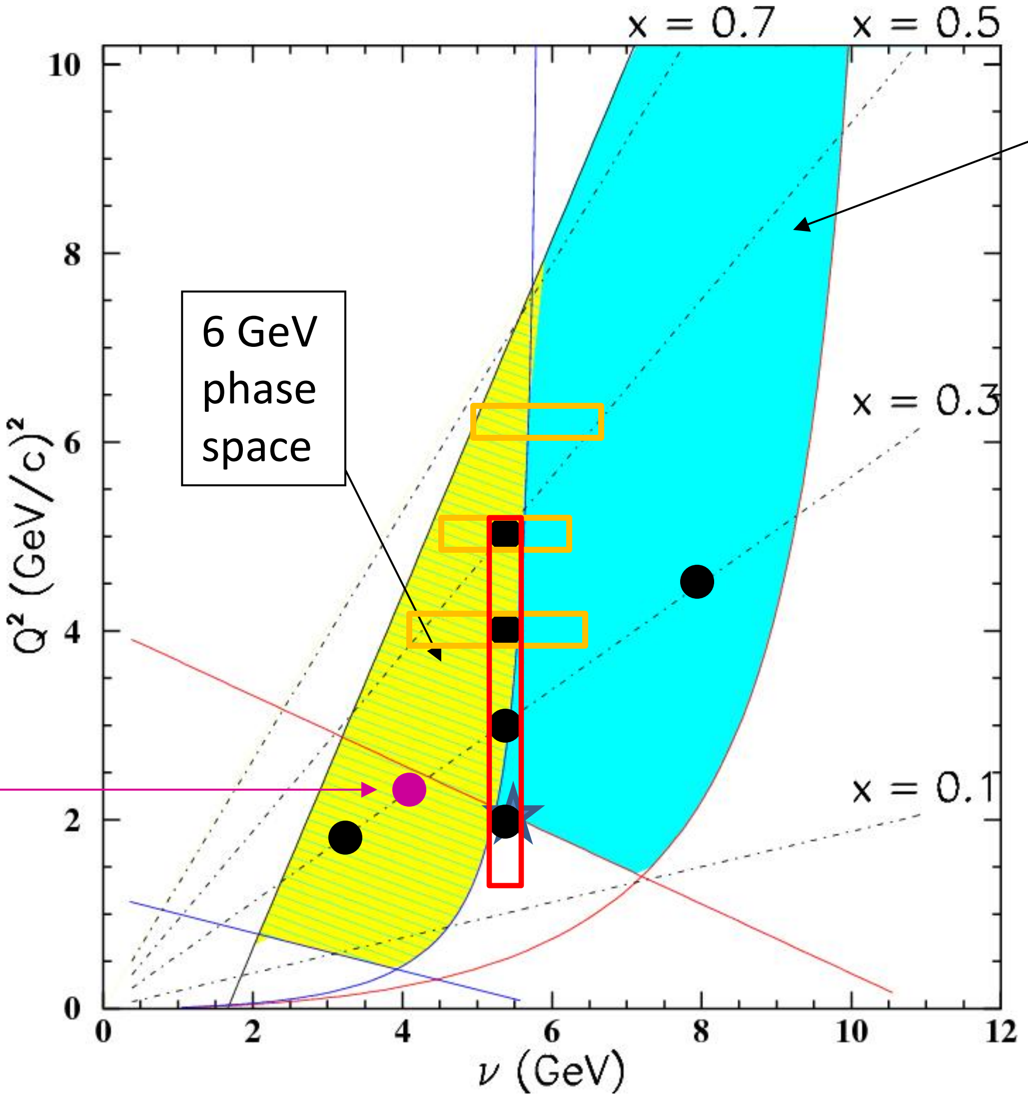



- Large acceptance of CLAS12 allows studies of $P_T$ and $Q^2$-dependence of SSAs in a wide kinematic range
- Comparison of JLab12 data with HERMES, COMPASS (and EIC) will pin down transverse momentum dependence and the non-trivial $Q^2$ evolution of TMD PDFs in general, and Sivers function in particular.

# Hall C SIDIS Program – HMS+SHMS

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






11 GeV
phase
space

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

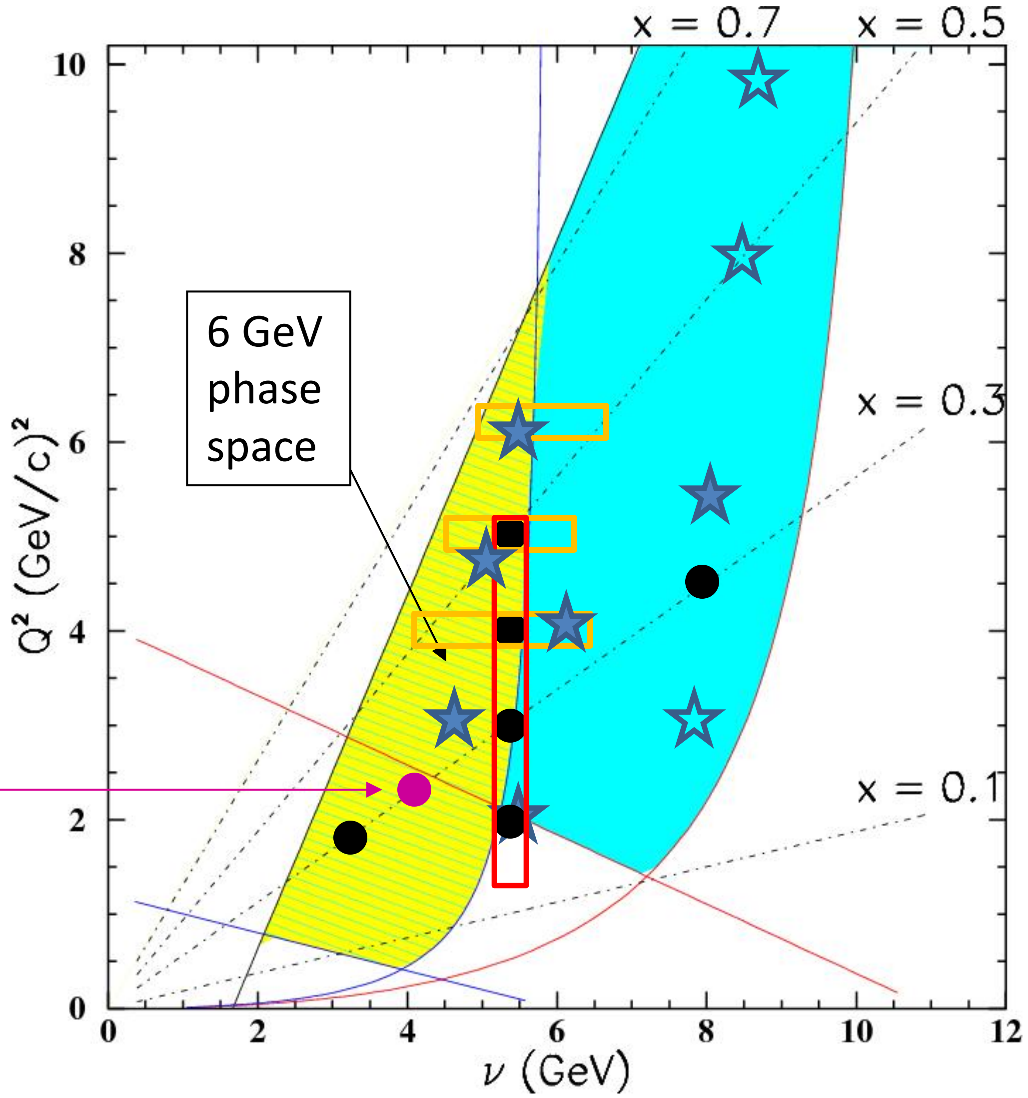
Ran in 2018-2019

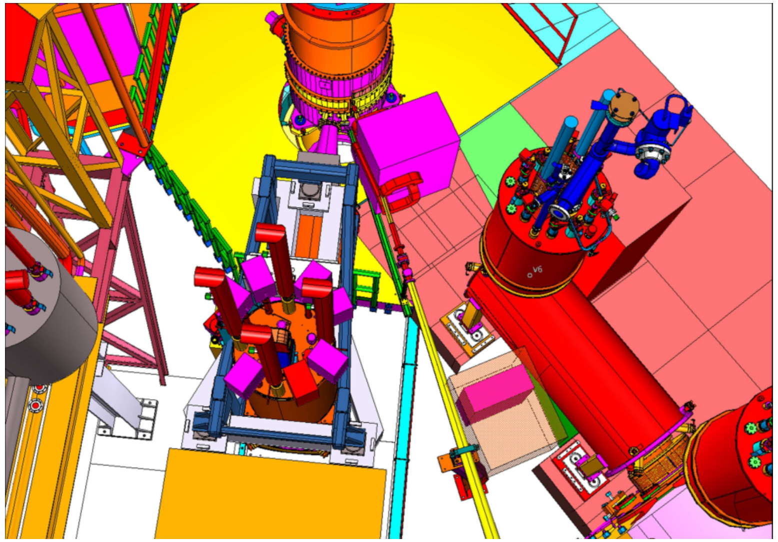
# Hall C SIDIS Program – HMS+SHMS+NPS

*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



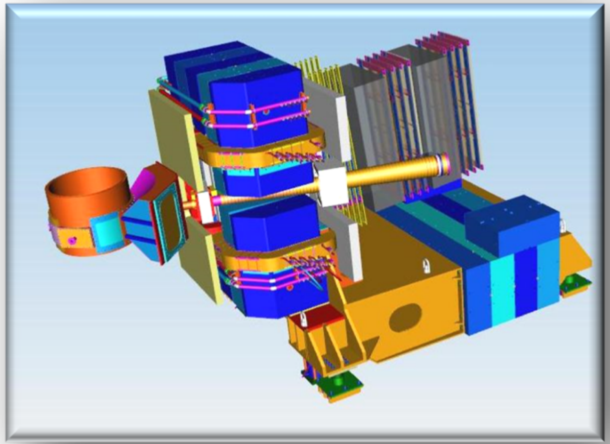



Calorimeter + sweeper magnet adds capability to detect neutral particles ($\gamma$ and $\pi^0$)

→ In addition to broadening SIDIS program, enables DVCS, DVMP ($\pi^0$), WACS measurements

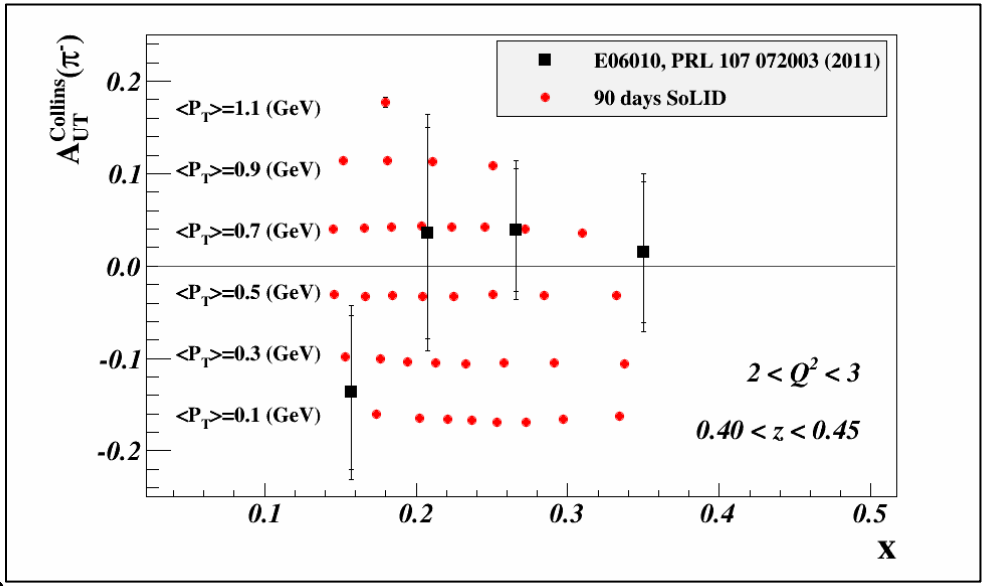
*Courtesy R. Ent*

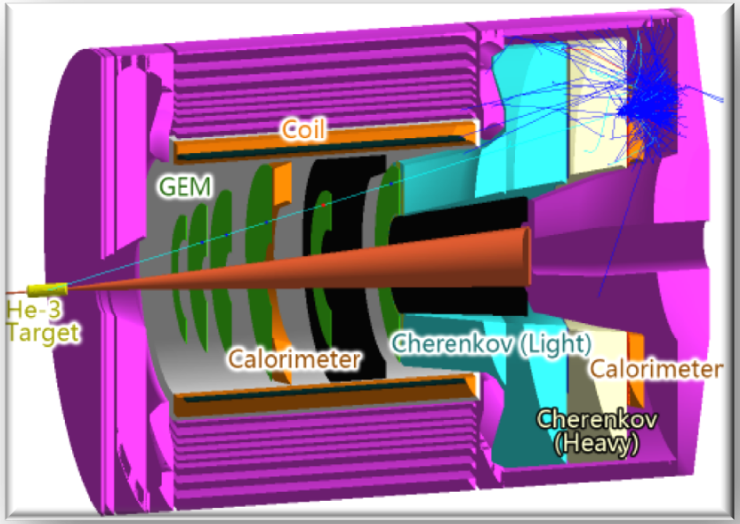
# Hall A – SIDIS with Super Big Bite and SOLID



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

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



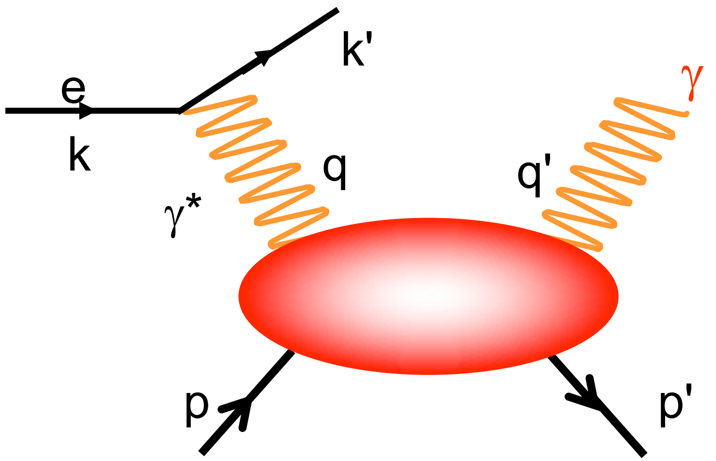



# Generalized Parton Distributions

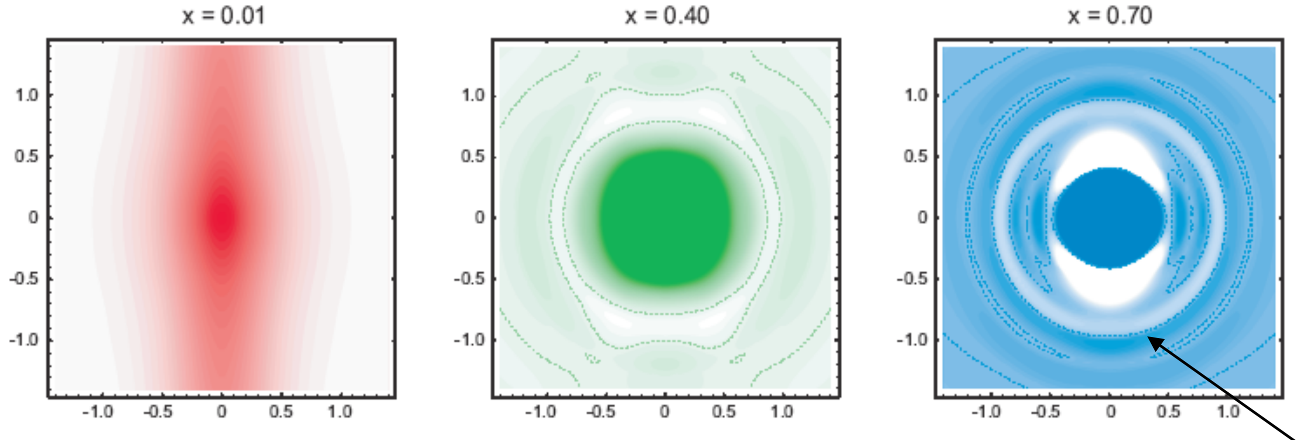
GPDs provide another handle for 3-D mapping of the quark structure of the nucleon.

→ 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

interference pattern

GPD program experimental requirements

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

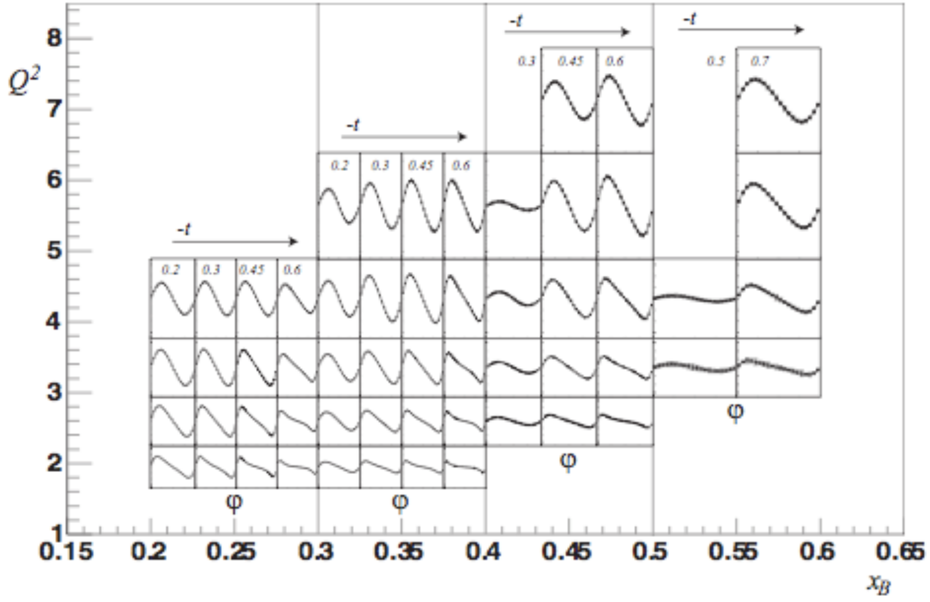
→ Measure $Q^2$ dependence at fixed x, access –t dependence

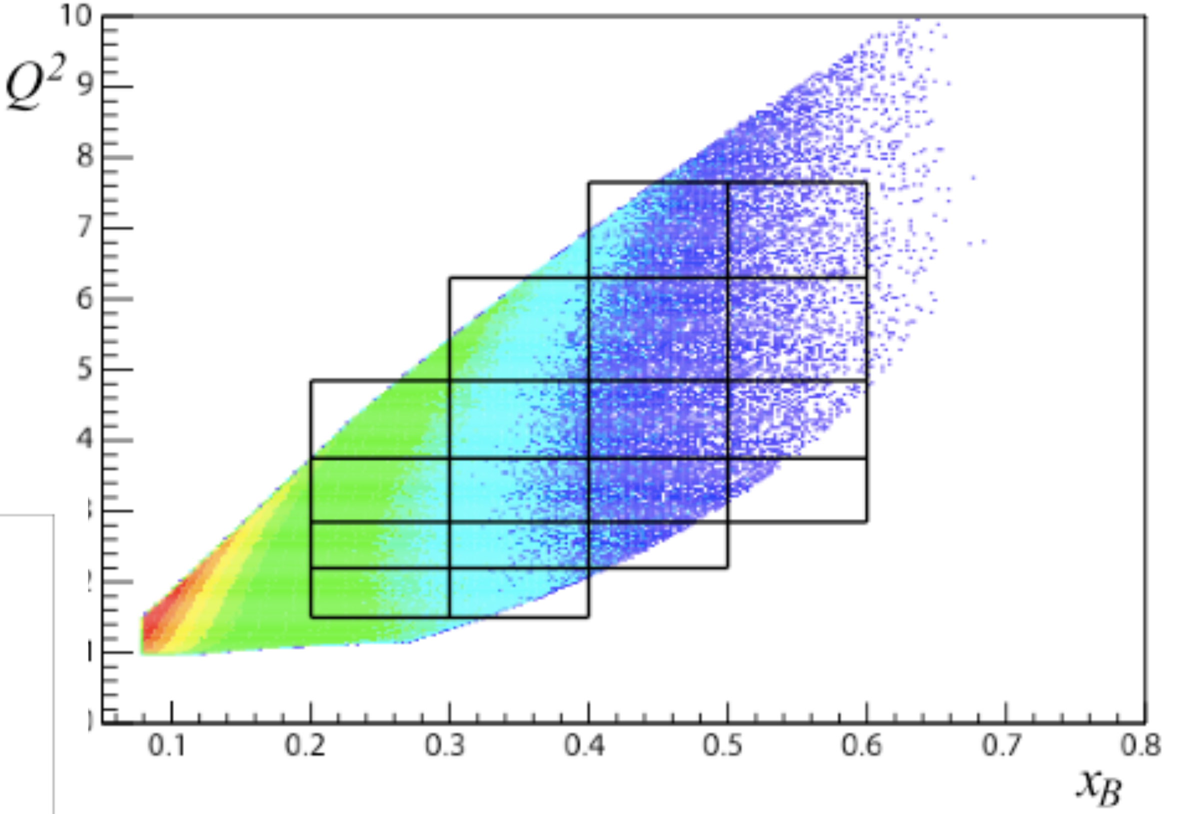
Deep exclusive channels: DVCS, vector and pseudo-scalar mesons

# 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

# E12-06-114 DVCS/Hall A Experiment at 11 GeV

100 PAC days approved:

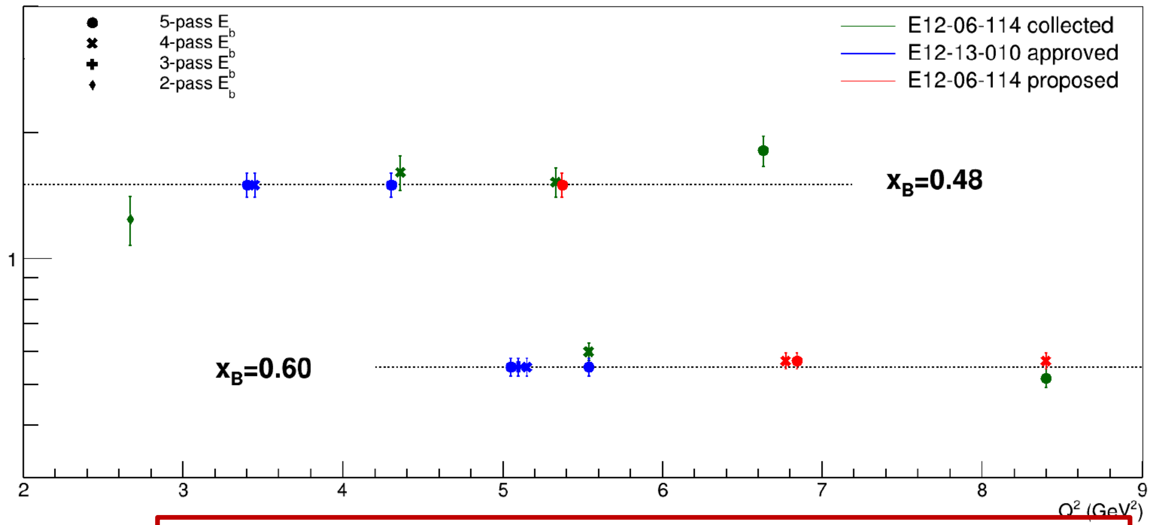
**- High impact experiment for nucleon 3D imaging program**

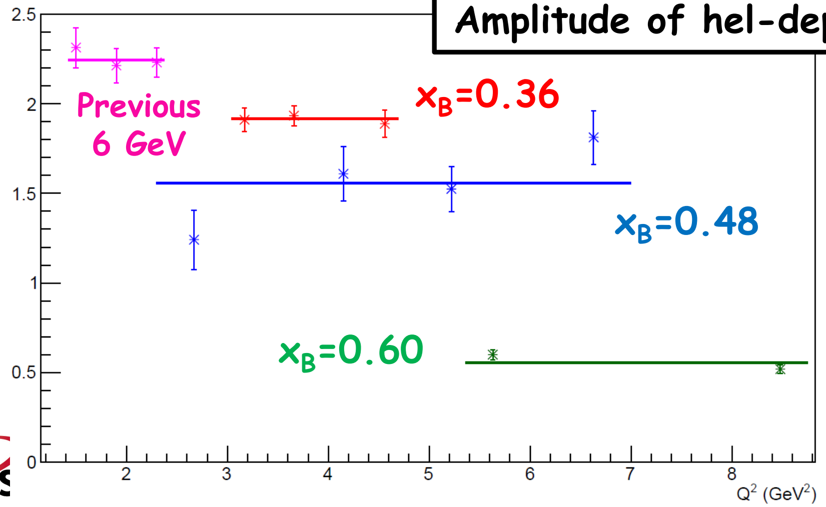
- High precision scaling tests of the DVCS cross section at fixed $x_B$

- CEBAF12 allows to explore for the first time the high $x_B$ region

50% of the data were taken in Hall A

Experiment to be completed in Hall C with NPS with those new settings

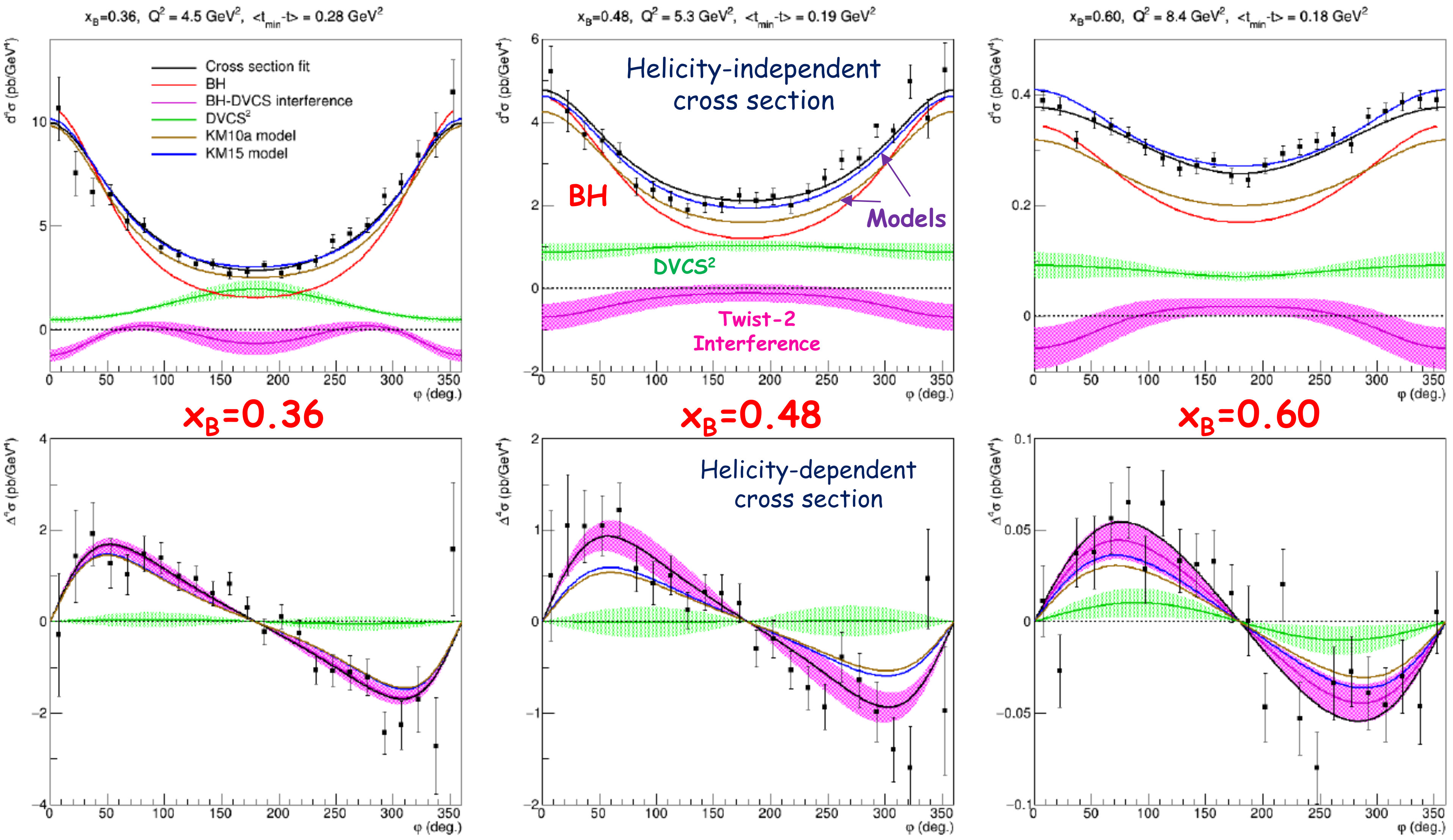



**Analysis status:**

- Analysis of DVCS cross sections completed for *all 9 kinematic settings* (presented at SPIN 2018)
- Publication being drafted, expected to be circulated by the end of **2019**
- $\pi^0$ electroproduction results and publication will follow soon afterwards

# Hall A DVCS Results

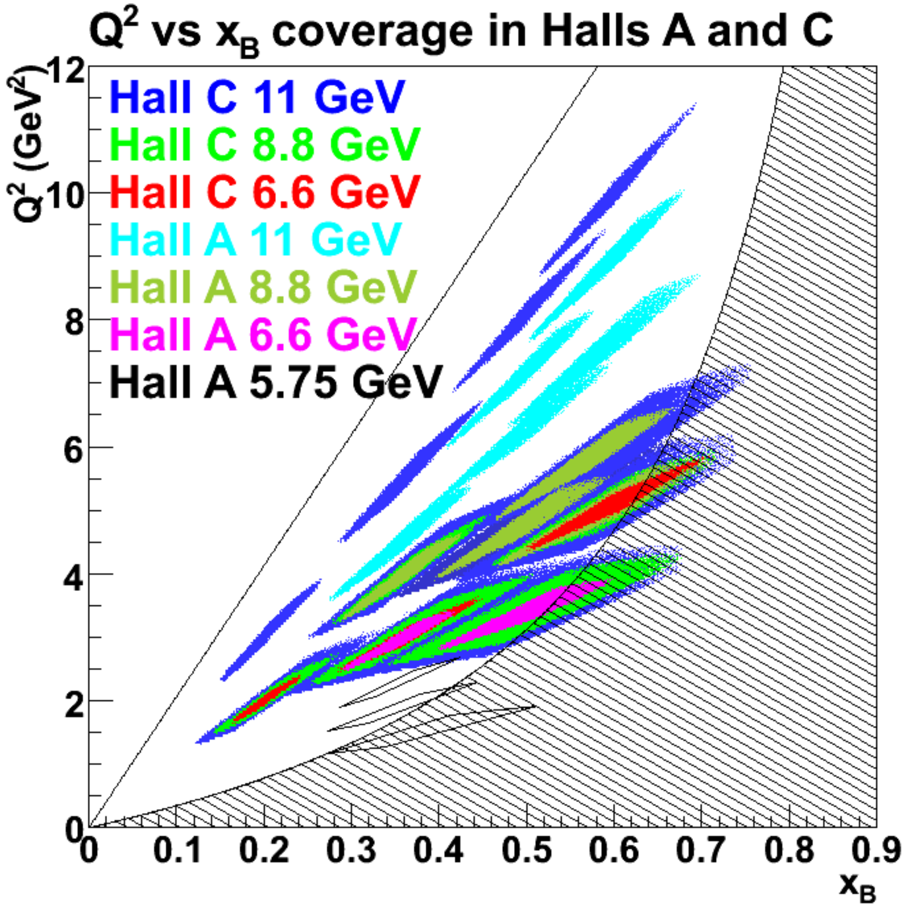


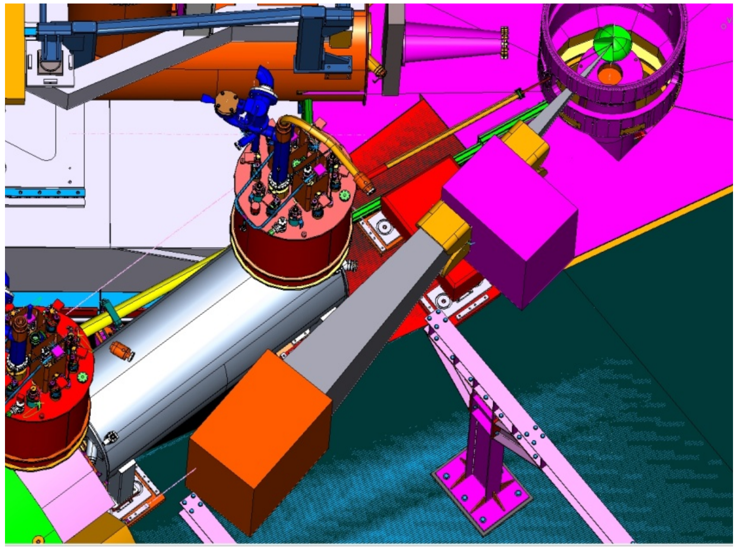

Sample of cross-section results

# 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 $\pi^0$ cross sections.
→ Rosenbluth separation to access $\sigma_L$ and $\sigma_T$ separately
$\sigma_L$ → access to leading twist GPDs (non-pole backgrounds!)
$\sigma_T$ → access to transversity GPD, $H_T$

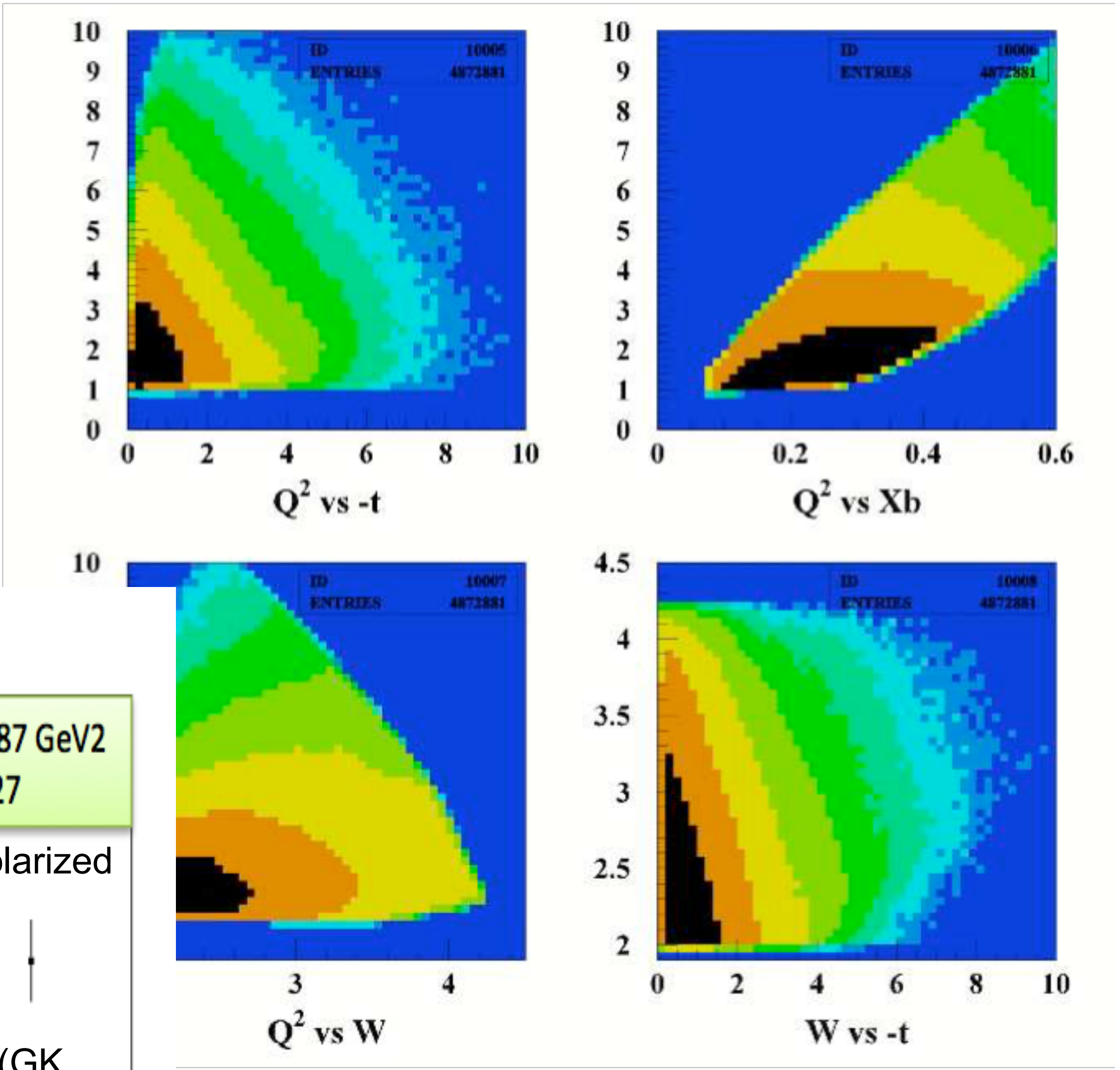


# Meson Production with CLAS12

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

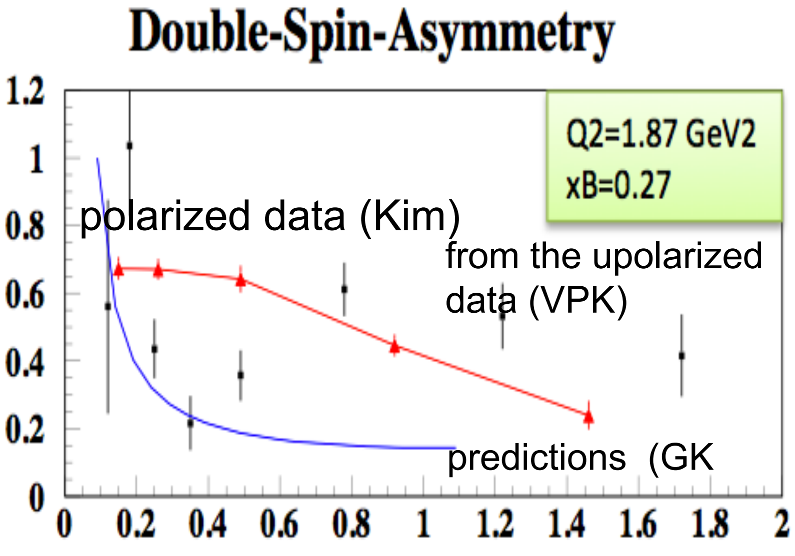
Study $Q^2$ (at low $-t$ ) dependence of all to look for evidence of factorization




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

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

Access $Q^2$ dependence of $H_T$ via double spin asymmetry

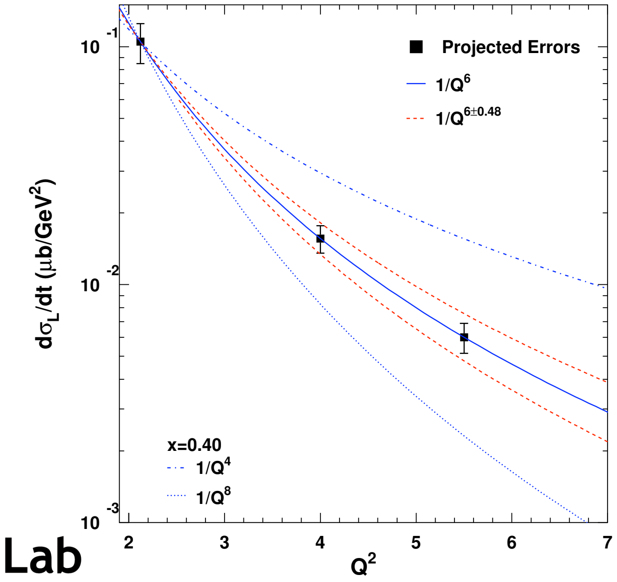



6 GeV data

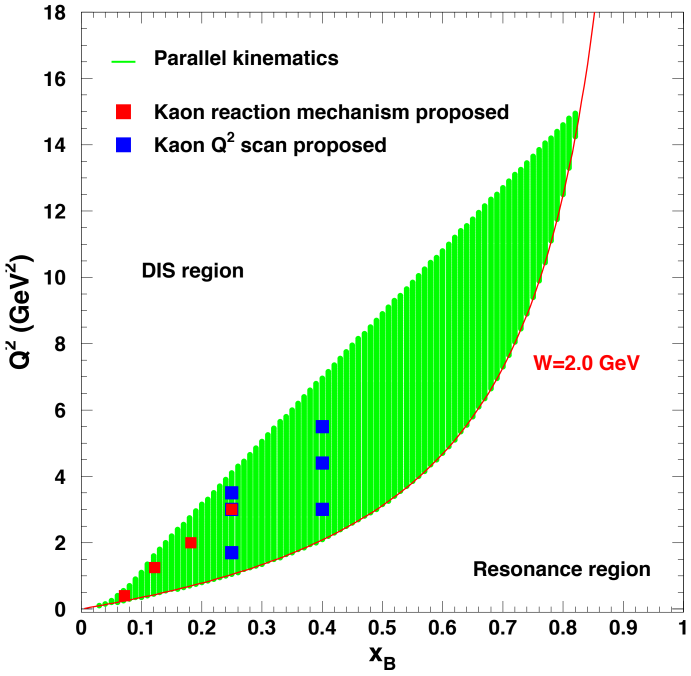
# Exclusive $\pi^+$ and $K^+$ Production at Large $Q^2$

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




*Exclusive Kaons*

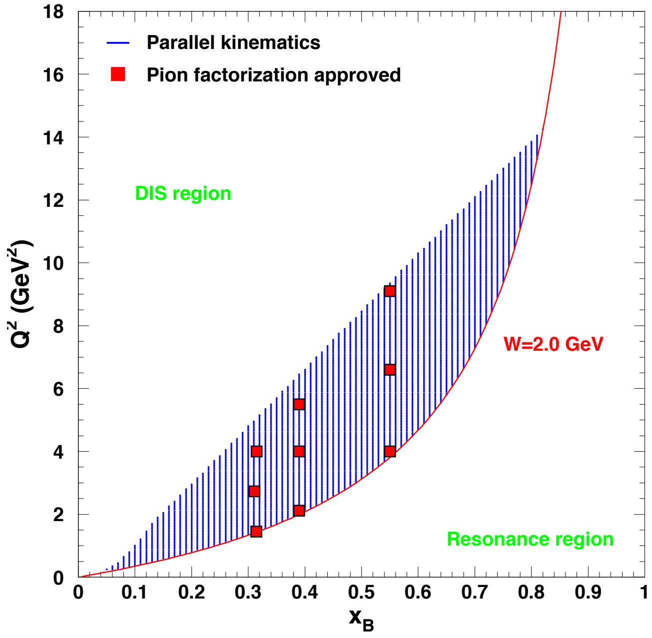



*E12-09-011: T. Horn, G. Huber, P. Markowitz*

↑

**Ran in Hall C Fall 2018-Spring 2019**

*Exclusive Pions*




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

Factorization theorem predicts:

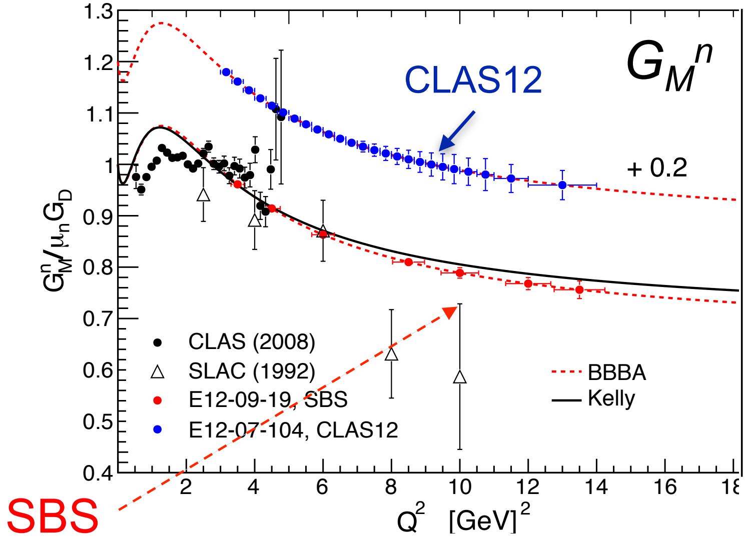
$\sigma_L \sim 1/Q^6$

$\sigma_T/\sigma_L \sim 1/Q^2$

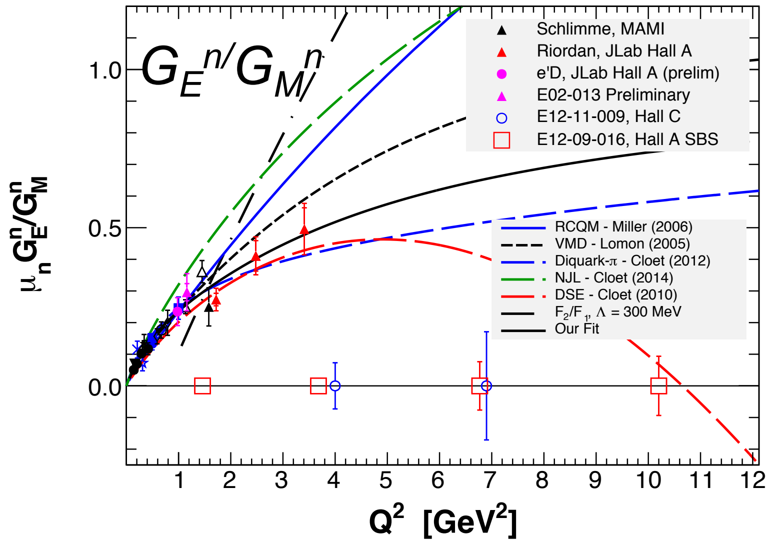
# Nucleon Elastic Form Factors

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



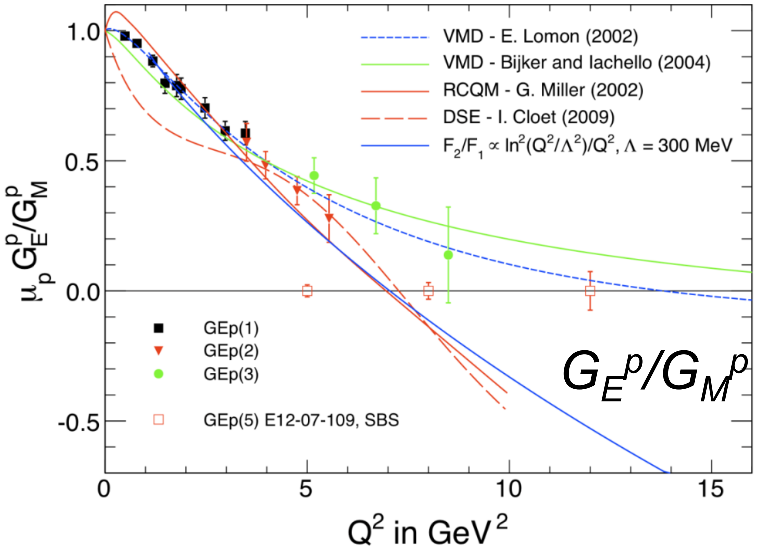

CLAS12 (Hall B)
SBS + BigBite (Hall A)



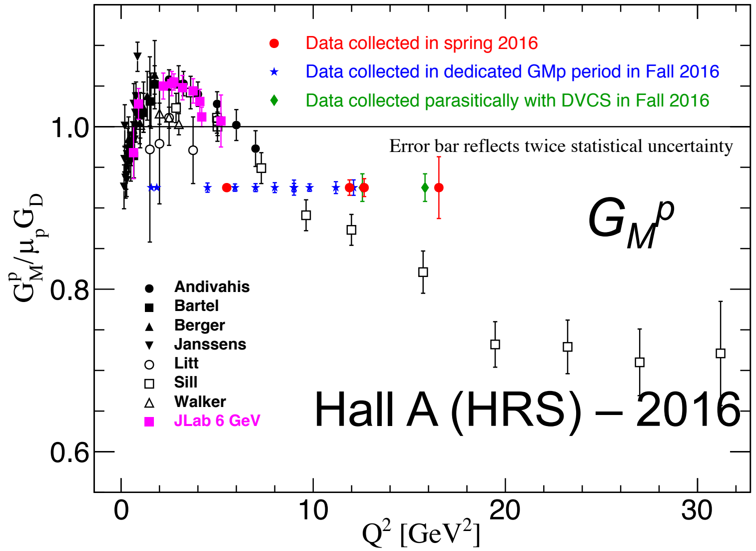

SBS + polarized $^3$He (Hall A)

Recoil polarization in Hall C

Proton recoil polarization using SBS (Hall A)



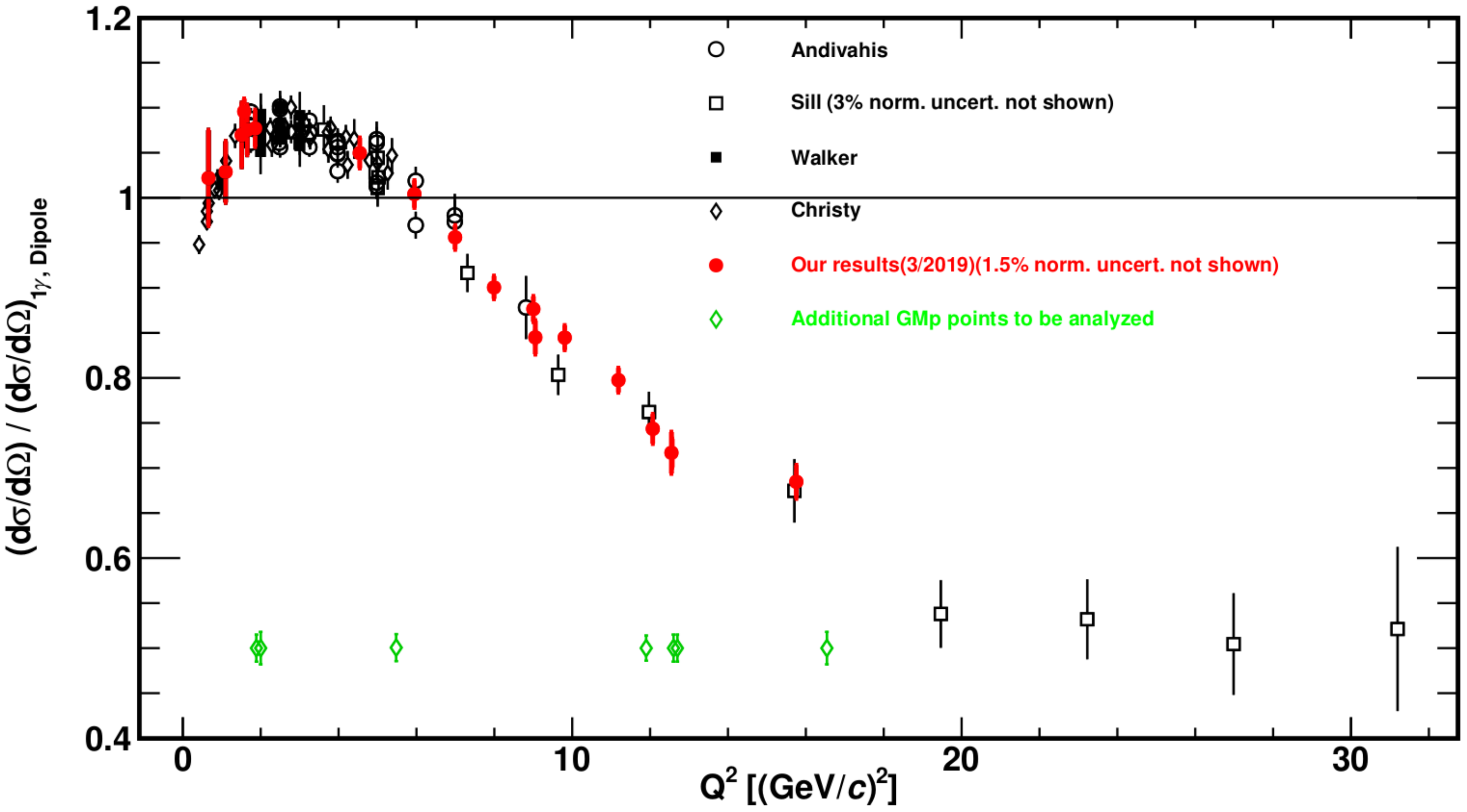

Elastic (e,p) cross sections in HRS (Hall A)



# GMp - E012-07-108 final cross sections

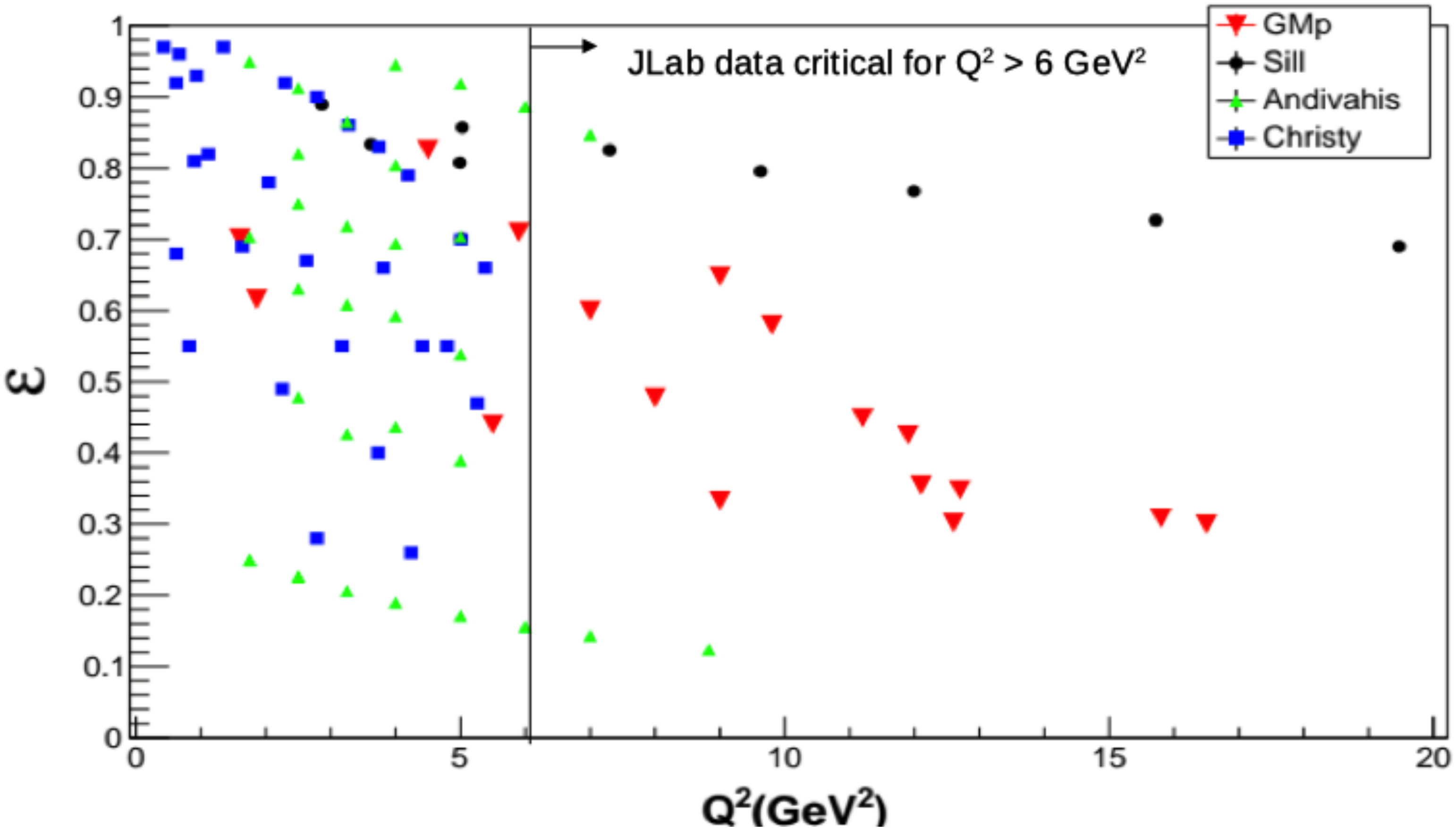
**Data taken 2015-2016 in Hall A**
**→ Results from Fall 2016 shown**

- Cross section relative to 1-γ cross section calculated with $G_E = G_M/\mu = G_{dipole}$
- Significant improvement in precision for $Q^2 > 6$.
- Systematic uncertainties on Fall 2016 LHRS data ~1.3% (pt-pt), 1.5% (norm)
- RHRS (additional 2% from optics)




*Plot courtesy Eric Christy, Hampton University*

# GMp and other High $Q^2$ data




$$\frac{d\sigma}{d\Omega} = \sigma_{Mott} \frac{\epsilon \left(G_E^p\right)^2 + \tau \left(G_M^p\right)^2}{\epsilon \left(1+\tau\right)},$$

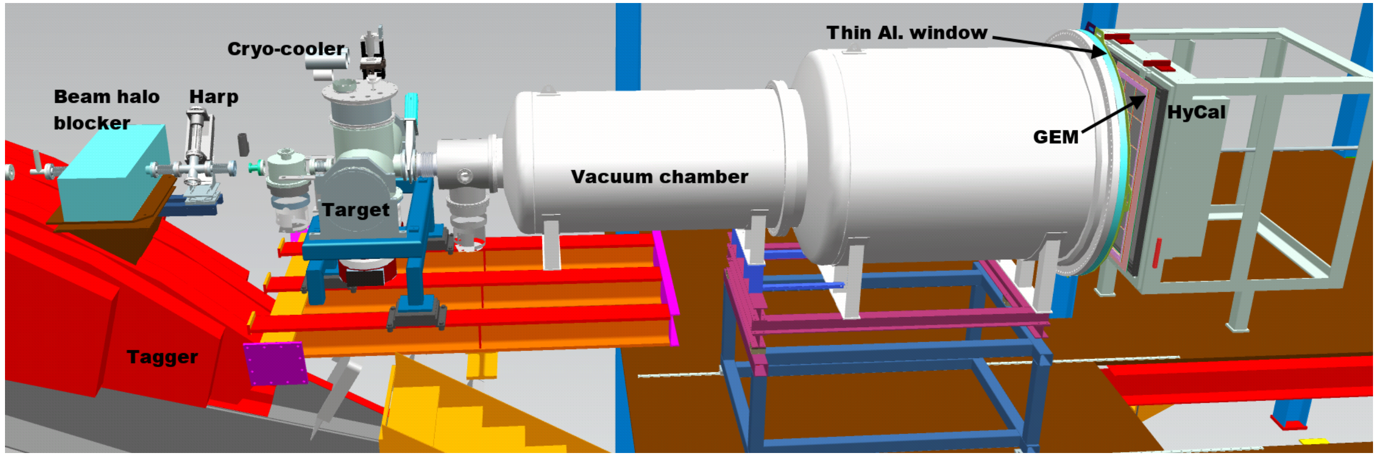
<u>GMp12 data at much smaller ε than Sill data</u>

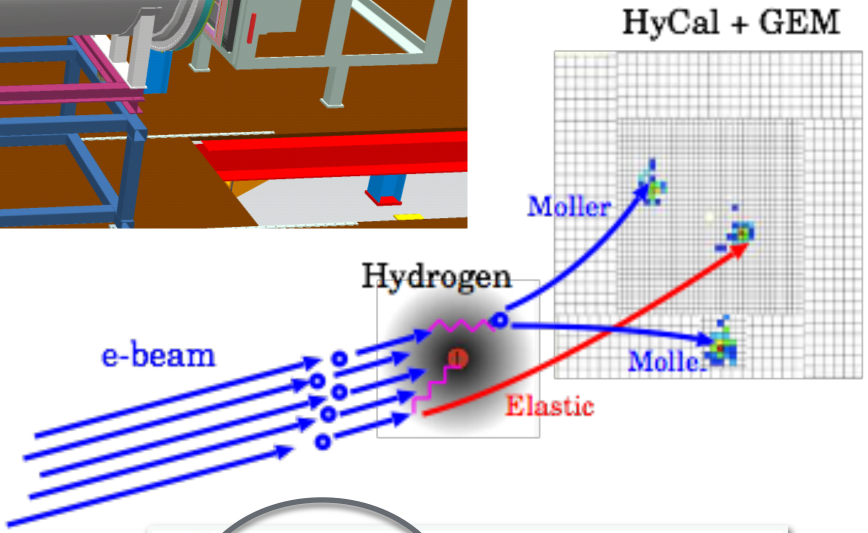
→ Less sensitivity to GE in extracting GM

→ Lever arm in ε provides sensitivity to:

- 2γ from global fit utilizing GE / GM from polarization transfer

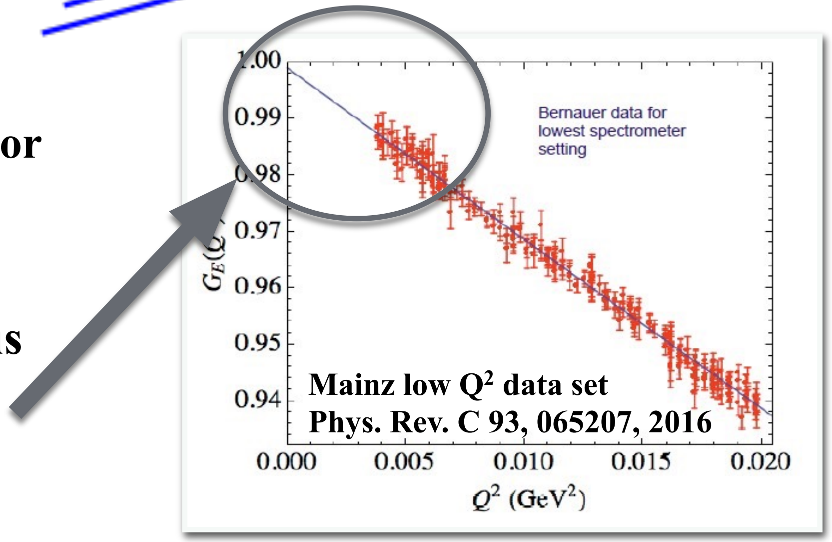
# The *PRad Experiment in Hall B at JLab*




- High resolution, large acceptance, hybrid HyCal calorimeter (**$PbWO_4$ and Pb-Glass**)
- Windowless $H_2$ gas flow target
- Simultaneous detection of elastic and Moller electrons
- $Q^2$ range of **$2x10^{-4}$ – 0.06 $GeV^2$**
- XY – veto counters replaced by GEM detector
- Vacuum chamber

**PRad current result supports a smaller radius**




**Spokespersons: A. Gasparian (contact), H. Gao, D. Dutta, M. Khandaker**

*Nilanga Liyanage Wednesday*

Jefferson

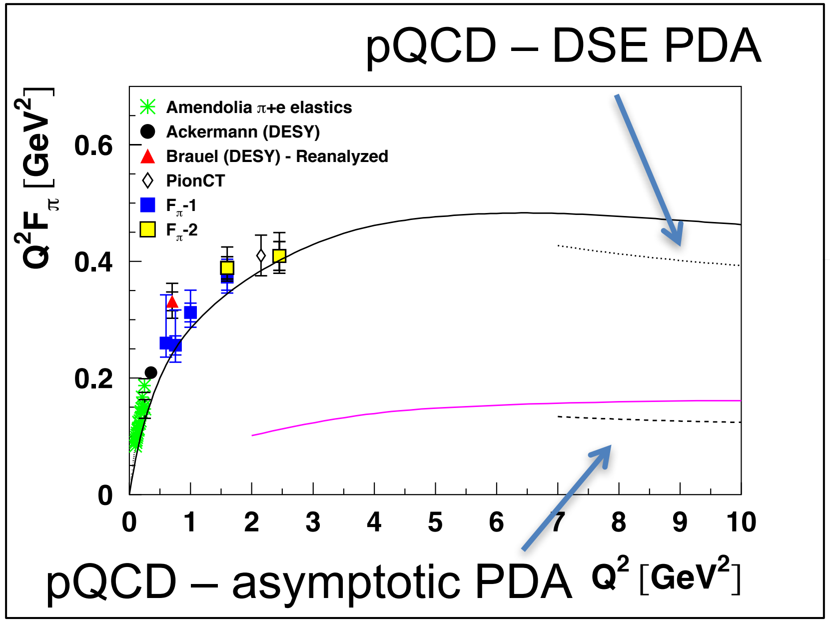
# Meson Form Factors: $F_\pi(Q^2)$

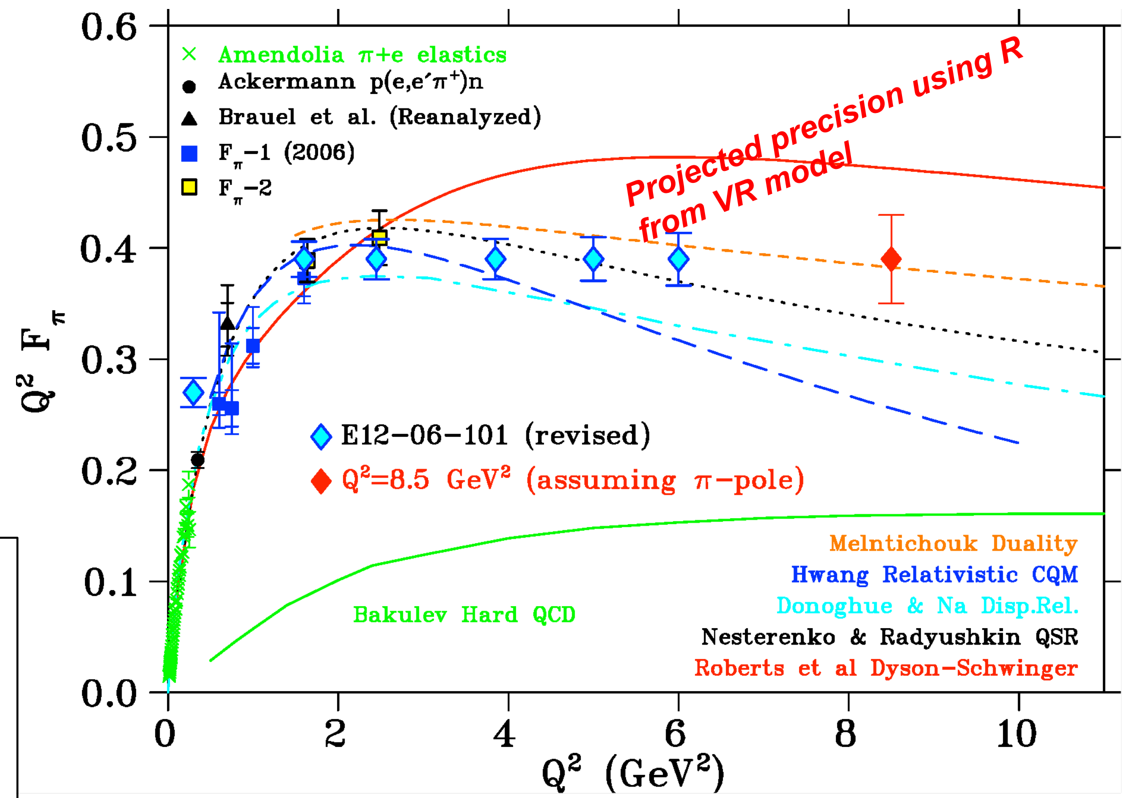
$$F_\pi(Q^2) \xrightarrow[Q^2\to\infty]{} \frac{16\pi\alpha_s(Q^2)f_\pi^2}{Q^2}$$

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




Data taken at lowest $Q^2$ as part of 2019 Hall C running

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

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

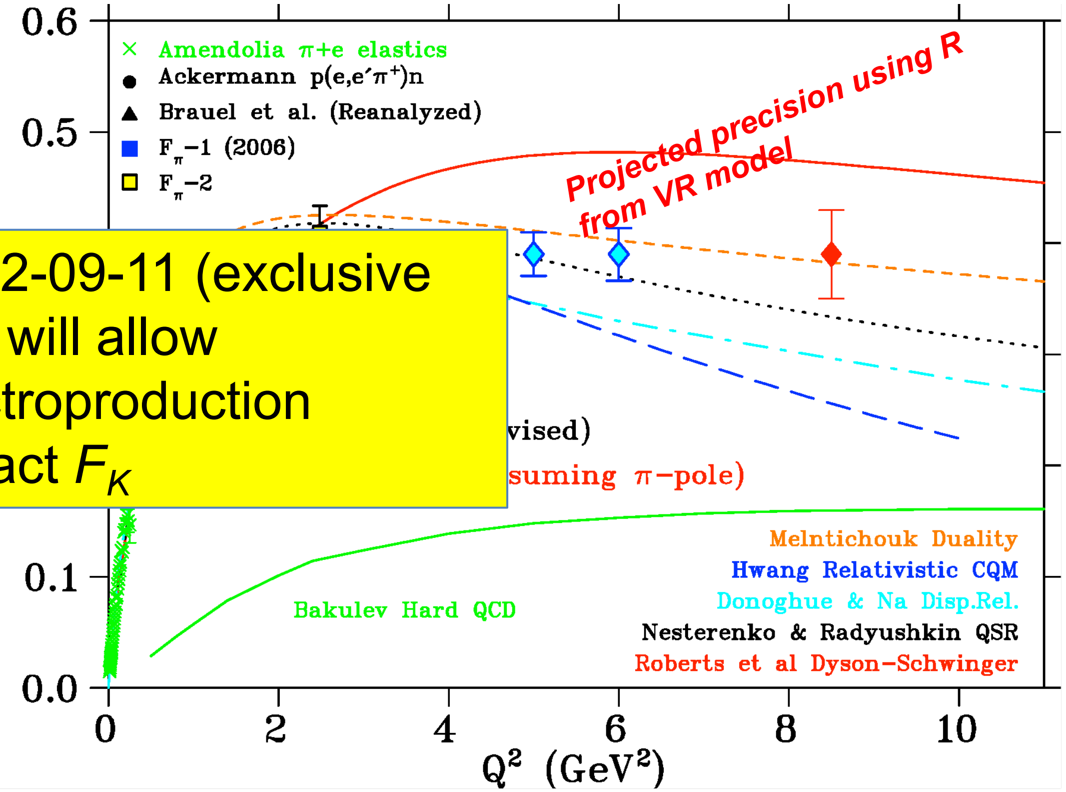
$$F_\pi(Q^2) \underset{Q^2\to\infty}{\longrightarrow} \frac{16\pi\alpha_s(Q^2) f_\pi^2}{Q^2}$$

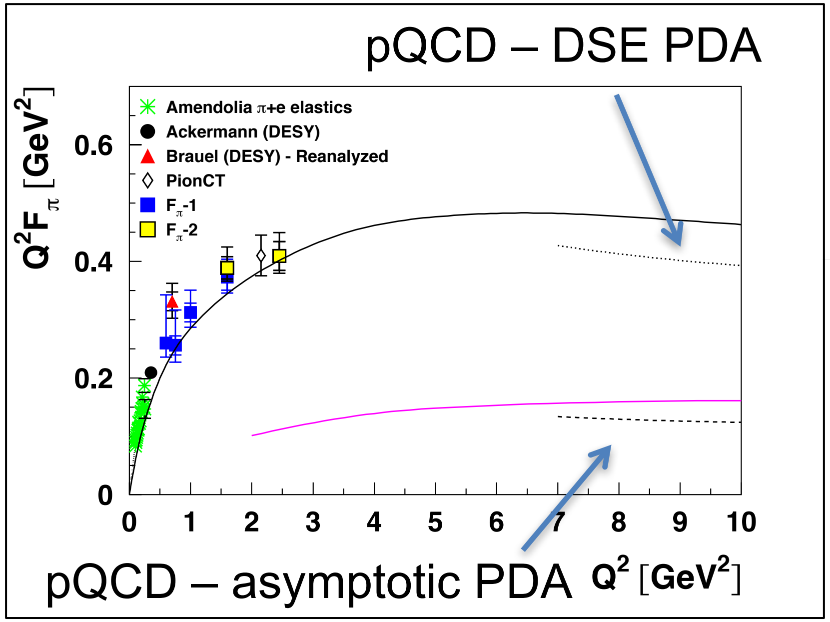
Is it possible to apply pQCD at accessible $Q^2$?

→ Use pion DA derived using D

→ DSE-based result consistent derived using constraints fro

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



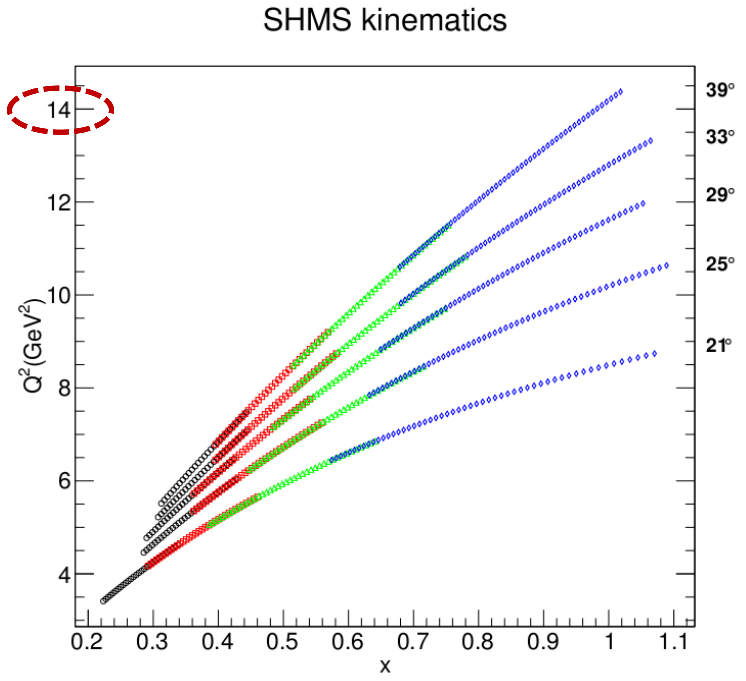

Data taken at lowest $Q^2$ as part of 2019 Hall C running

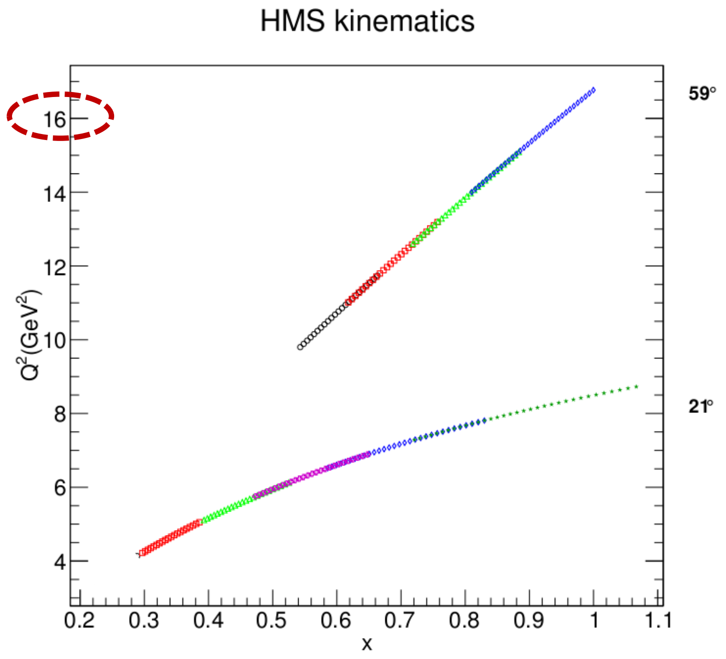
JLab 12 GeV upgrade + HMS/SHMS will allow measurement up to $Q^2$=*8.5* GeV$^2$

# Inclusive Reactions – Structure Functions and PDFs

Jefferson Lab experiment **E12-10-002**: H(e,e') and D(e,e') cross section measurements

- Constraints for Parton Distribution Functions (CTEQ-JLab)
- Quark-hadron duality studies
- Non-singlet moments of the $F_2$ structure function and comparisons to Lattice calculations
- Modeling of nucleon resonances

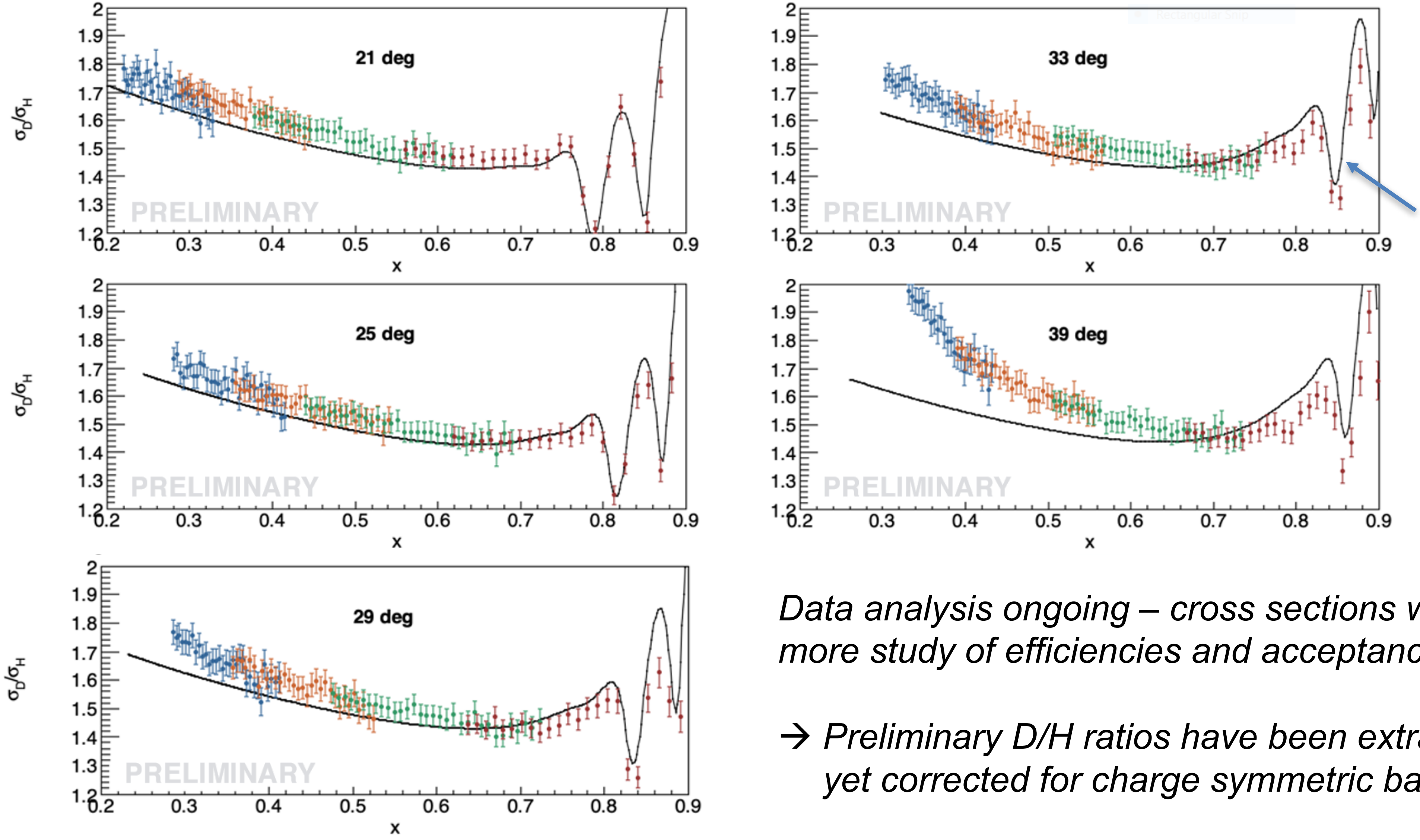



Ran in Hall C 2018 → Most data taken in new SHMS with cross-checks in HMS

*Large x Structure Functions, Sanghwa Park, Thursday*

# Hall C E12-10-002 D/H Ratios

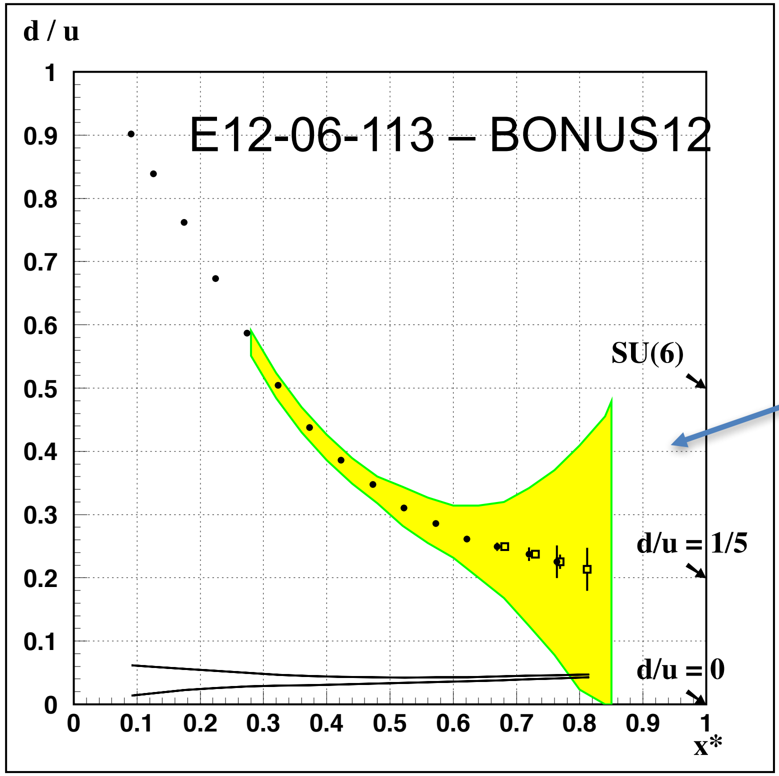



*Data analysis ongoing – cross sections will require more study of efficiencies and acceptance*

→ *Preliminary D/H ratios have been extracted (not yet corrected for charge symmetric backgrounds*

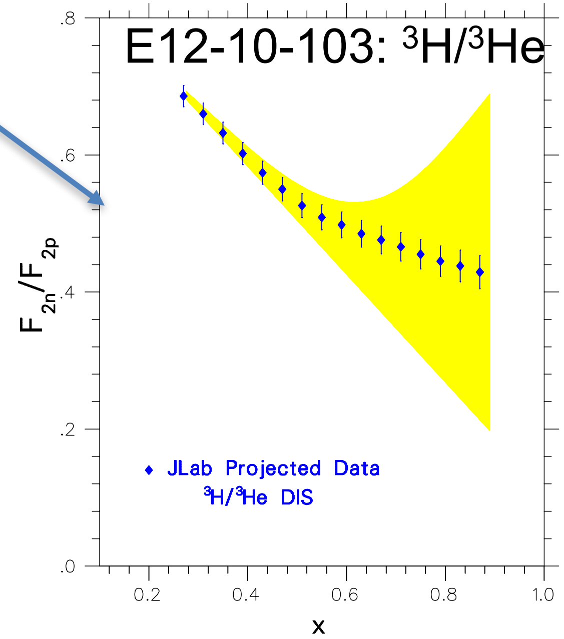
*First publication expected within the next 6 months*

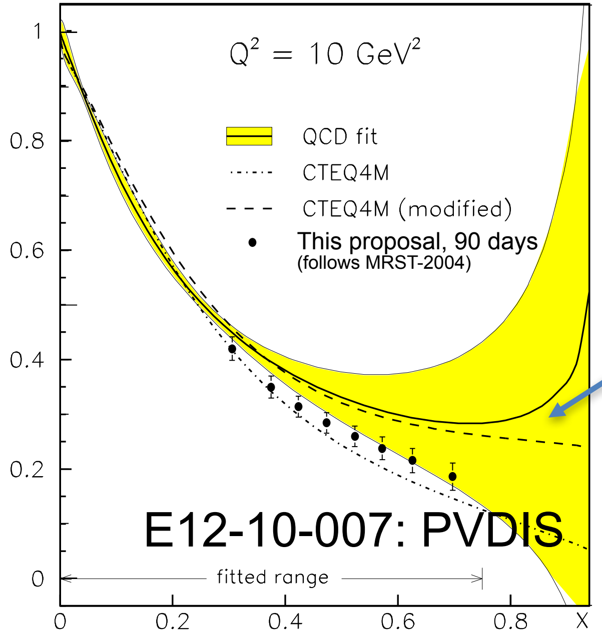
# Measurements of $F_2^n/F_2^p \rightarrow d/u$




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

Hall A: Standard HRS with $^3$H target




Hall A: PVDIS with SOLID

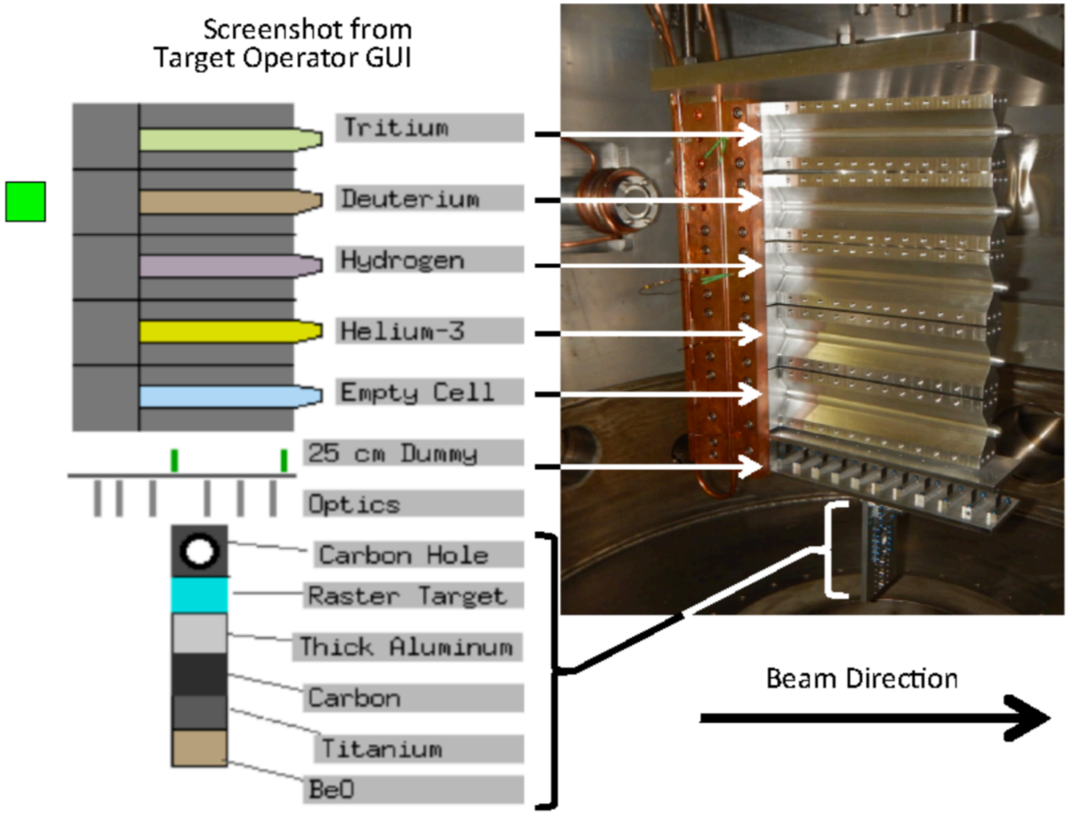
JLAB-12 GeV will allow extraction of d/u using a variety of techniques

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

# Tritium Program in Hall A

Large program of experiments made use of a tritium target, along with $^3$He, D, and H to explore an exciting, diverse program

→ MARATHON (E12-10-103): *Measurement of the F2n/F2p, d/u Ratios and A=3 EMC Effect in Deep Inelastic Scattering off the Tritium and Helium Mirror Nuclei*
→ E12-11-112: *Precision measurement of the isospin dependence in the 2N and 3N short range correlation*
→ E12-14-009: *Ratio of the electric form factor in the mirror nuclei $^3$He and $^3$H*
→ E12-14-011: *Proton and Neutron Momentum Distributions in A = 3 Asymmetric Nuclei*
→ E12-17-003: *Determining the Unknown Lambda-n Interaction by Investigating the Lambda-nn Resonance*




Tritium target cell:

- Low activity (~ 1 kCi)
- High-pressure sealed cell
- 40K gas
- Beam current < 22.5μA

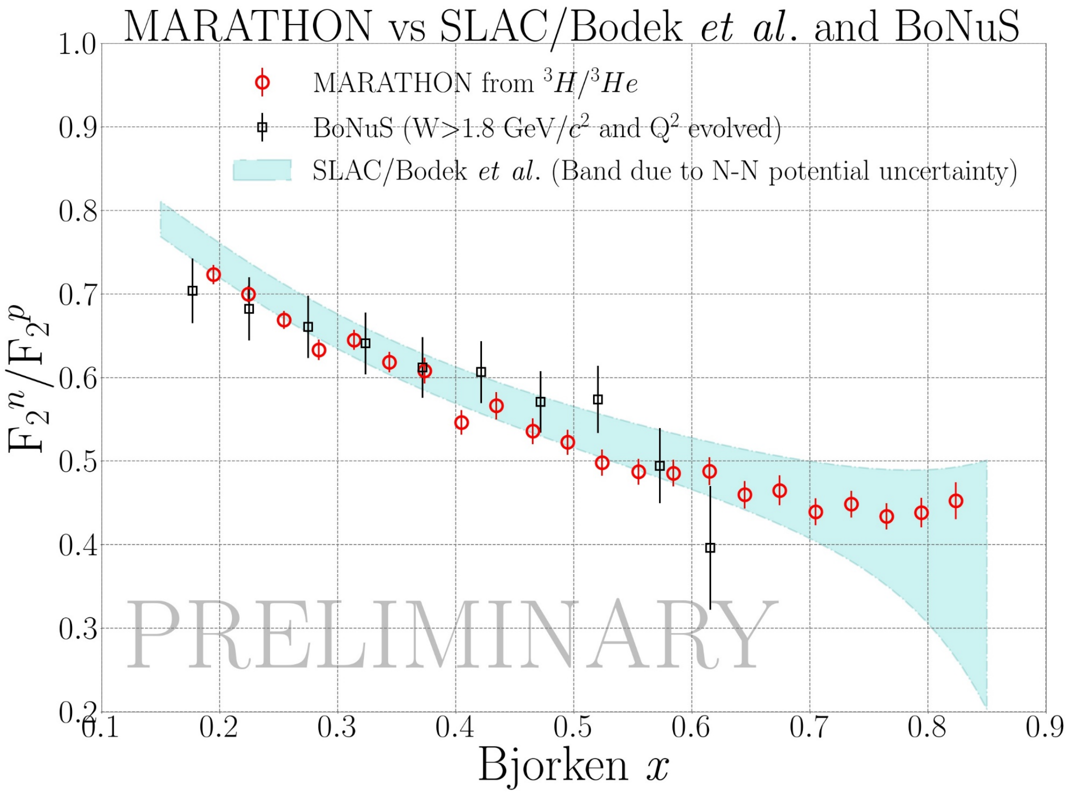
# MARATHON

MARATHON* experiment ran in Hall A in 2018 → $\sigma_n/\sigma_p$ (u/d) using $^3H$ and $^3He$ targets → using knowledge of *difference* in nuclear effects for $^3H/^3He$

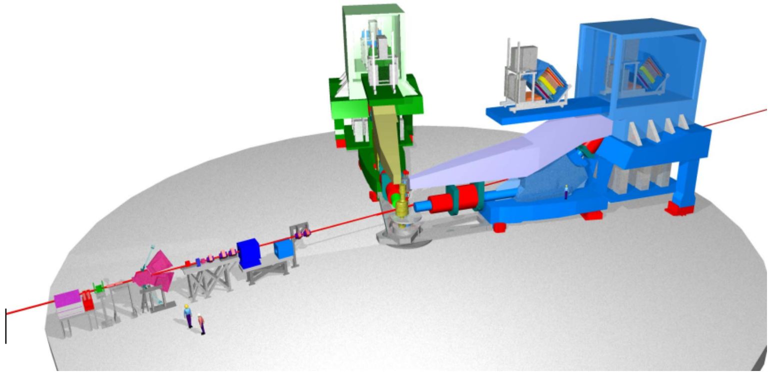
$$R(^3He) = \frac{F_2^{^3He}}{2F_2^p + F_2^n} \qquad R(^3H) = \frac{F_2^{^3H}}{F_2^p + 2F_2^n}$$

$$R^* = \frac{R(^3He)}{R(^3H)} \quad \Rightarrow \quad \frac{F_2^n}{F_2^p} = \frac{2R^* - \sigma^{^3He}/\sigma^{^3H}}{2\sigma^{^3He}/\sigma^{^3H} - R^*}$$

E12-10-103: $^3H/^3He$




*Plot courtesy Makis Petratos*



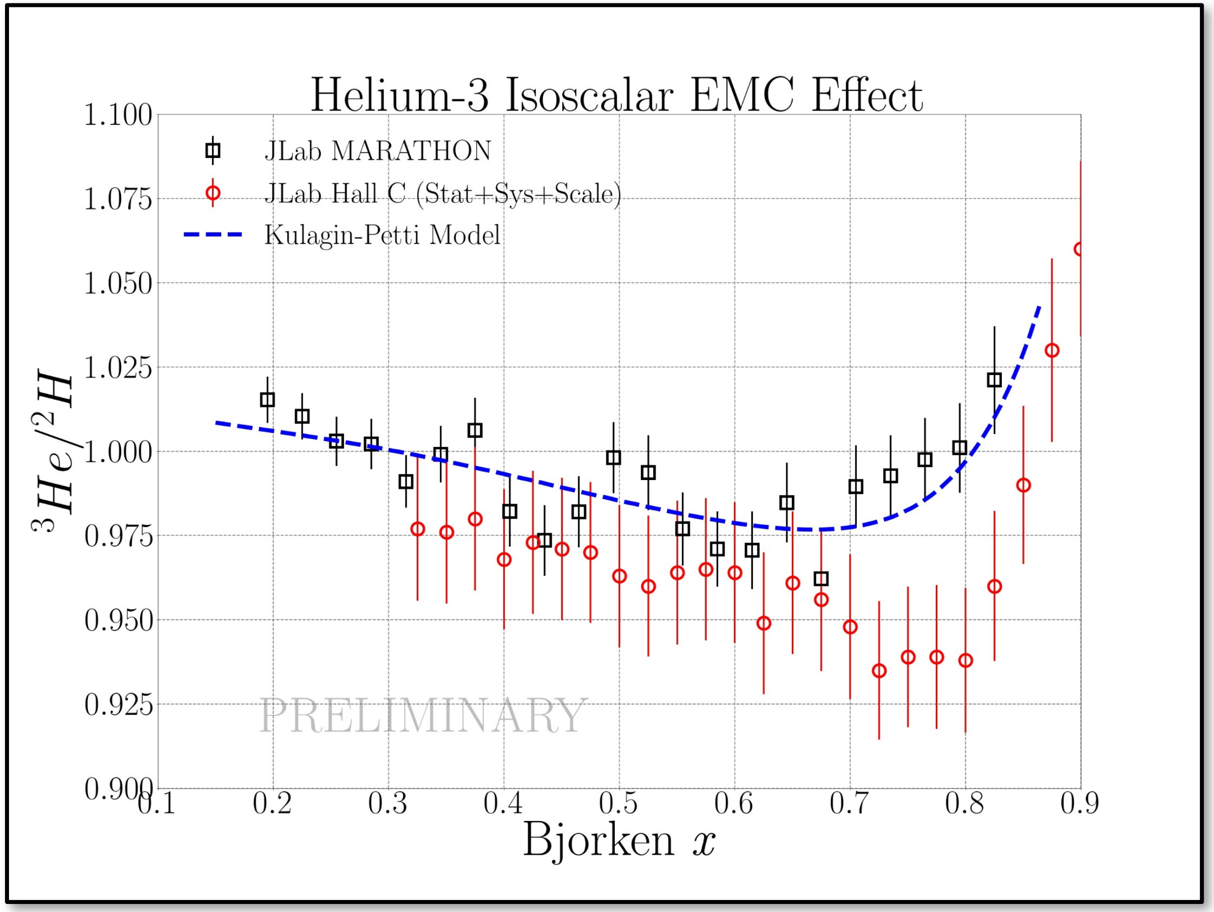
*****MeA****surement of theFn2/Fp2,d/u****RA****tios and A=3 EMC Effect in DeepInelastic Electron Scattering Offthe****T****ritium and* ***H****elium Mirr****O****r****N****uclei*

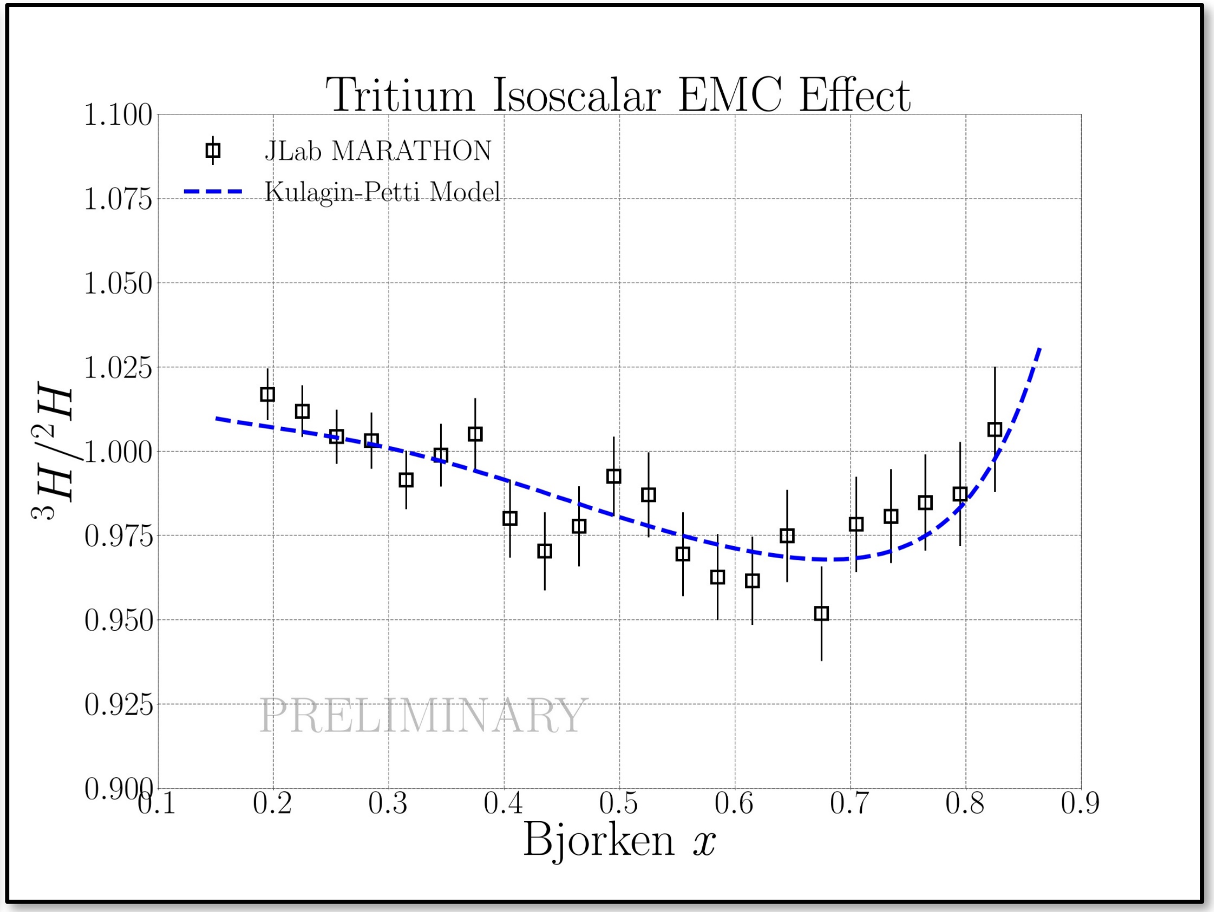
# EMC Effect in $^3H$ and $^3He$

MARATHON measured EMC Effect for both $^3He$ and $^3H$

→ MARATHON $^3He$ result agrees with 6 GeV measurement in DIS region (W>2 GeV)

→ ***First measurement of EMC Effect in $^3H$***

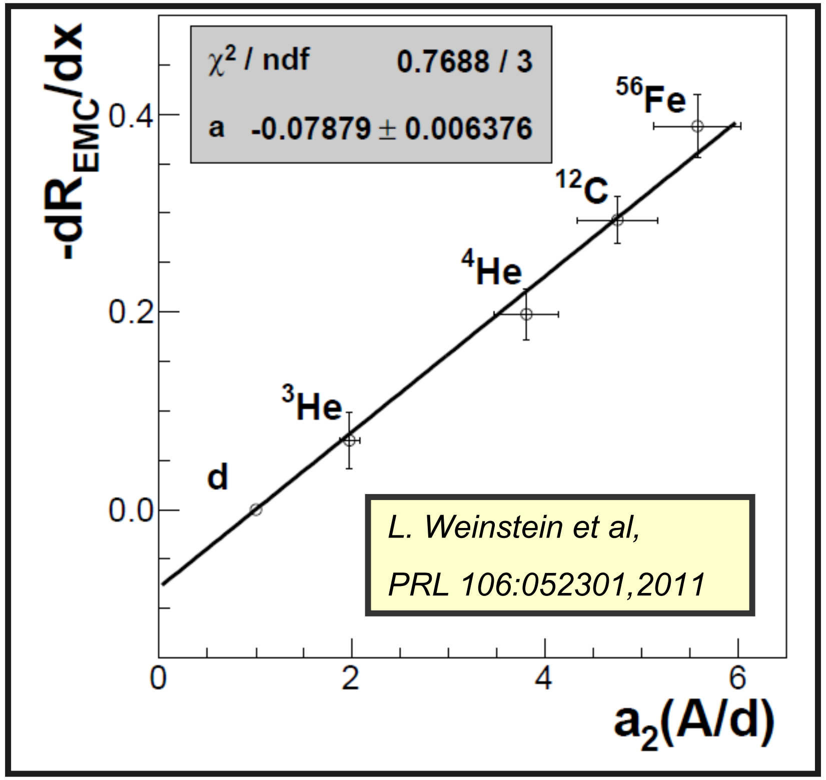



*Plots courtesy Makis Petratos*

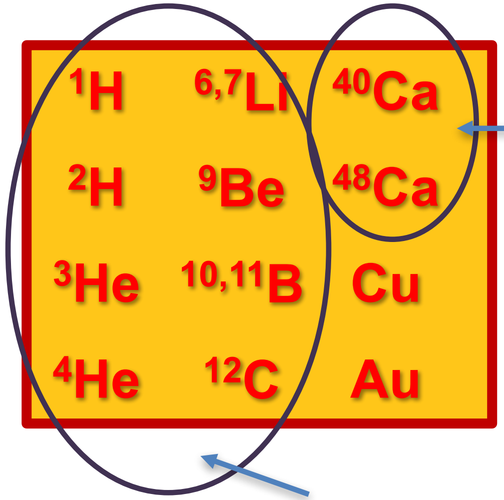
Jefferson Lab

# 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?

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***




**Examine isospin dependence**

**A dependence in light nuclei, some with significant cluster structure**

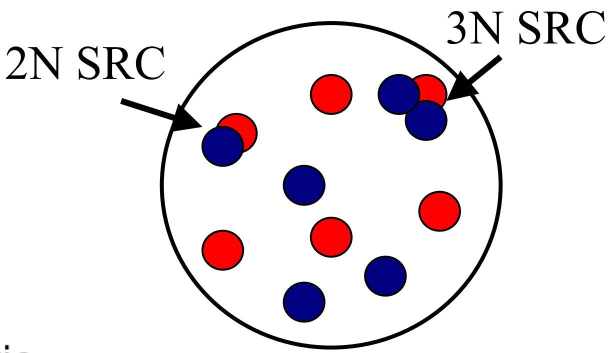
Additional information from $^{3}$H/$^{3}$He from **Hall A** experiments using special tritium target
→E12-10-103 (DIS)
→E12-11-112 (x>1)

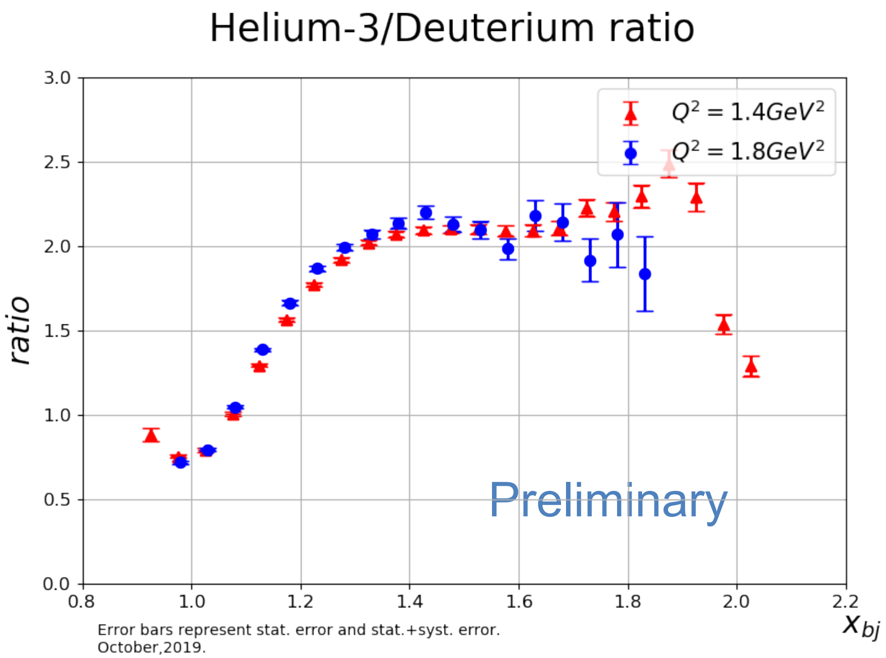
***C, $^{10}$B, $^{11}$B data taken in Hall C in 2018***

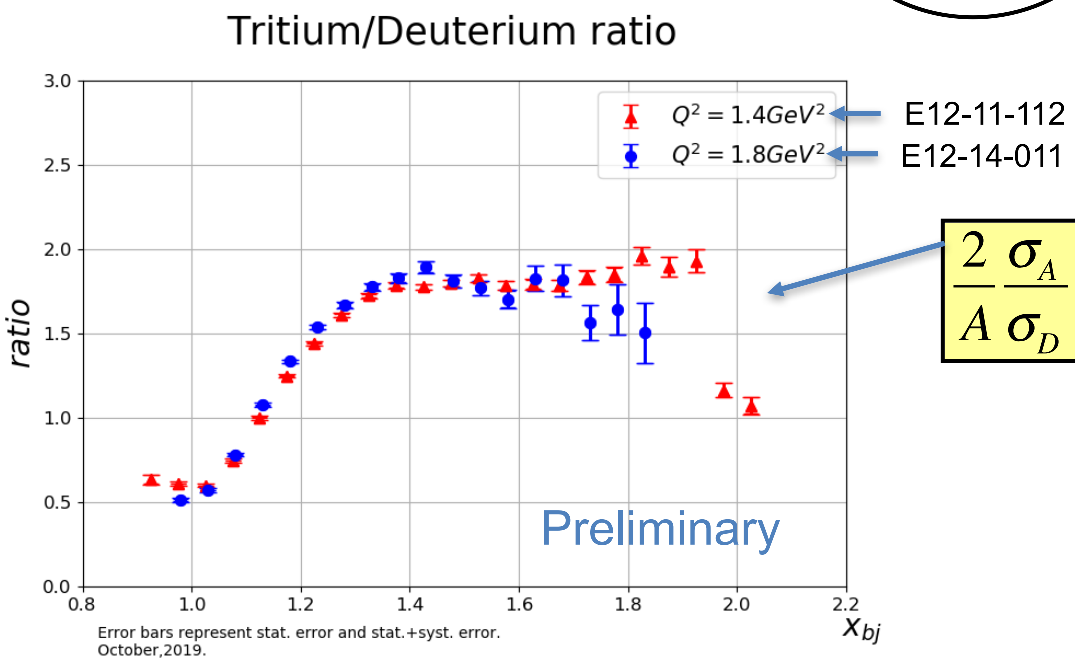
# Short Range Correlations in $^3H/^3He$ (Inclusive)

Probability of finding a correlated nucleon pair can be extracted from inclusive cross section ratios (A/D) at ***x>1*** → beyond QE peak

→ Comparison of $^3He$ and $^3H$ can provide information on composition of SRCs




$$\frac{2}{A}\frac{\sigma_A}{\sigma_D} = a_2(A)$$

*Plots courtesy of Shujie Li, U. New Hampshire*

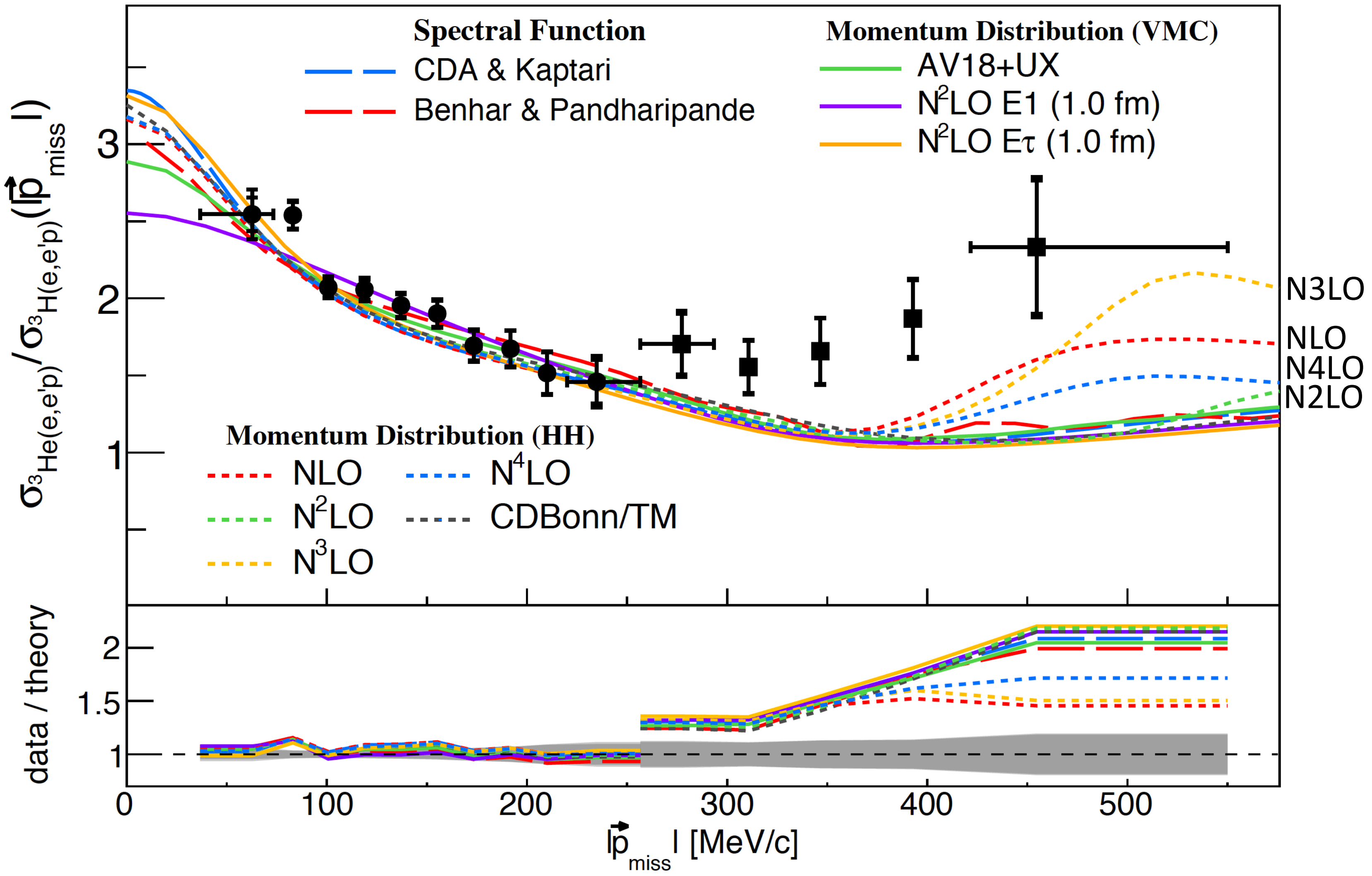
E12-11-112 in Hall A made first measurement of relative inclusive SRC ratio in $^3H$

# Short Range Correlations in $^3H/^3He$ (Exclusive)

Missing momentum dependence of A(e,e'p) at x>1 kinematics

At large missing momentum, $^3He/^3H$ ratio should approach 1 in simple np dominance picture

→ Increase in ratio at large Pm could be due to unexpected FSI effects, NN potential issues?



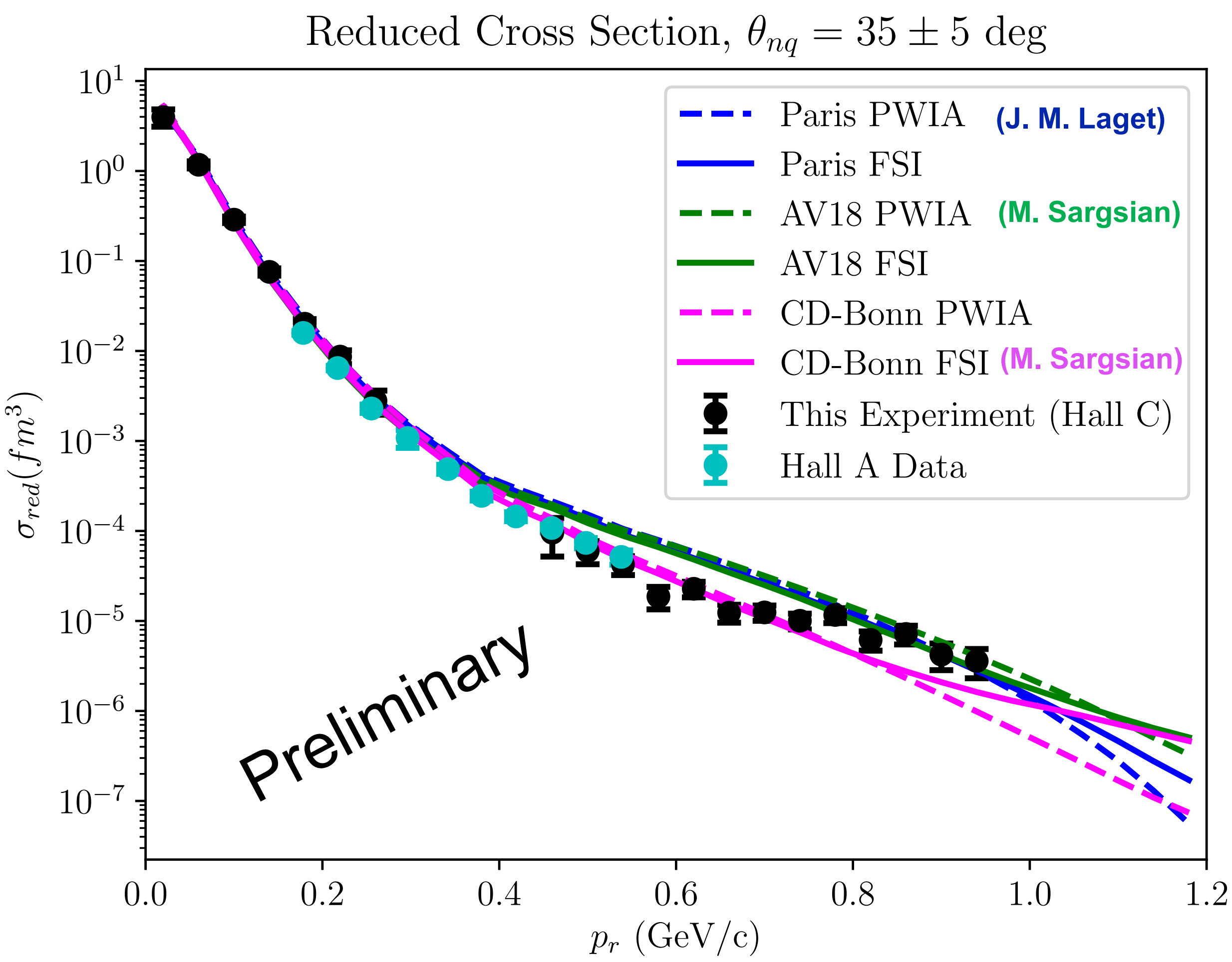
# Deuteron Electrodisintegration

→ Inclusive/exclusive ratios can be used to access relative number of SRCs in nucleus, but don't give direct information on short-range interaction

→ *D(e,e'p)n* simplest reaction for accessing details of high-momentum (short distance) structure

→ FSI's important – theory can guide measurements to kinematics where they are small

→ Hall C E12-10-003 extends measurements up to $P_m$ of 1 GeV

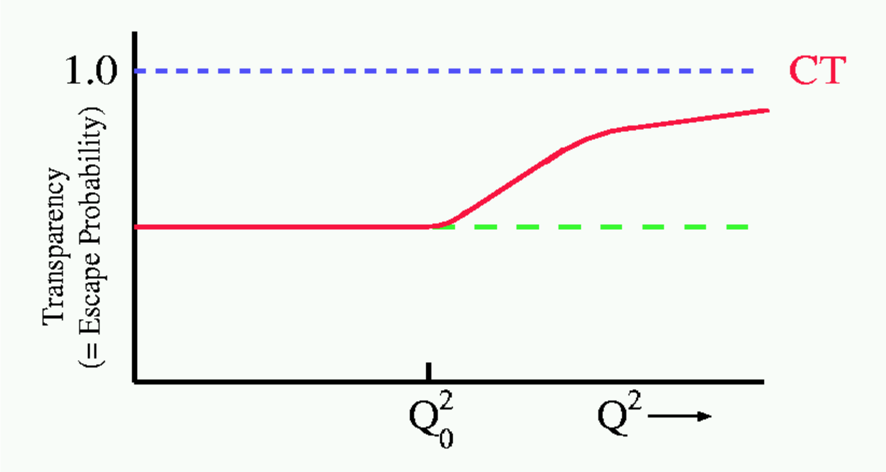



*Plot courtesy Carlos Yero*

Results not well described by any model above $P_m$=700 MeV/c

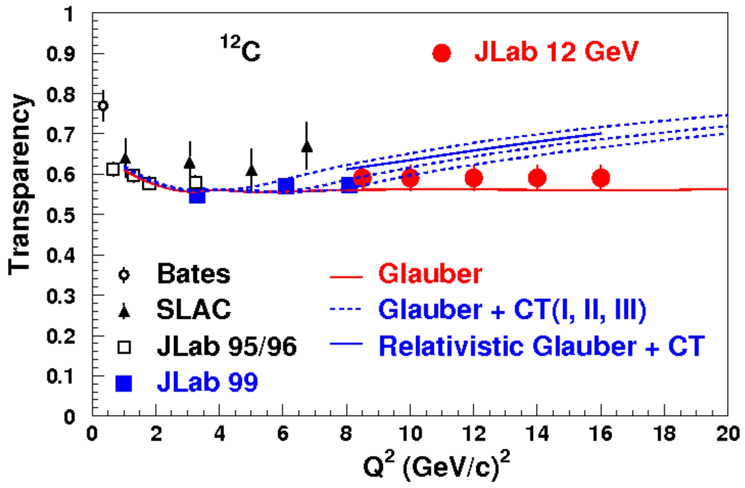
# Color Transparency

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



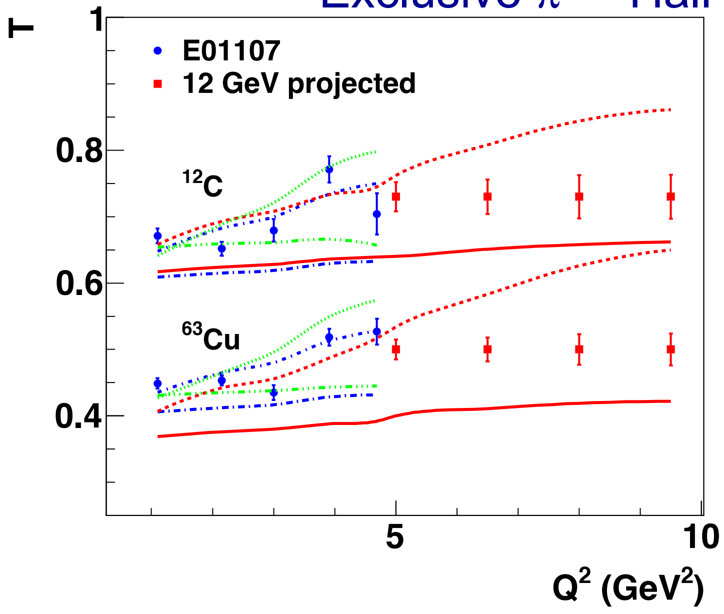

***Color Transparency is closely intertwined with the notion of soft-hard factorization in exclusive processes***

Protons – Hall C

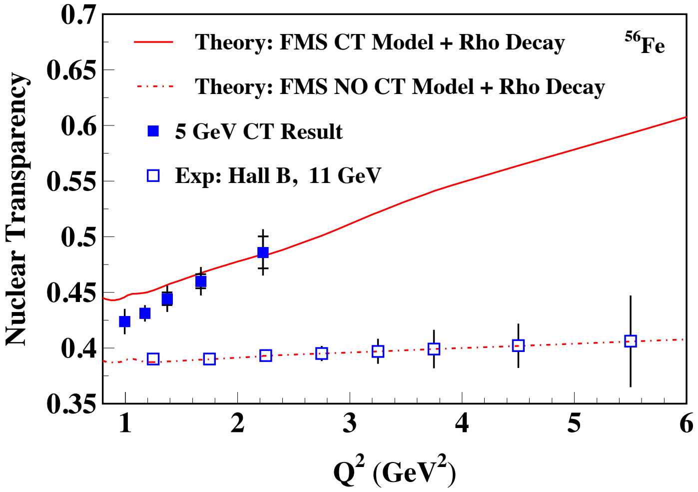



A(e,e'p)/H(e',p)

Exclusive $\pi^+$ – Hall C




Exclusive $\rho^0$ – CLAS12

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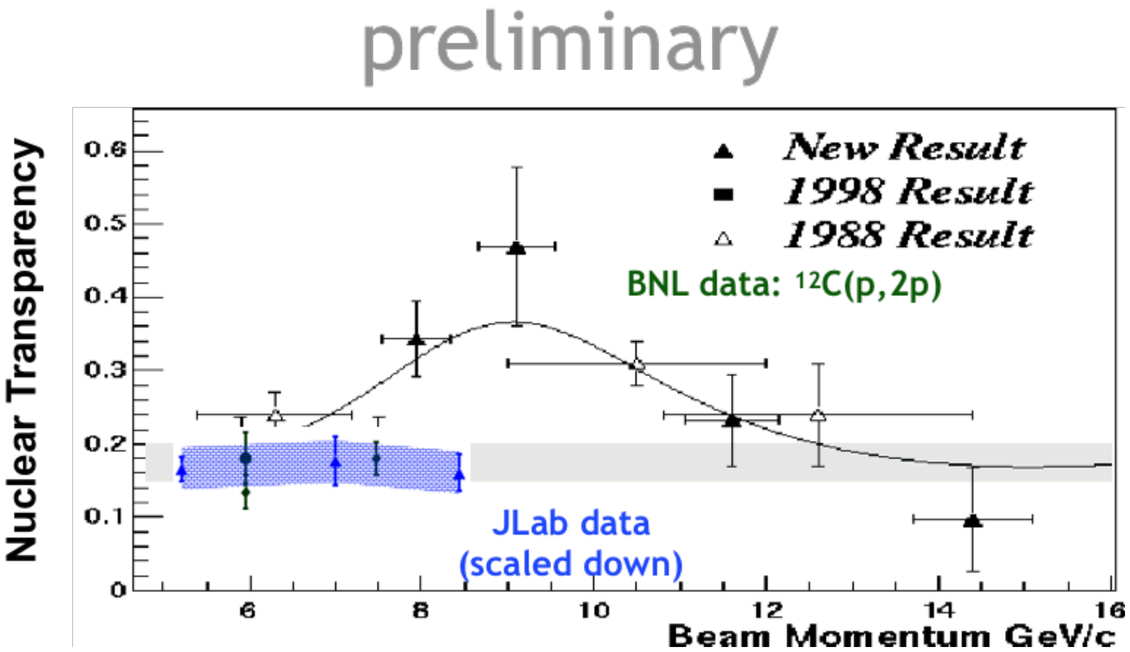
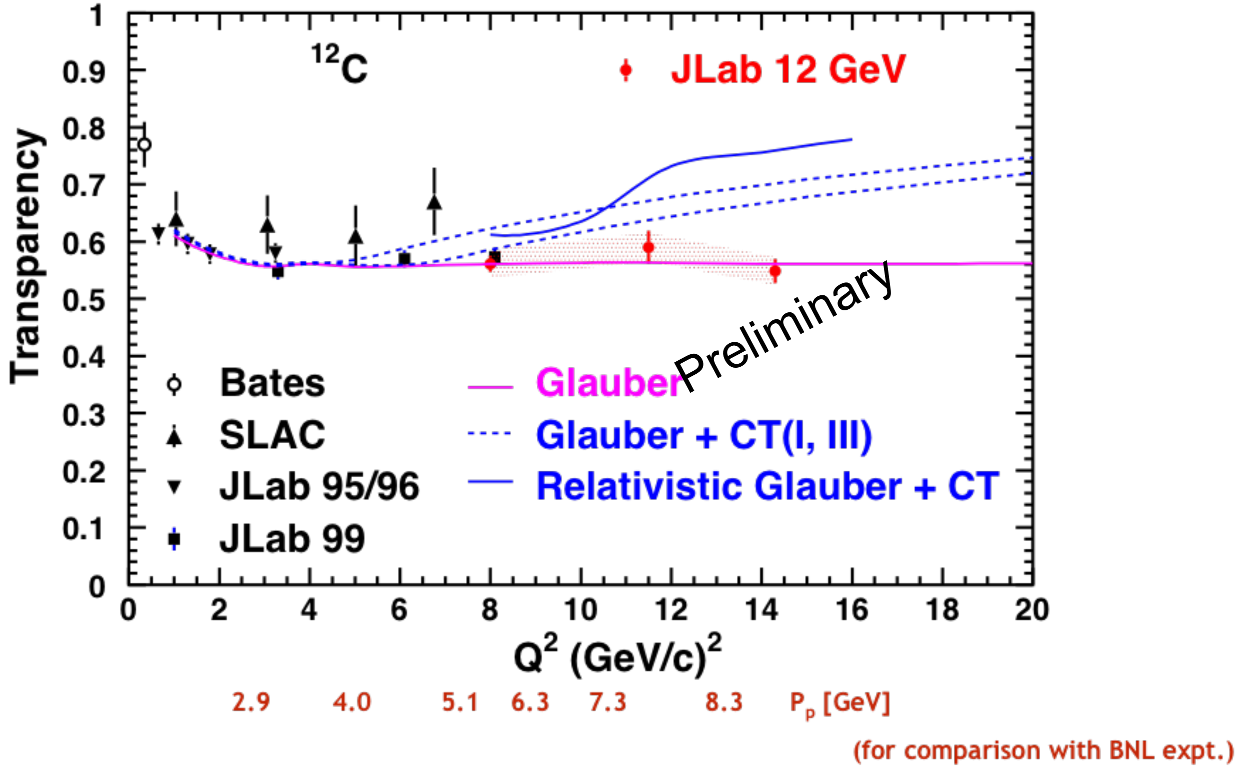
# Color Transparency – E12-06-1007

First experiment to run in Hall C after 12 GeV Upgrade (2018)

→ Preliminary results show no sign of transparency up to $Q^2$=14.3 $GeV^2$



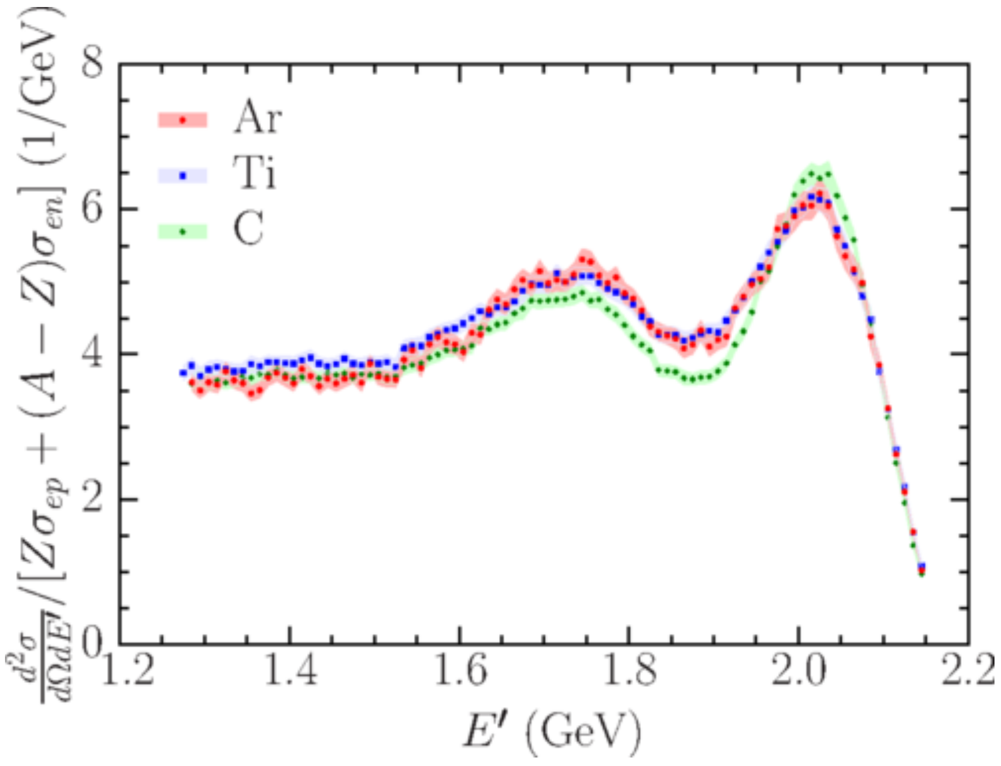




JLab $Q^2$ accesses kinematics comparable to Brookhaven (p,2p) results which has been interpreted as a sign of Color Transparency

# Hall A: $^{40}$Ar Spectral Function

Neutrino experiments rely on detailed Monte Carlos to analyze/reconstruct event information
→ Targets/detectors are almost always medium to heavy nuclei
→ Knowledge of detailed nuclear structure important for controlling uncertainties

Next-generation neutrino experiments will make use of liquid Argon detectors – electron scattering data sparse




*H. Dai et al.,PRC 99, 054608 (2019)*

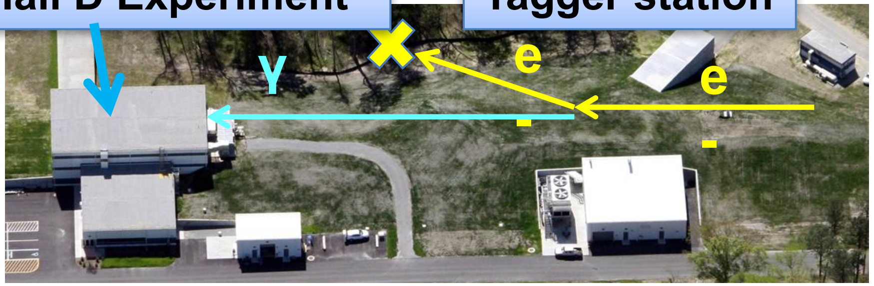
E12-14-012 made dedicated measurement of electron scattering from Argon to access spectral function
→ Inclusive cross sections already published

# Hall D: Experiments with Photon Beam

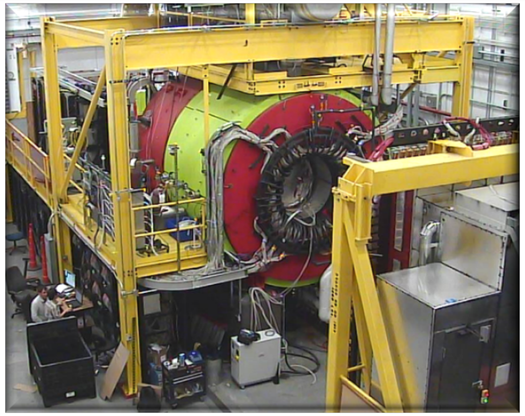
- Linearly polarized photon beam ~9 GeV
- Experiment GlueX: Search for gluonic excitations in light meson spectra (data taking in 2017 and 2018)

Hall D Experiment

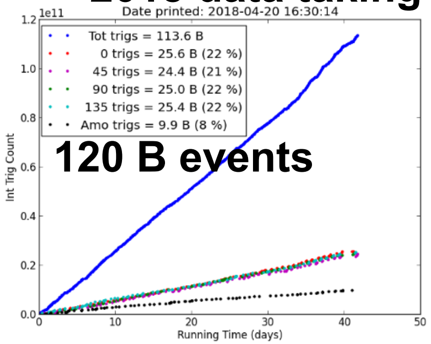
Tagger station

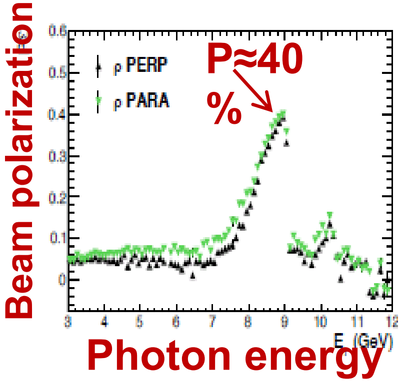



Large-acceptance spectrometer

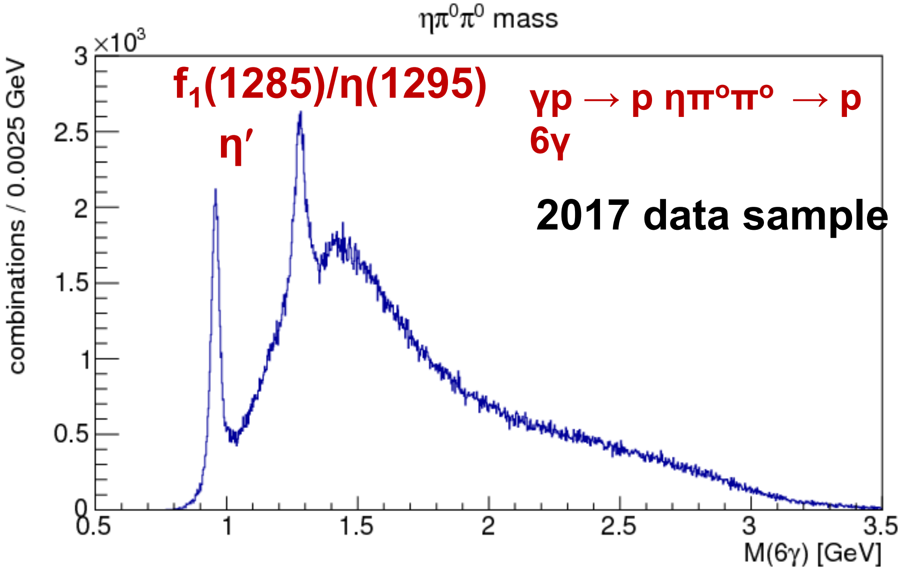


2018 data taking




Regular mesons: event reconstruction

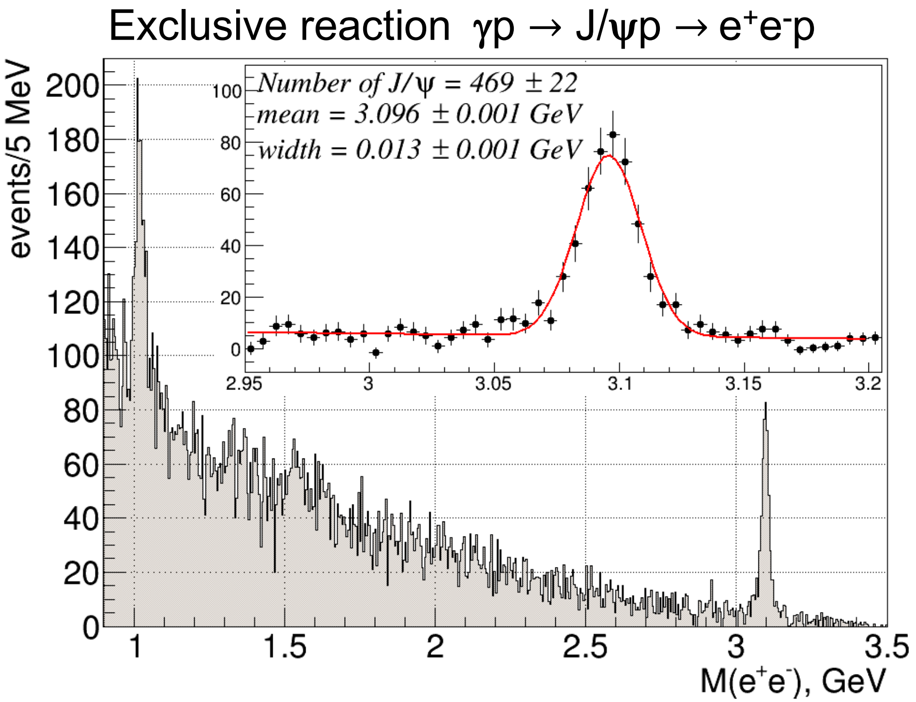


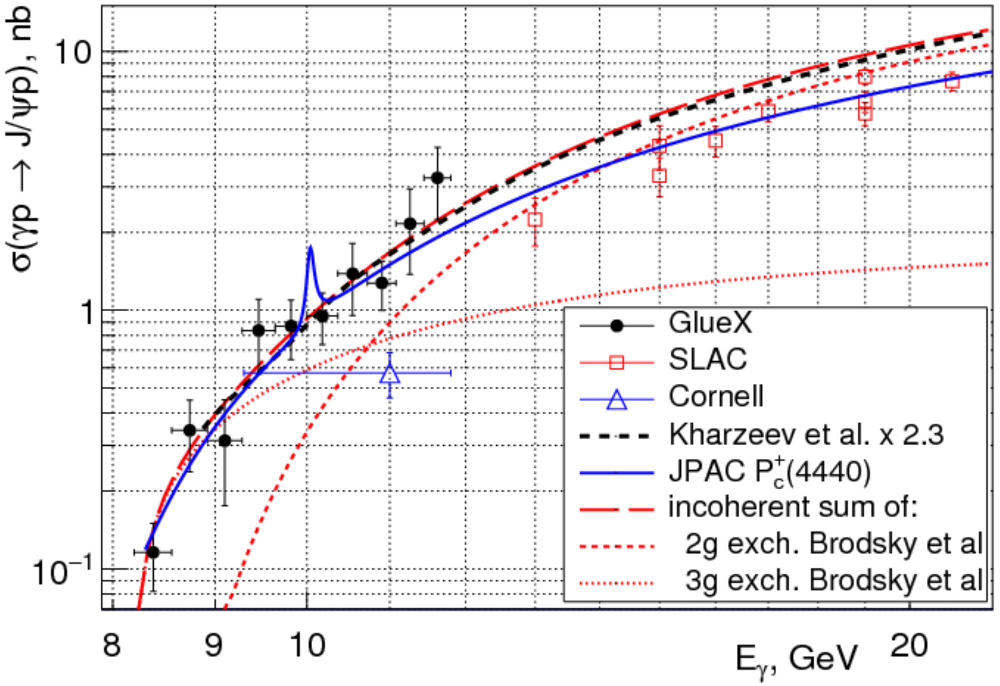
# JLab Hall D GlueX: Near-threshold J/ψ photoproduction

GlueX Collaboration, A.Ali *et al* PRL 123, 072001 (Aug 2019)

**γ+p→J/ψ+p    J/ψ→e⁺e⁻**

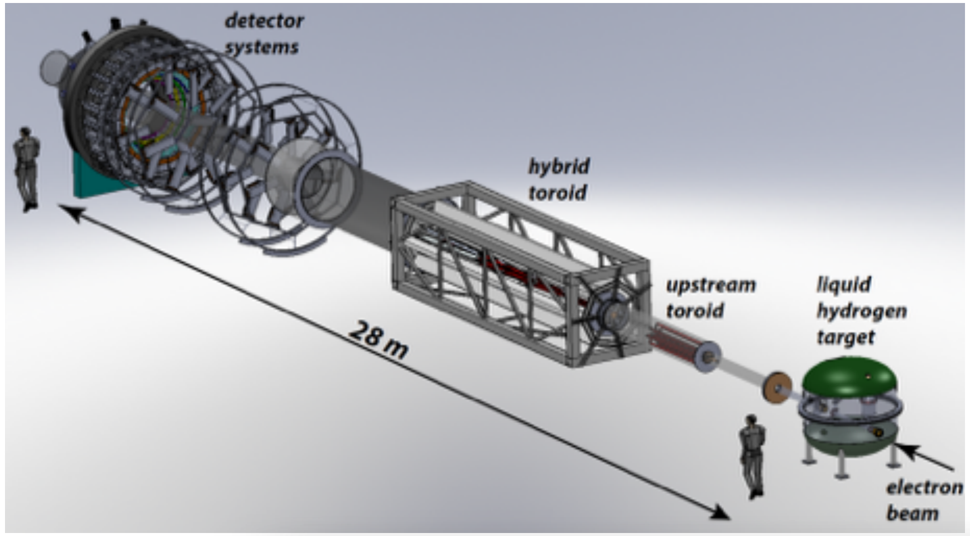
- Probes gluonic field in the nucleon at high x
  - measured cross section is larger than expected from two-gluon-exchange models
  - agrees with theoretical calculations with large gluonic contribution to the mass of the proton
- Search for LHCb pentaquarks $P_c$ produced in the s-channel: **γ p → Pc → J/ψ p** at Eγ ≈ 10 GeV
  - no evidence found, model-dependent upper limits on $Br(P_c \to J/\psi p)$ of 2-4% at 90%CL



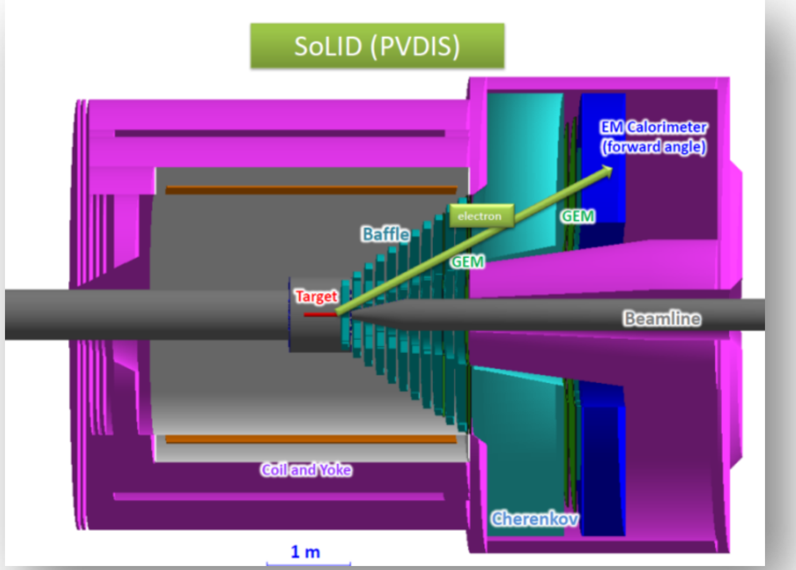



# New Physics – JLab 12 GeV Parity Program

MOLLER: Elastic *e*-*e* scattering



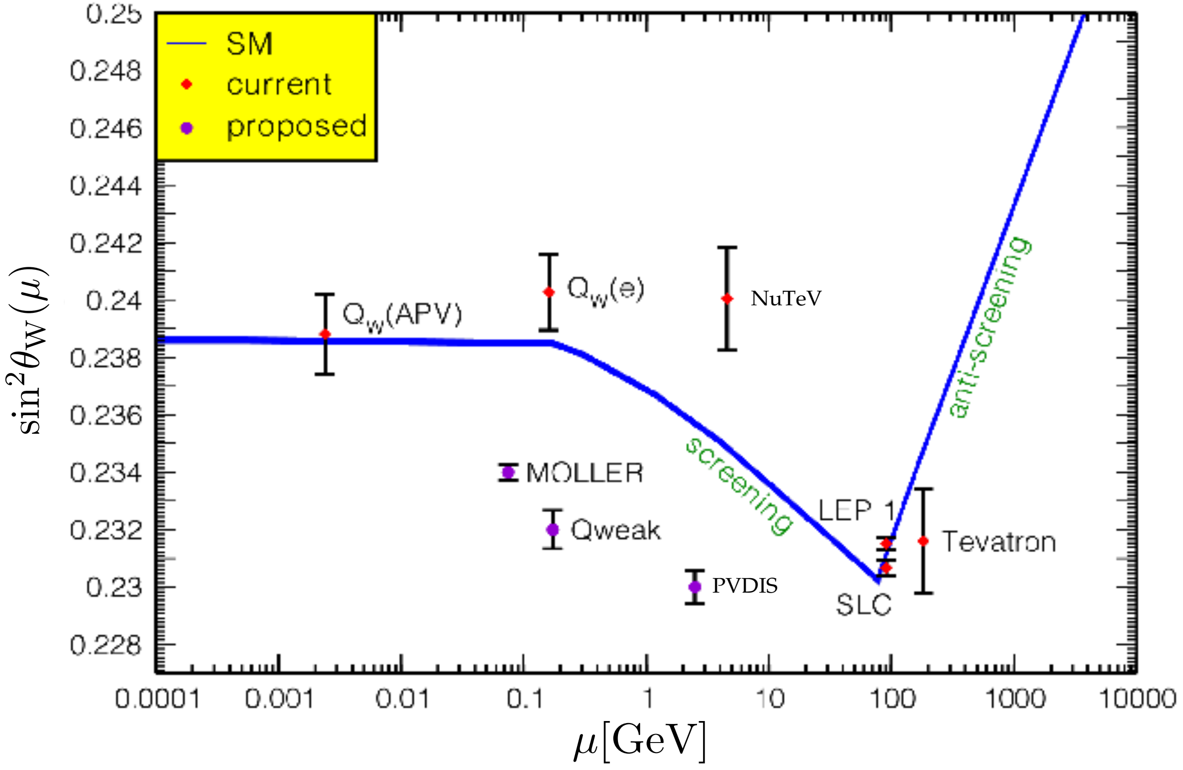

SOLID: parity violating DIS




Building on JLab 6 GeV parity program

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

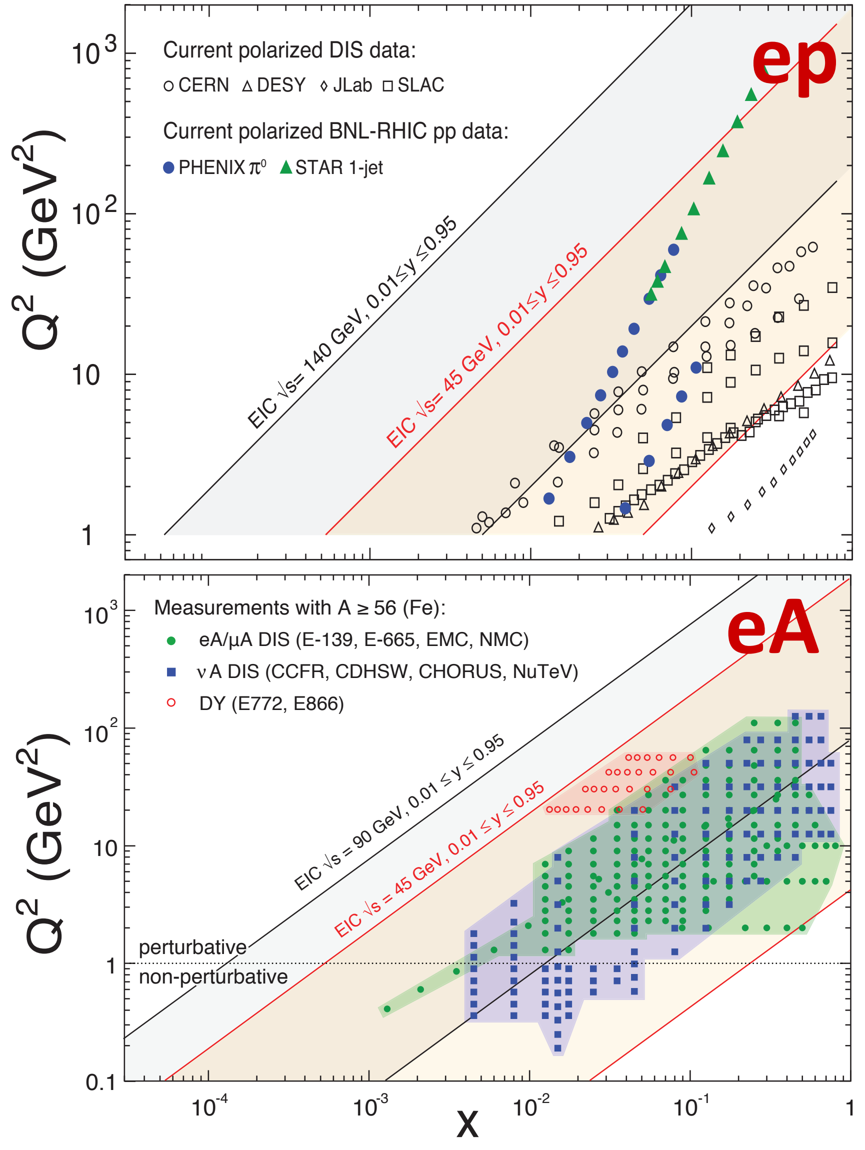
→ Sensitive to running of weak mixing → new physics at TeV scales



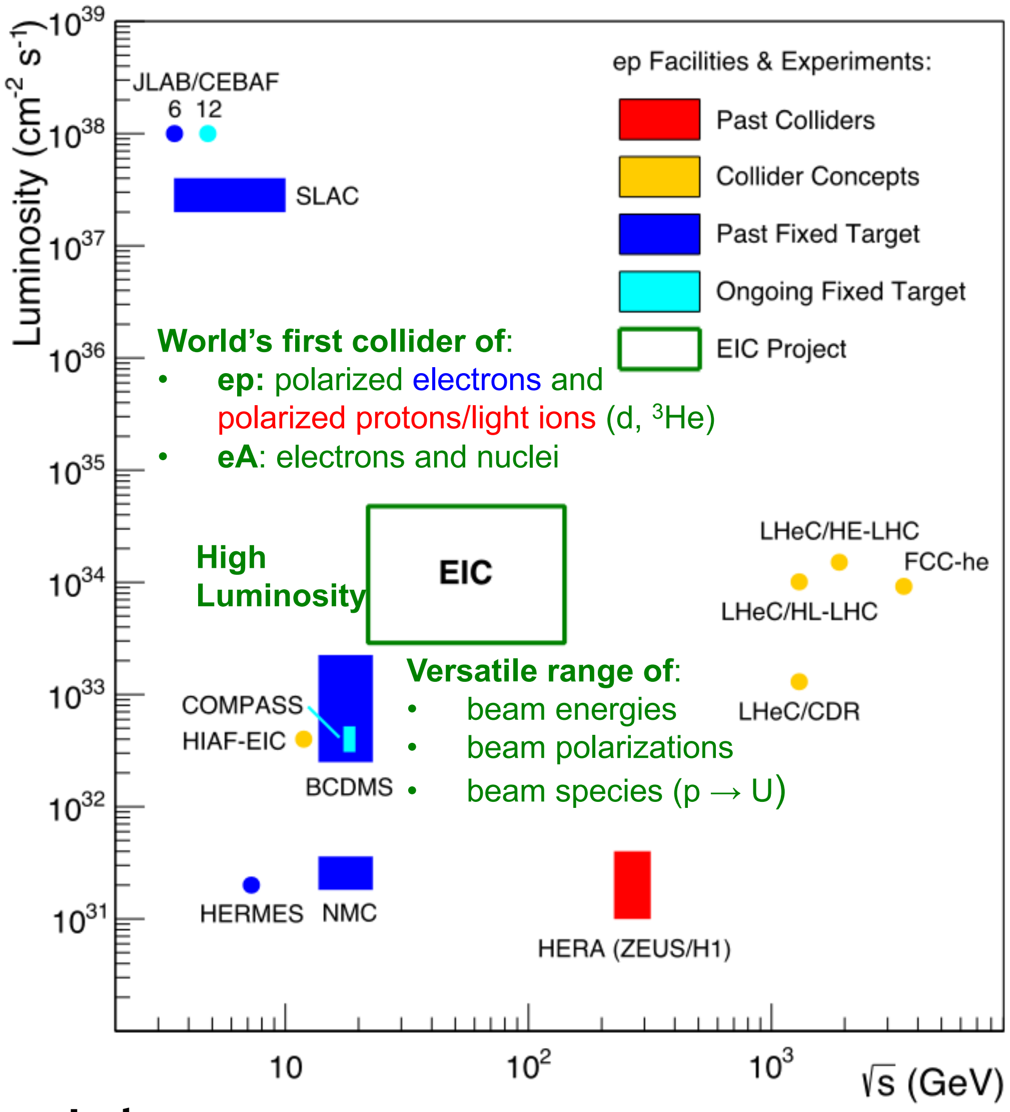

*Krishna Kumar, Wednesday*

# From JLab 12 GeV to EIC

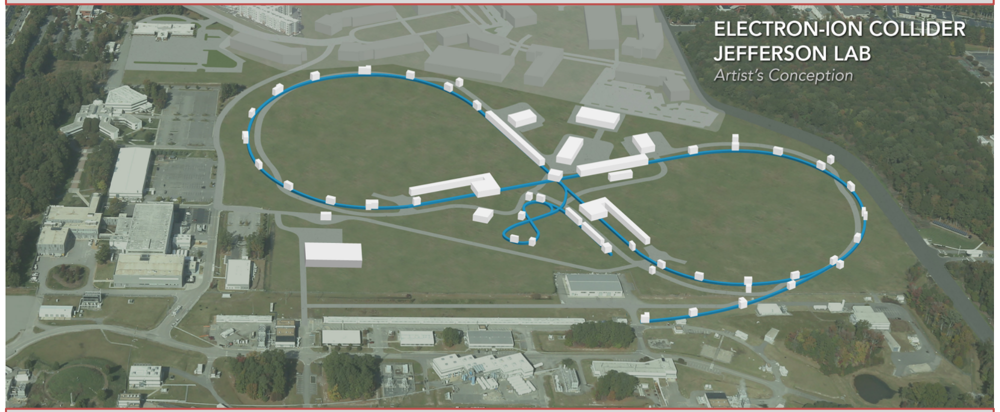
- JLab 12 GeV will provide a plethora of information at large *x*
  - Primarily sensitive to valence quarks
- EIC will provide unprecedented precision at lower *x* to study sea-quark, gluon structure of nucleons/nuclei
  - Overlap with fixed target programs
  - High luminosity, highly polarized beams required for TMD/GPD 3D imaging programs



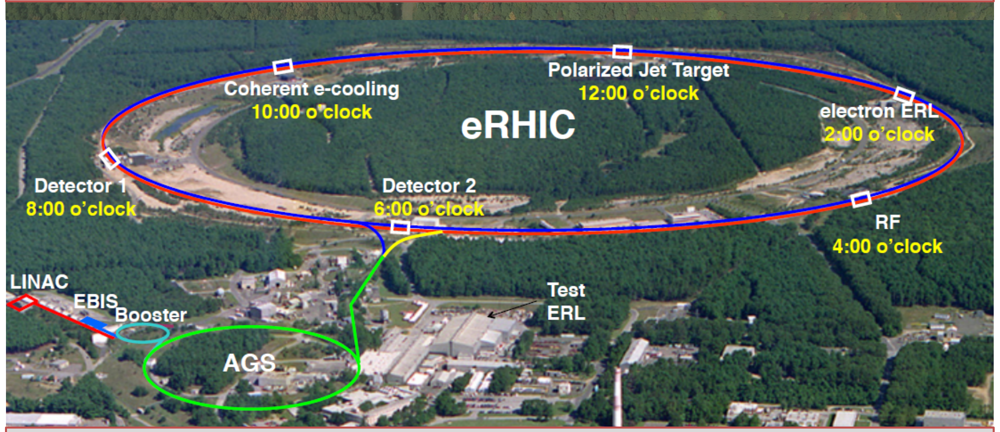
# The Electron-Ion Collider: Frontier accelerator facility in the U.S.




**Highest priority for new construction**
for the U.S. Nuclear Physics program




**Proposal by Jefferson Lab**




**Proposal by Brookhaven National Lab**

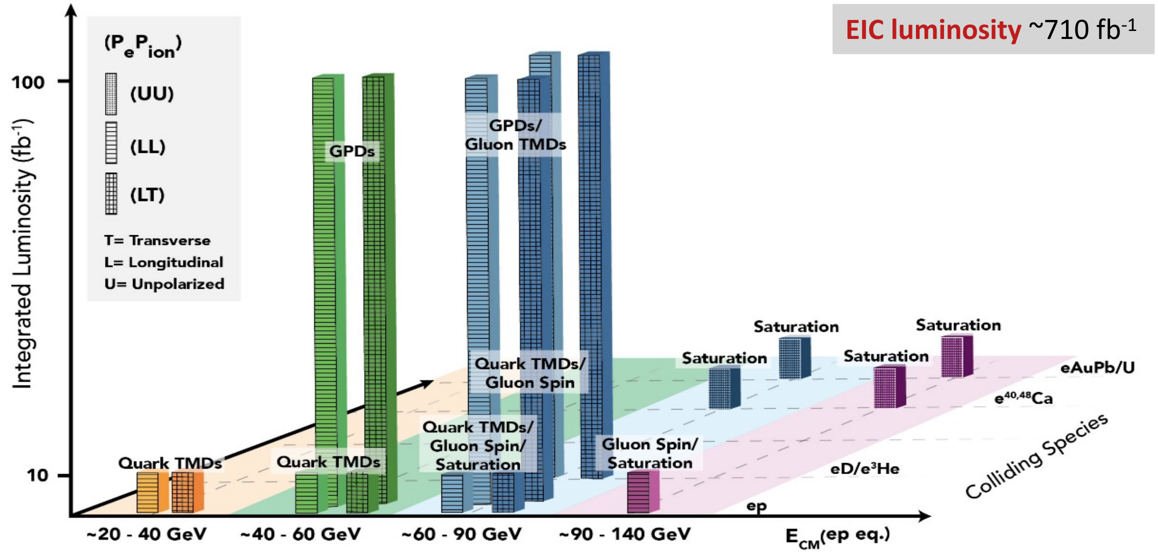
# Electron-Ion Collider Requirements

EIC nucleon imaging program drives the maximum luminosity requirement → $10^{34}$ $cm^{-2}s^{-1}$

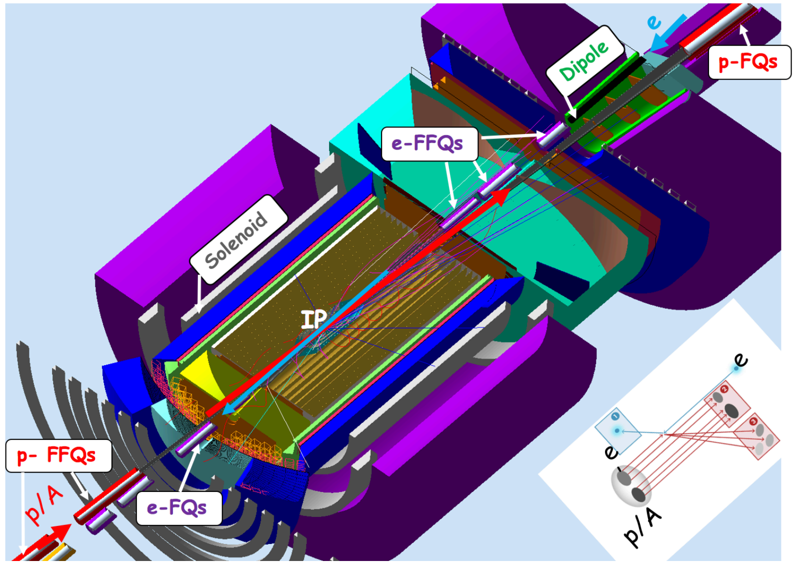
→ Highly polarized electron/ion beams also required (>70%)

→ High precision polarimetry, luminosity measurements needed to fully leverage statistical power

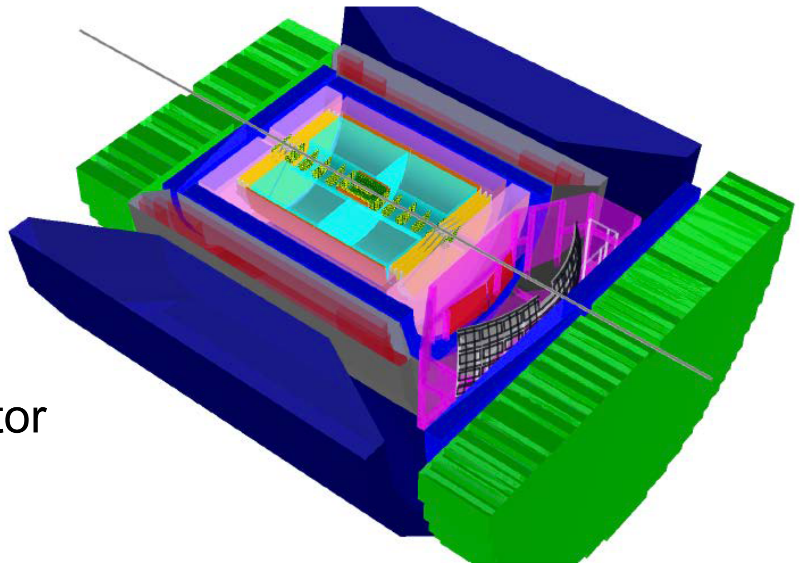
→ ~100% acceptance detectors, preferably at multiple interaction points




JLEIC Detector Concept




eRHIC Detector Concept



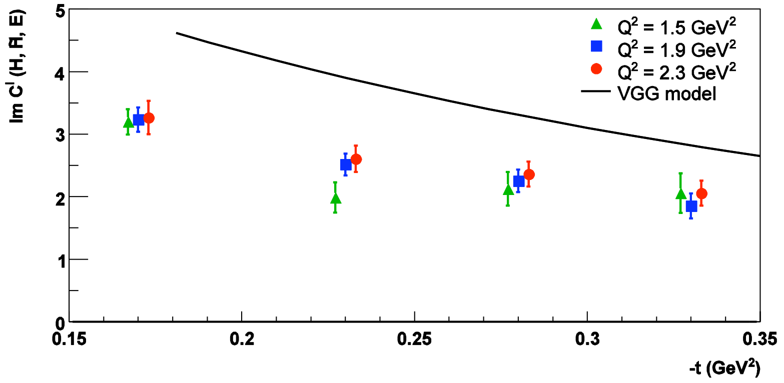
# Summary

- 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
- Hall D program focused on exploring meson states with linearly polarized photons
- Planned future equipment will augment these capabilities
  - Neutral particle spectrometer in Hall C → SIDIS and exclusive $\pi^0$, 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
- EIC will provide an unprecedented opportunity to explore nucleon/nuclear structure – highest priority for new construction in U.S.

# EXTRA

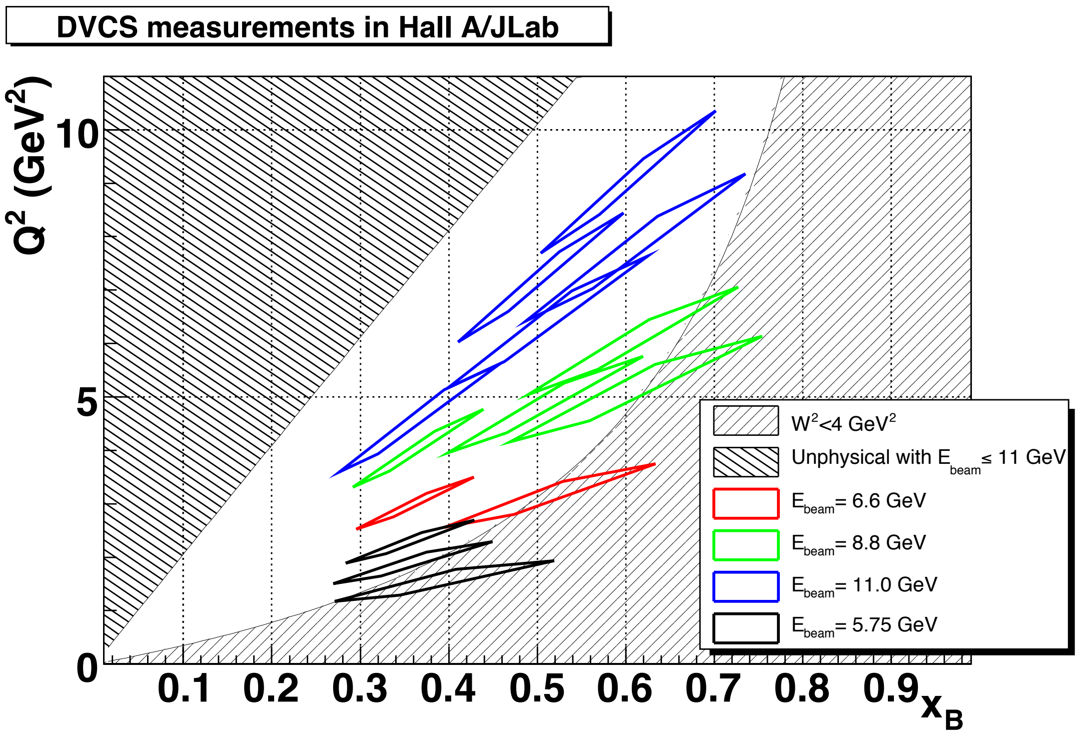
# DVCS in Hall A

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



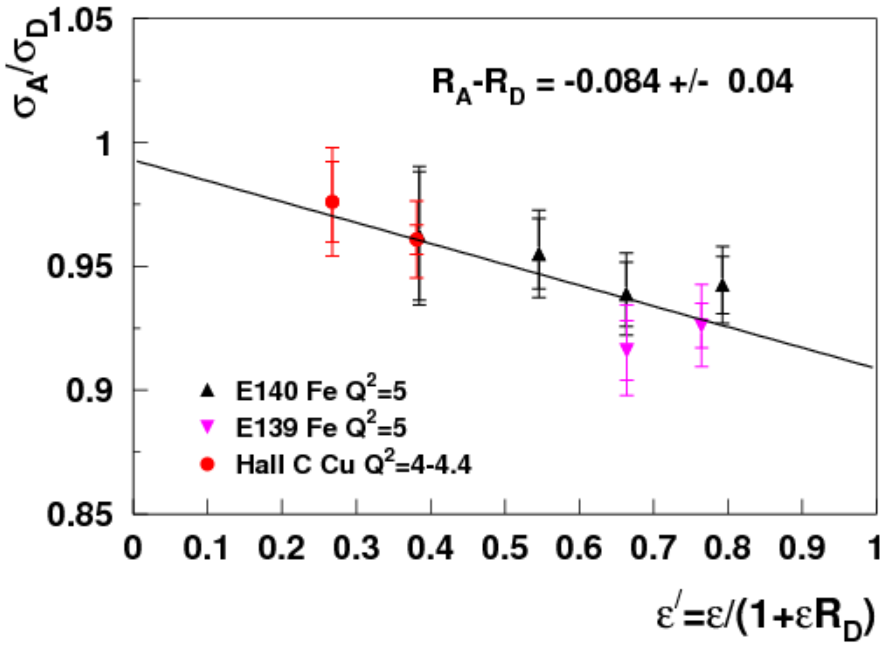

[C. Muñoz Camacho et al., PRL**97**, 262002 (2006)]

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

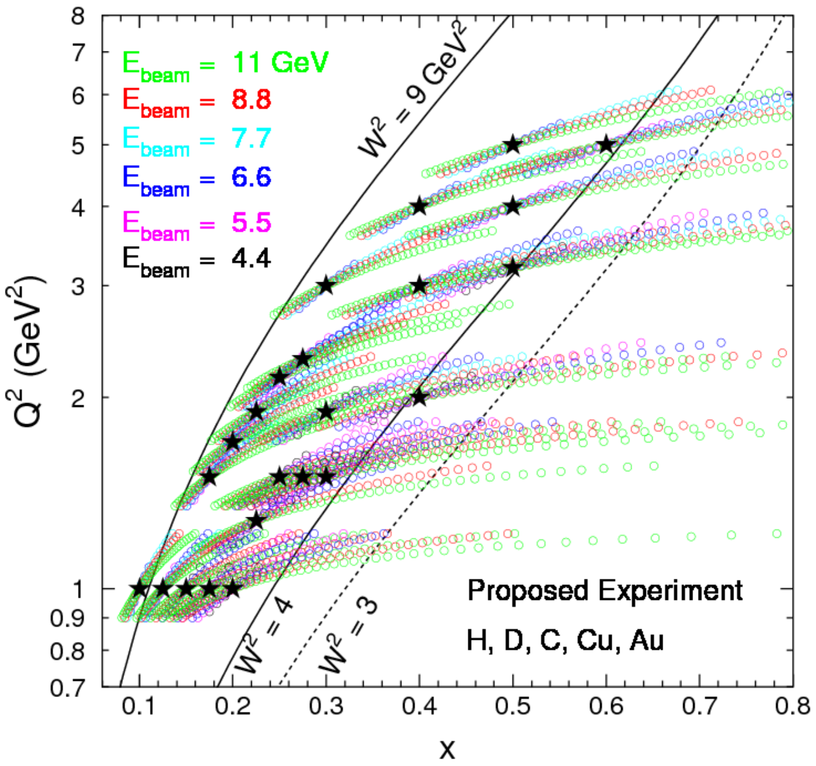



12 GeV experiment greatly increases $Q^2$ range at fixed x, and –t
→ Initial running in Hall A recently completed!

# 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 $R_A$-$R_D$

# E12-09-017: Transverse Momentum Dependence of Semi-Inclusive Pion Production

*Spokespersons: P. Bosted, R. Ent, E. Kinney, H. Mkrtchyan*

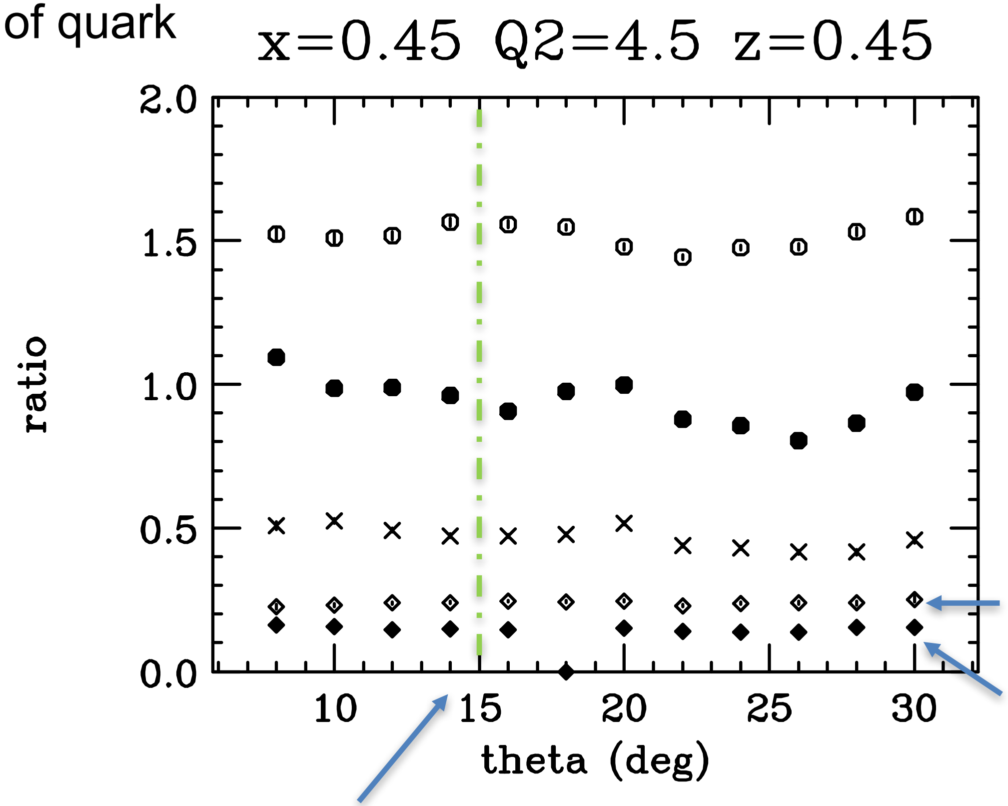
***Ran 2018-2019***

Transverse momentum of pion = convolution of $k_t$ of quark and $p_t$ generated during fragmentation

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

Kinematics:

1. $x=0.31$, $Q^2=3.1$ GeV$^2$
   → $z=0.9$-$0.45$ at $P_T=0$, $P_T=0$-$0.6$ at $z=0.35$
2. $x=0.3$, $Q^2=4.1$ GeV$^2$
   → $z=0.9$-$0.45$ at $P_T=0$, $P_T=0$-$0.6$ at $z=0.35$
3. $x=0.45$, $Q^2=4.5$ GeV$^2$
   → $z=0.9$-$0.45$ at $P_T=0$, $P_T=0$-$0.6$ at $z=0.35$




Ratios of LH2 $\pi$+ yields to:

$\pi$+ from LD2

$\pi$− from LD2

$\pi$− from LH2

$\pi$+ from Al

$\pi$− from Al

$P_T=0$

Experiment goal: Extract information about transverse distribution of up and down quarks by measuring $P_T$ dependence of $\pi^+/\pi^-$ cross sections and ratios from LH2 and LD2

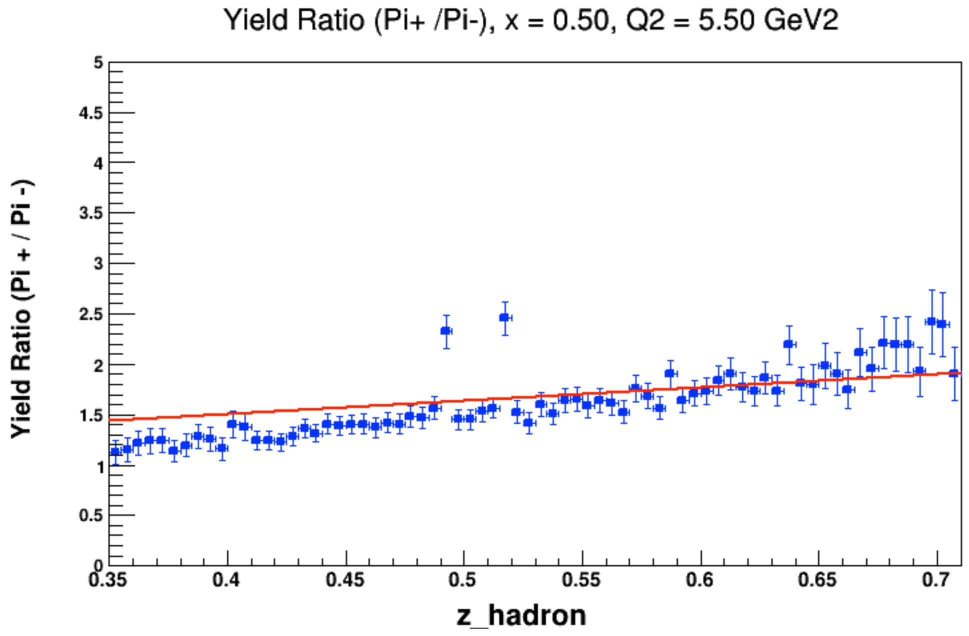
# E12-09-002: Charge Symmetry Violating Quark Distributions via $\pi^+/\pi^-$ in SIDIS

**Experiment: Measure Charged pion electroproduction in semi-inclusive DIS off deuterium**

Ratio of $\pi^+/\pi^-$ cross sections sensitive to CSV quark distributions

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

$\delta d$-$\delta u$ where
$\delta d = d^p - u^n$ and $\delta u = u^p - d^n$




→ $\overline{u}(x) \neq \overline{d}(x)$ extraction relies on the implicit assumption of charge symmetry

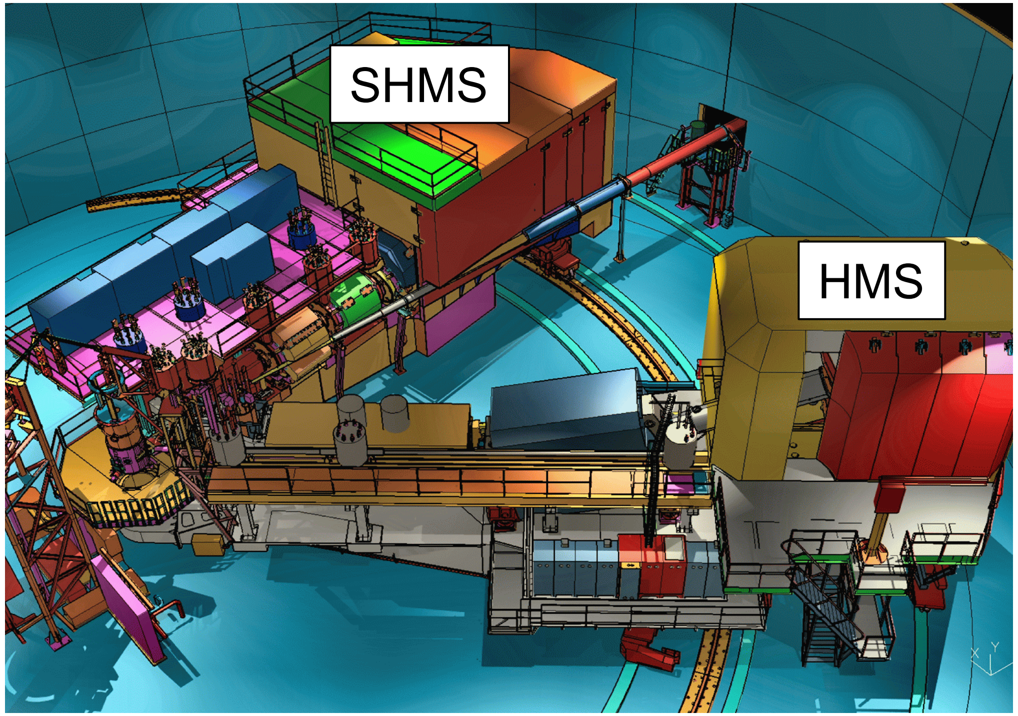
→ Viable explanation for NuTeV anomaly → $\sin^2\theta_W$

→ CS is a necessary condition for many relations between structure functions

In addition, precise cross sections and $\pi^+/\pi^-$ ratios will provide information on SIDIS reaction mechanism at JLab energies

*Spokespersons: W. Armstrong, D. Dutta, D. Gaskell, K. Hafidi*

# 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*

$\vartheta_0$=*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*

$\vartheta_0$=*5.5 to 40 degrees*

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

# Semi-inclusive Processes

Interest in semi-inclusive processes dominated originally by potential use in "flavor" tagging

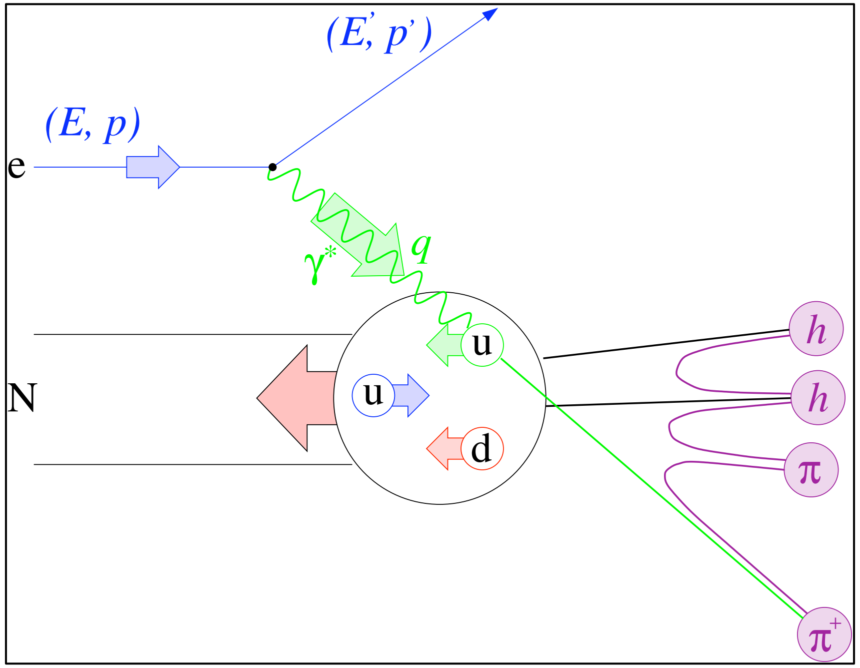
→ deconvolution of polarized PDFs

→ 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

# Hall C – Cross Sections in SIDIS

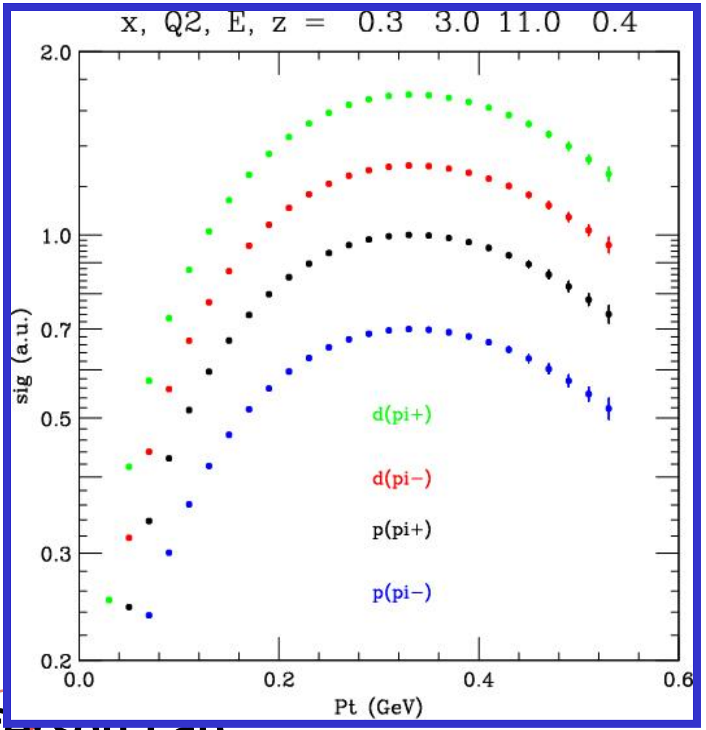
$$\sigma = \sum_q e_q^2 f(x) \otimes D(z)$$

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 $\phi$ dependence at small $P_T$, access to large $P_T$ at fixed $\phi$

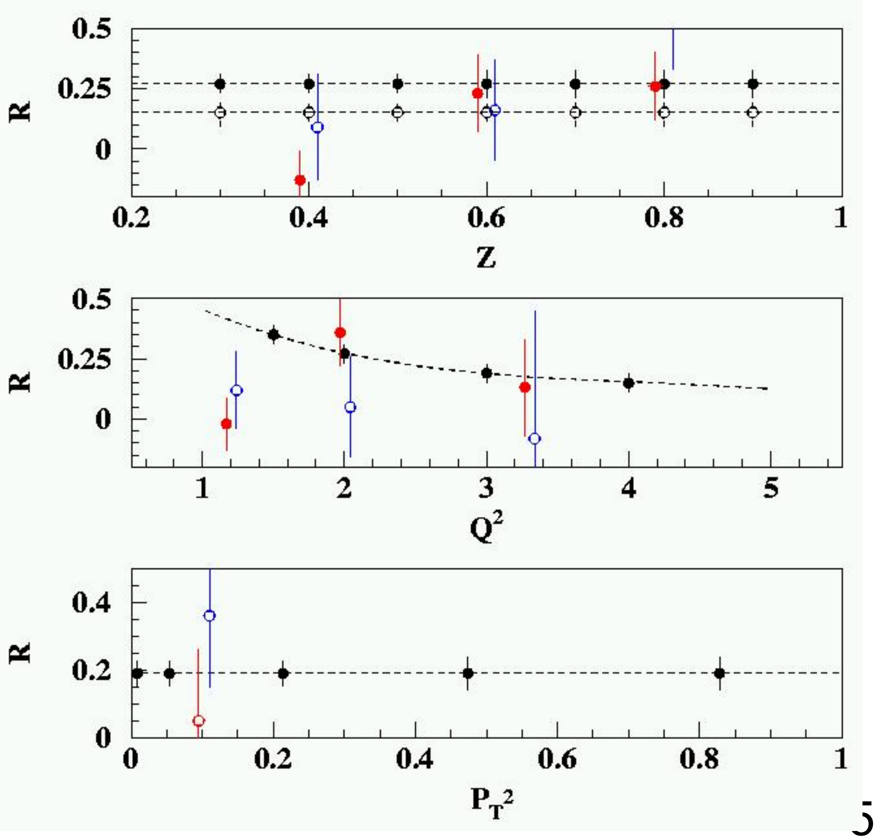



SHMS/HMS will allow precise L-T separations

→ Does $R_{DIS} = R_{SIDIS}$?

Measure $P_T$ dependence to access $k_T$ depedence of parton distributions

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

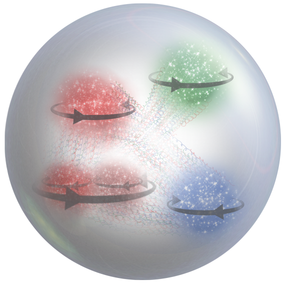


# Partonic Structure of Nucleons in 3D via SIDIS

| 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

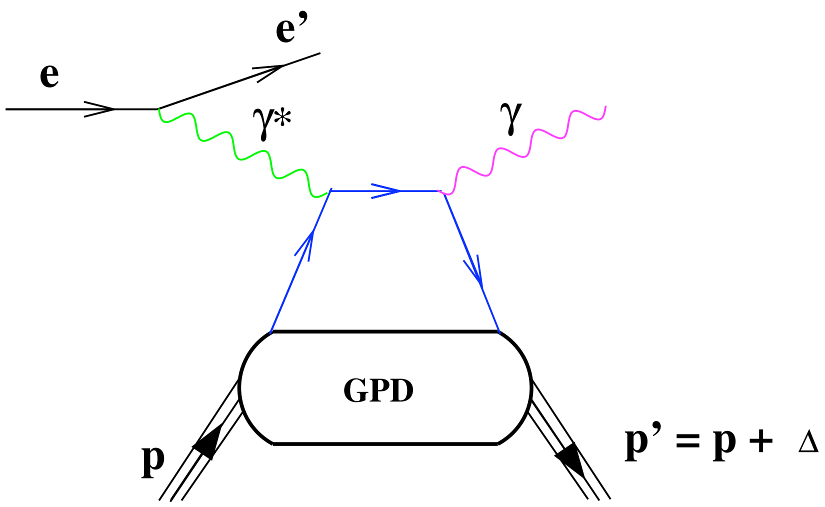
*U=unpolarized*
*L=long. polarized*
*T=trans. polarized*

→ 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

# Exclusive Reactions – Leading Twist GPDs



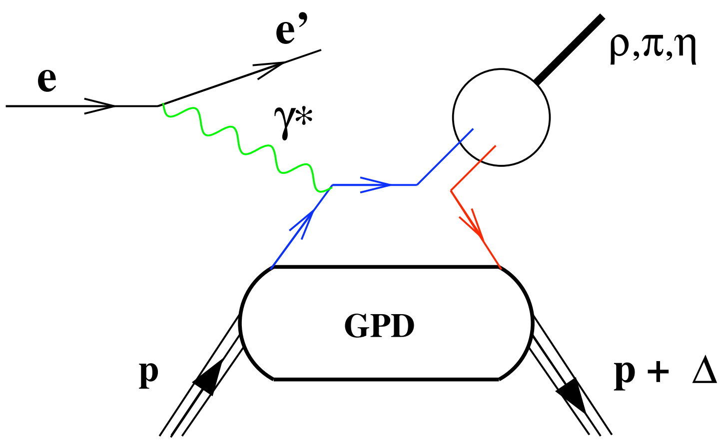

DVCS:

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

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):

$$H, E$$

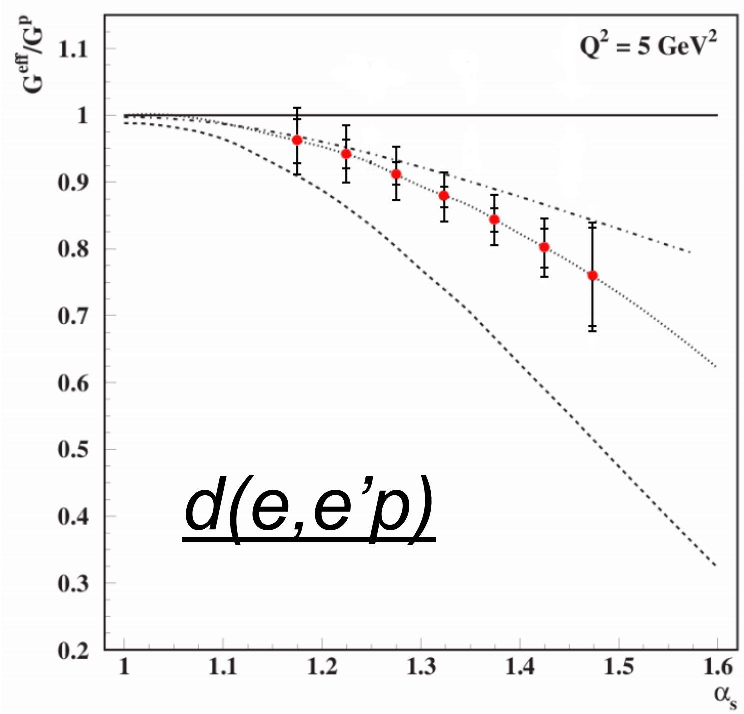
**Note: need $\sigma_L$**

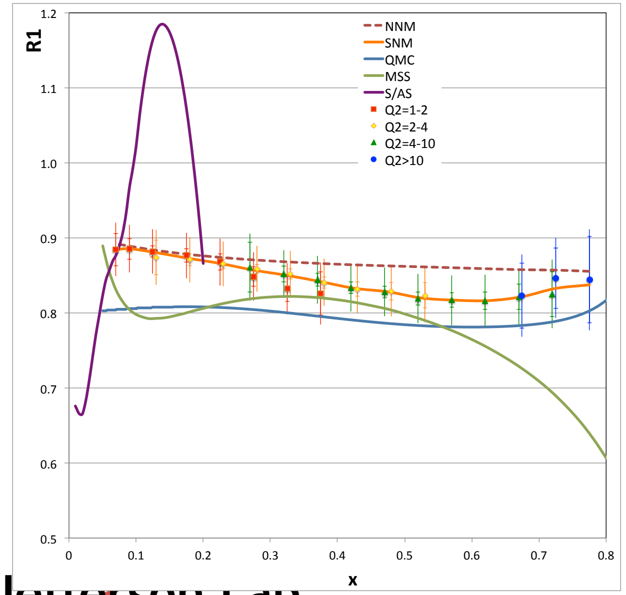
# In-Medium Structure Functions

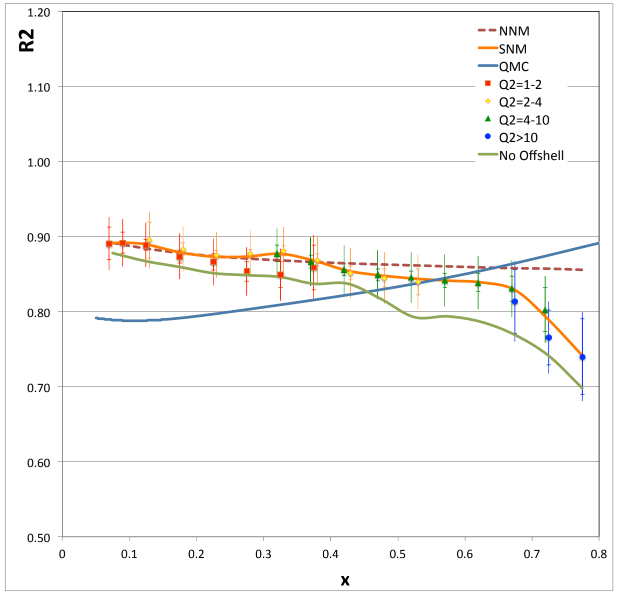
Measure structure function of high momentum nucleon in deuterium by tagging the spectator
→Final state interactions cancelled by taking double ratios
→Requires new, large acceptance proton/neutron detector at back angles

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)

# Deep Exclusive $\pi^0$

$\sigma_L$ → access to leading twist GPDs (non-pole backgrounds!)

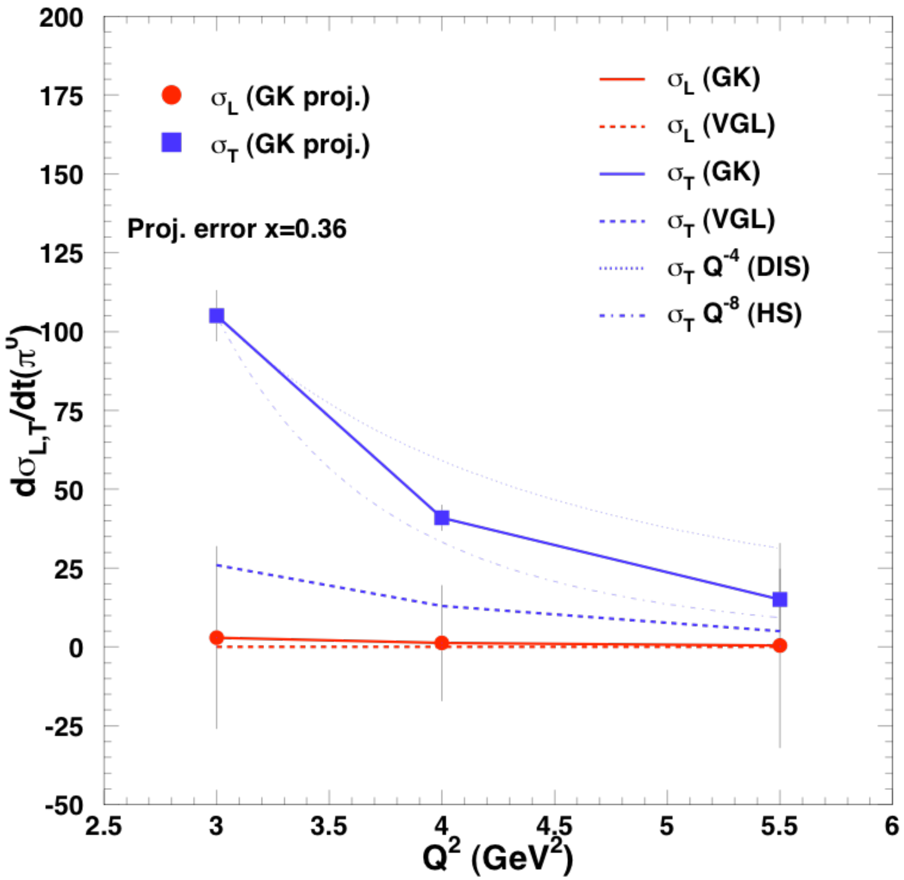
$\sigma_T$ → access to transversity GPD, $H_T$

L-T separation required to see if $\sigma_T$ 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