Recent Hall C results and future plans with the 12 GeV upgrade

Stephen Wood – Hall C – Jefferson Lab

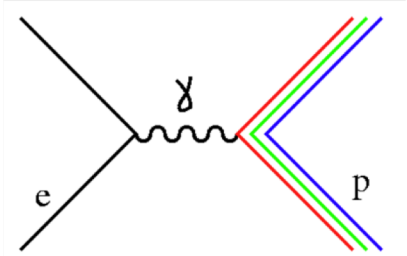
Outline

Selected Recent Hall C results

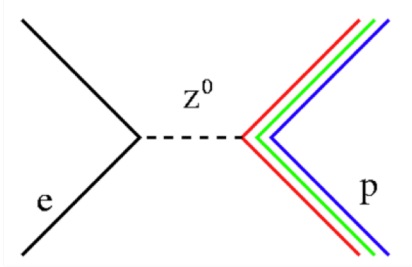
12 GeV Upgrade and first experiments in the “12 GeV” Era

Future Plans

Qweak – Weak charge of proton



As $Q^2 \to 0$



measures Q^p – proton's electric charge

measures Q^p_{weak} – proton's weak charge

The Qweak experiment measures the parity-violating analyzing power A_z @

$$A_z \underset{\substack{Q^2 \to 0 \\ \theta \to 0}}{\longrightarrow} \frac{-G_F}{4\pi\alpha\sqrt{2}}[Q^2 Q^p_{weak} + Q^4 B(Q^2)]$$

Contains $G^{\gamma}_{E,M}$ and $G^{Z}_{E,M}$
Extracted using global fit
of existing PVES experiments!

$$A_z = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} = -226.5 \pm 9.3 \times 10^{-9} \text{ @ } \langle Q^2 \rangle = 0.025 \text{ (GeV/c)}^2$$

$$Q^p_{weak} = 1 - 4\sin^2\theta_W \sim 0.072 \text{ (at tree level)}$$

0.0719 ± 0.0045

- Qweak is a well-defined experimental observable
- Qweak has a definite prediction in the electroweak Standard Model
- Qweak is sensitive to new parity violating physics at the TeV scale

Nature
557, 207 (2018)

Qweak

Parameters:

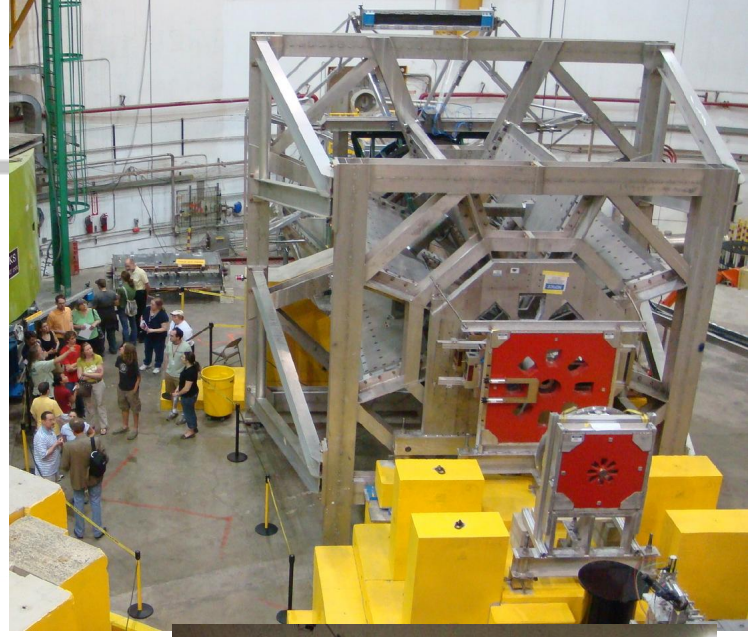
l_{beam} = 180 μA, $\mathcal{L}$ = 1.7 x 10^{39} $cm^{-2}s^{-1}$

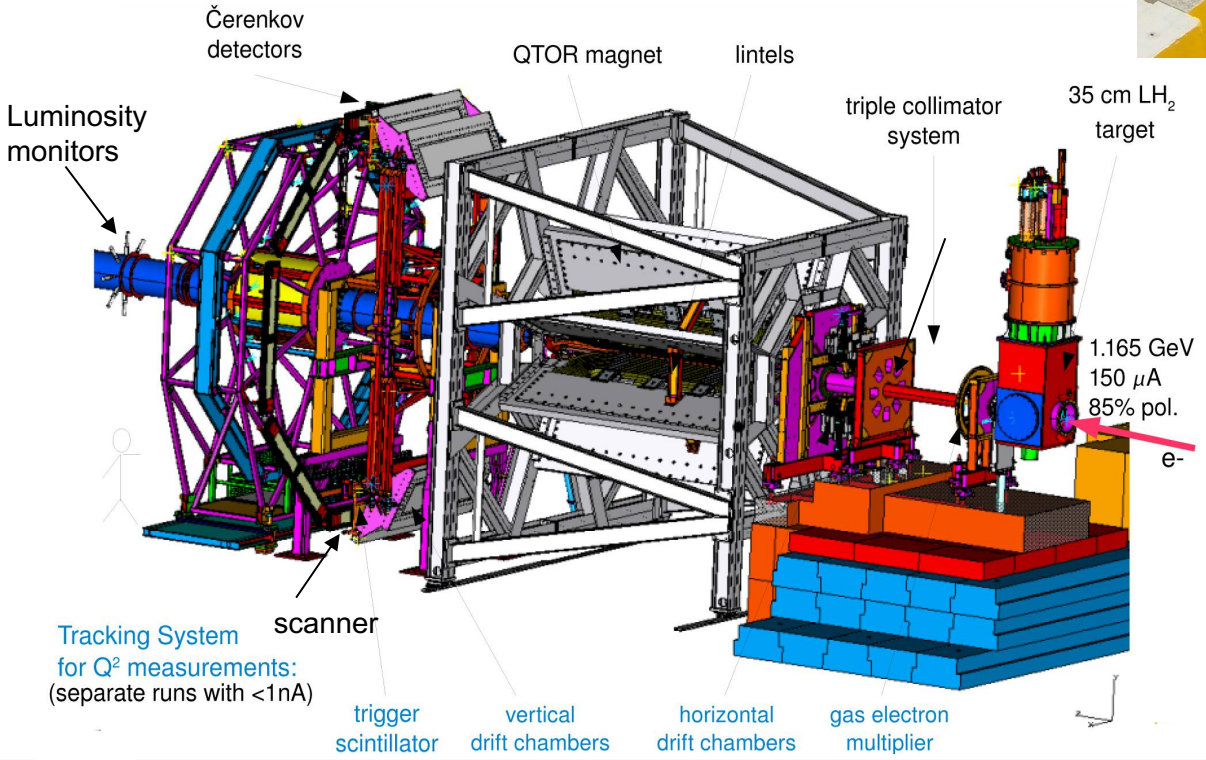
E_{beam}= 1.15 GeV, Beam Pol = 89% ± 0.6%

θ = 6° - 12°, <θ> = 7.9°, $<Q^2>$ = 0.025 $(GeV/c)^2$

Integrated Rate ~ 7 GHz

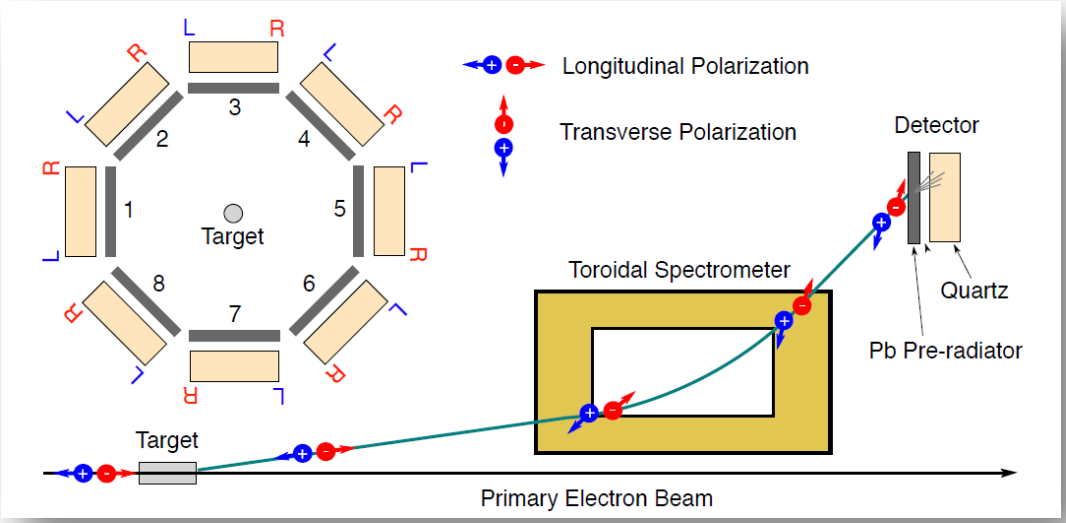
Target = 34.4 cm LH_2, 3 kW, 50 ppm

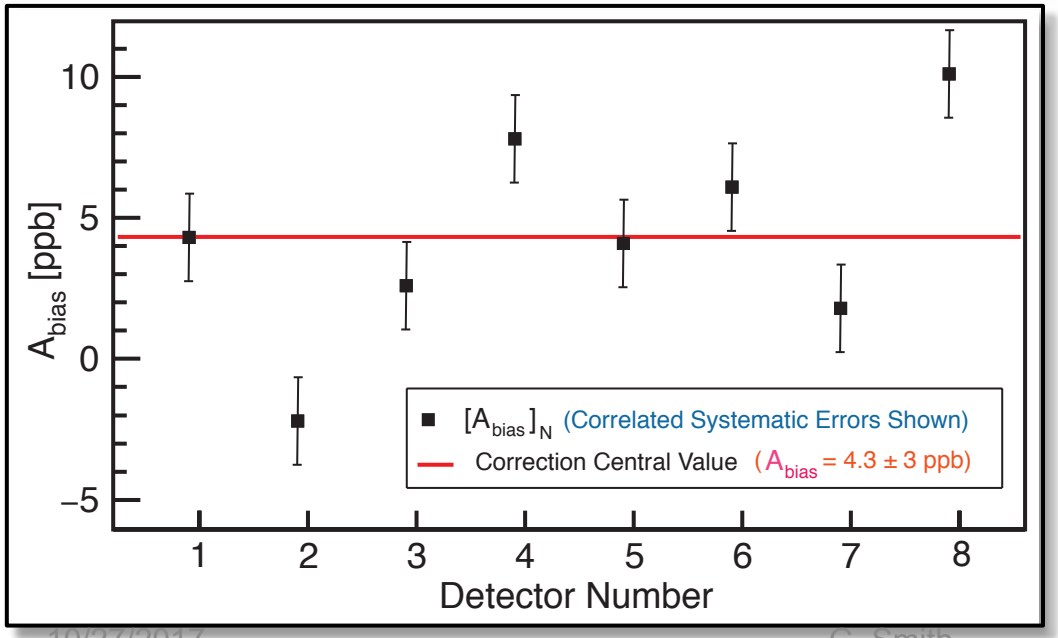




- Experimental method described in NIM A781, 105 (2015)

Detector Optical Imperfections: A_{bias} Systematic





Saw a large, consistent asymmetry $A_{diff} = (A_R - A_L) \sim 290$ ppb in the L & R PMTs of each detector bar.

Effect: Transverse P picked up via g-2 precession thru magnet "analyzed" by Pb pre-radiator just in front of bars → L/R asymmetry across each bar.

Qweak parity signal = $(A_R + A_L)/2$, **so effect cancels to first order.**

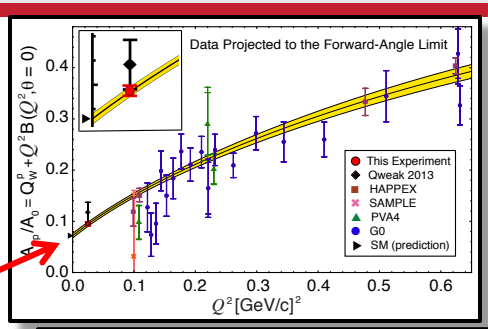
Imperfections in bars led to small errors in this cancellation. Correction determined by data-driven and simulation approaches. (agreed to within 1 ppb)

Q_{weak} – precision measurement of PV asymmetry in elastic e-p scattering → proton's weak charge

$A = -226.5 \pm 9.3$ ppb

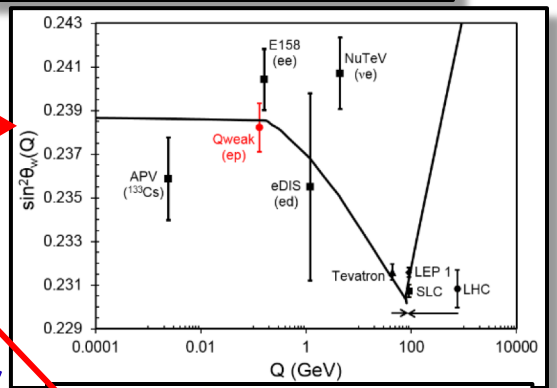
Q_W^p (this result) 0.0719 ± 0.0045

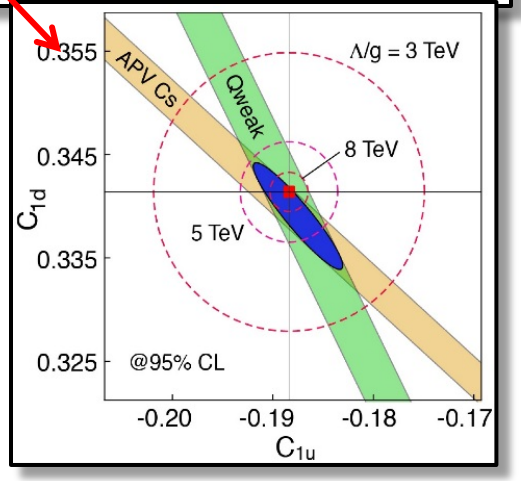
Q_W^p (SM) 0.0708 ± 0.0003



Implications:

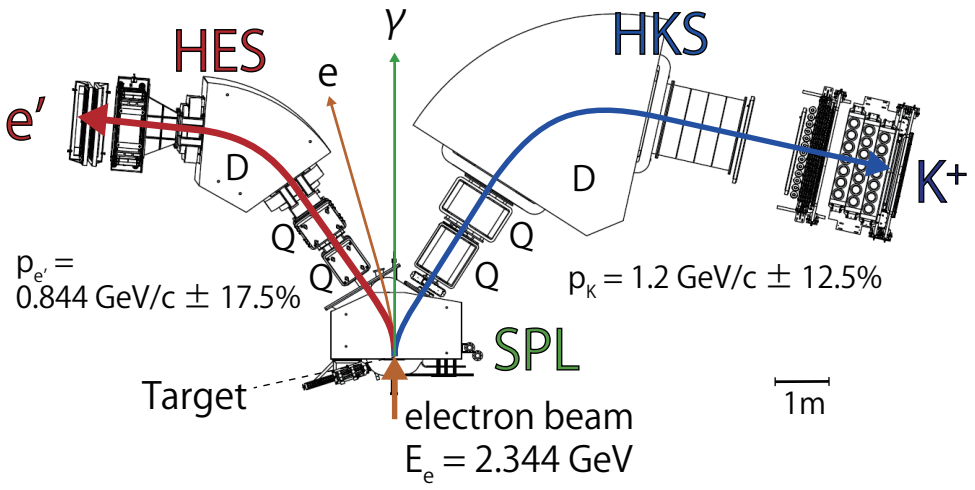
- Measured Q_W^p in good agreement with SM
  - Robust result to changes in method used to obtain it
- Sensitive measure of $\sin^2\theta_W$ at low Q
- Mass reach for new neutral-current semi-leptonic PV physics ruled out at 95% CL for:
  - $\Lambda/g < 7.4$ TeV, (< 3.6 TeV for arbitrary flavor ratios)
- Will play a role in future analyses of bounds (or discoveries) of a variety of new BSM physics
- Completes "weak charge triad" (u, d, e)
- Builds scientific & technical foundation for next generation of measurements

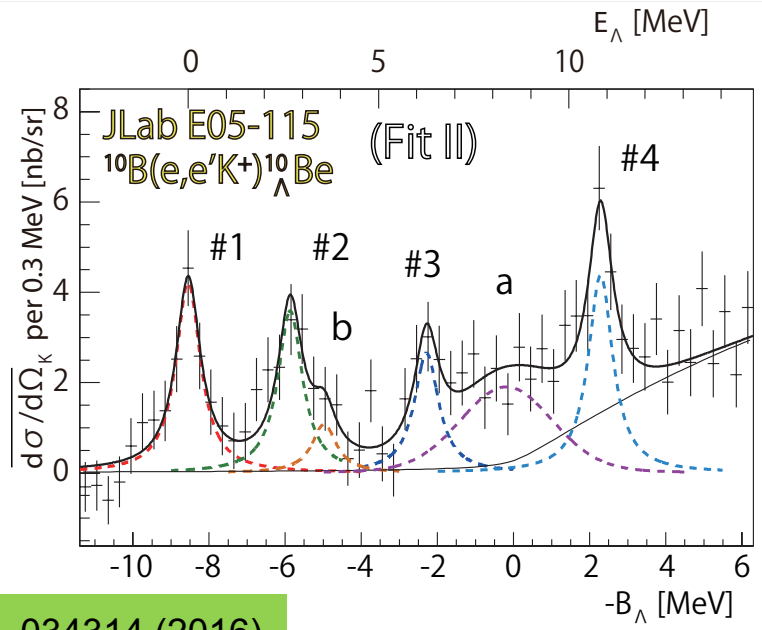


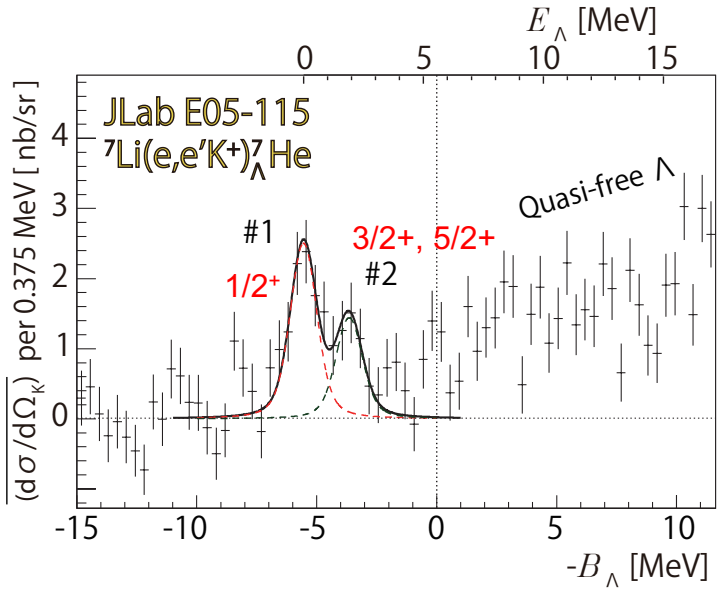


Jefferson Lab

Hypernuclei via A(e,e′K⁺)







Phys Rev C 93, 034314 (2016)
Phys Rev C 94, 021302 (2016)

Absolute energy scale calibrated with p(e,e′K⁺)Λ and p(e,e′K⁺)Σ⁰ reactions.

Results compared to mirror hypernuclei to test Charge Symmetry Breaking predictions for hypernuclei.

$^{28}_{\Lambda}$Al and $^{52}_{\Lambda}$V in progress

Future hypernuclear studies at JLab

Halls A and C hypernuclear collaborations merging for future studies in Hall A.

Two experiments approved.

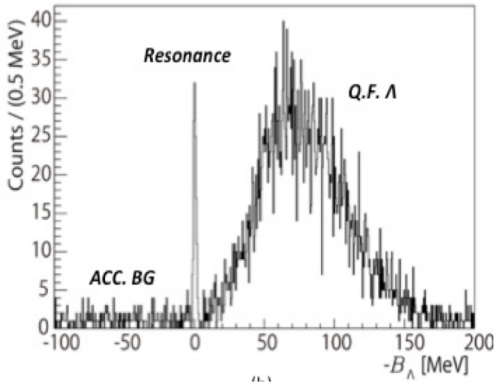
1. "JLab Tritium Era": Tritium target presently installed for several experiments. (DIS high x & x>1 comparison of ^{3}H and ^{3}He, short-range correlations).

   Late 2018 will run ^{3}H(e,e′K$^+$)ΛnnDetermine Λn interaction strength.

   Also run ^{3}He(e,e′K$^+$)Λpn

   (^{3}He contamination in ^{3}H)

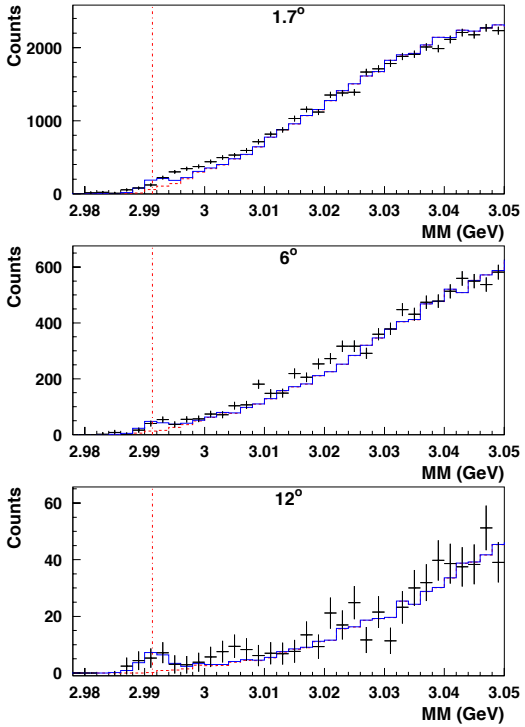
10 PAC days: ~ 120 counts



2. E12-15-008 – hypernuclear spectroscopy of $^{40}_{\Lambda}$K & $^{48}_{\Lambda}$K

   (e,e′K$^+$) on ^{40}Ca and ^{48}Ca targets

   ΛN interaction in medium at densities relevant to neutron stars.



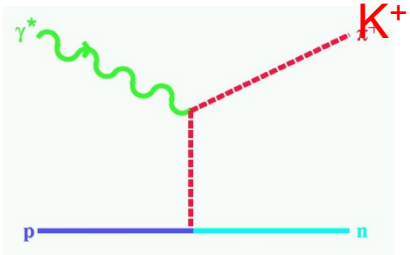
^{3}He(e,e′K$^+$)Λpn resonance previously observed in Hall C. Bound?
Phys. Rev. Lett. 93, 242501 (2004) (JLab E91-016)

Kaon Form Factor

Possible to extract Kaon form factor from longitudinal term of L/T separated p(e,e′K+) cross sections using VGL Regge model.

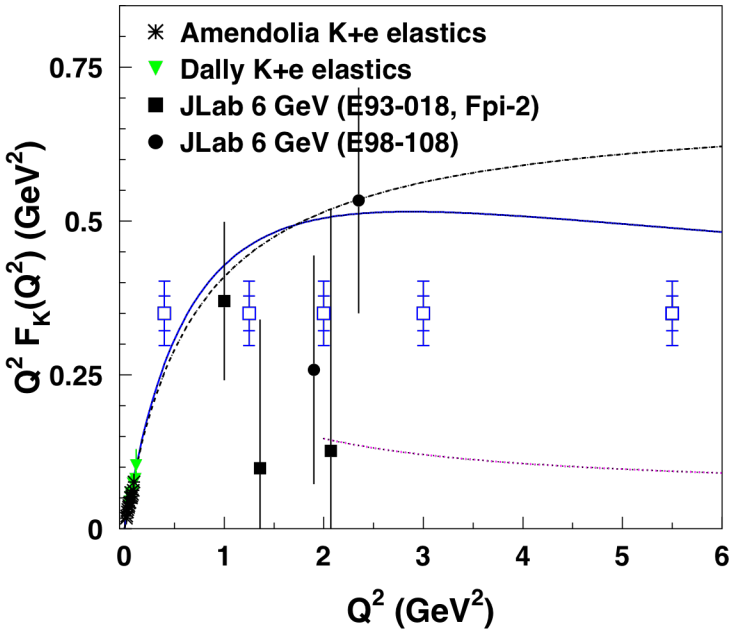
(Same method as used for F_π)

Old Hall A and C p(e,e′K+) reanalyzed to extract F_K.



Carmignotto et.al
Phys Rev C 97, 025204 (2018)

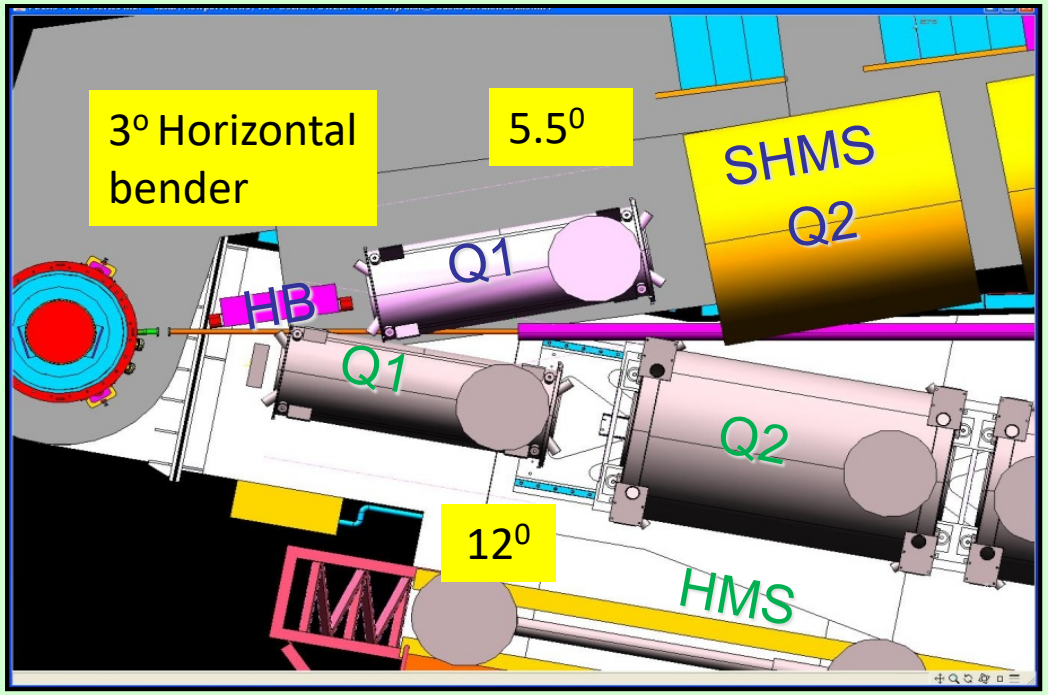
E12-09-011, scheduled to run this year will study scaling behavior of separated σ_L, σ_T and extract F_K up to 5.5 GeV^2.



Hall C after 12 GeV Upgrade

- Beam Energy: 2 – 11 GeV/c
- NEW Super High Momentum Spectrometer (SHMS)
  - P≤11 GeV/c (replaces ≤ 2Gev/c)
  - Horizontal Bender, 3 Quads, Dipole
  - dP/P 0.5 – 1.0x10^{-3}
  - Acceptance: 4msr, ΔP/P=30%
  - 5.5° < θ < 40°
  - Good e^-/π^- $e^+/\pi^+/K^+/p$ PID
- High Momentum Spectrometer (HMS)
  - P → 7.5 GeV/c
  - dP/P 0.5 - 1.0x10^{-3}
  - Acceptance: 6.5msr, Δp/p=18%
  - 10.5° < θ < 90°
  - Good e^-/π^- $e^+/\pi^+/K^+/p$ PID
- Minimum opening angle: ~17°

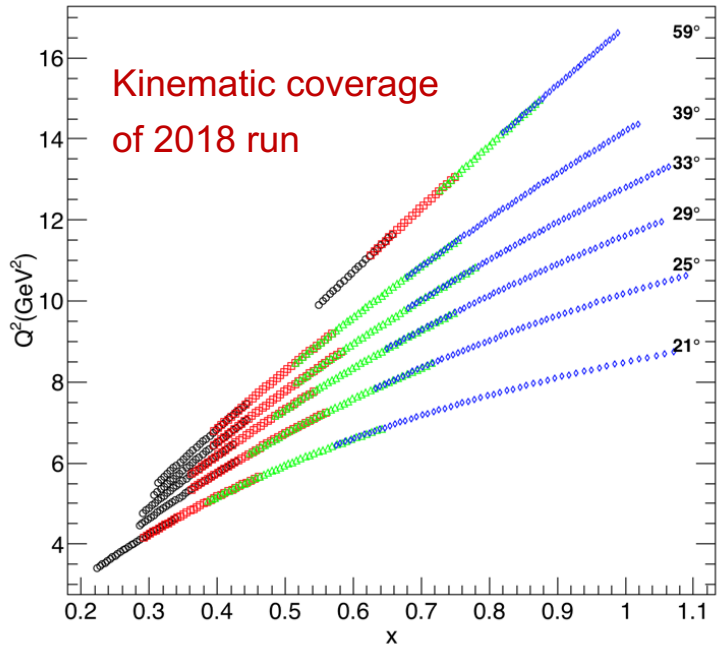
- Well shielded detector huts
- 2 beamline polarimeters
- Ideal facility for:
  - Rosenbluth (L/T) separations
  - Exclusive reactions
  - Low cross sections (neutrino level)

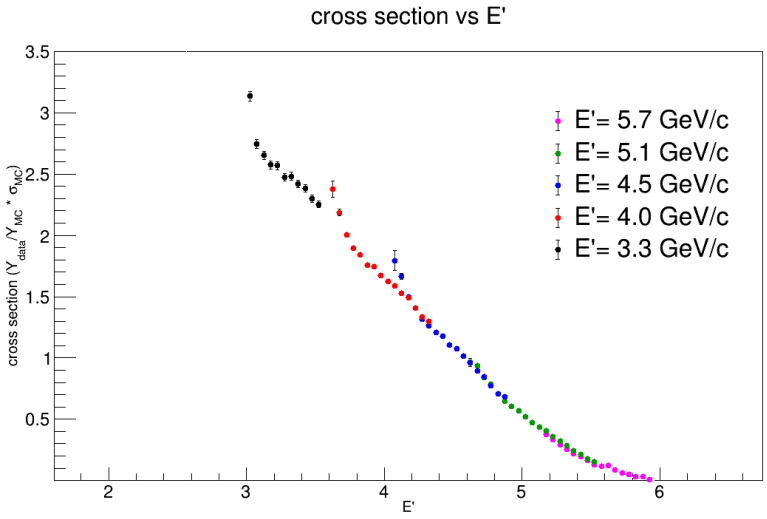


E12-10-002 Precision F_2 structure function at high x

Extend proton and deuteron F_2 structure function precision measurements to larger x and Q^2. Measuring p(e,e′) and d(e,e′) cross sections to 3% in the resonance region and beyond up to $Q^2 \sim 17$ GeV^2 and x ~ 0.99

- Constrain Parton Distribution Functions at large x
- Distinguish different mechanisms of spin-flavor symmetry breaking (d/u at large x) with precision F_2^n/F_2^d (combining with BONUS/Hall B (E12-06-113) F2n/F2d)
- Extend studies of local quark-hadron duality in proton and neutron F_2

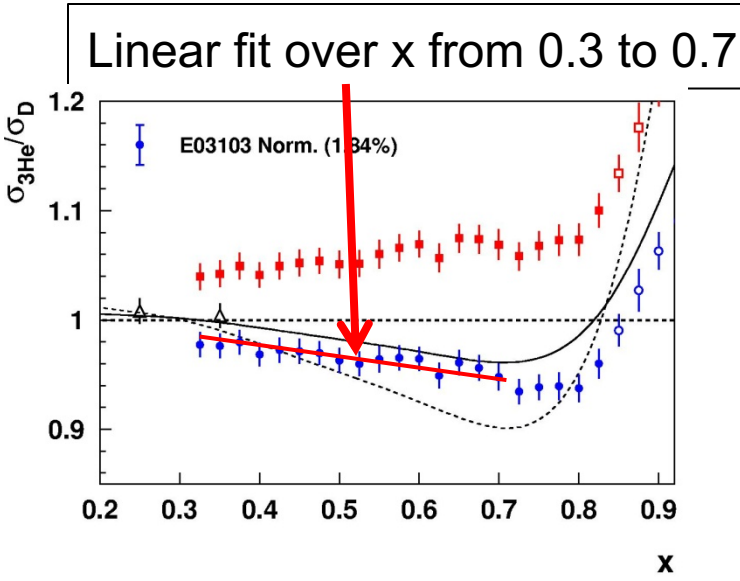




EMC effect

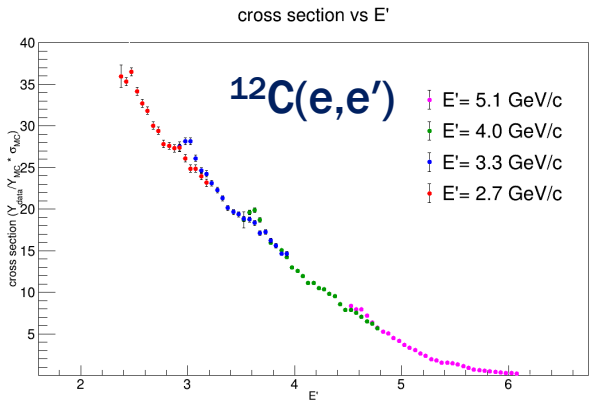
Detailed study of EMC effect planned in Hall C. (E12-10-008)

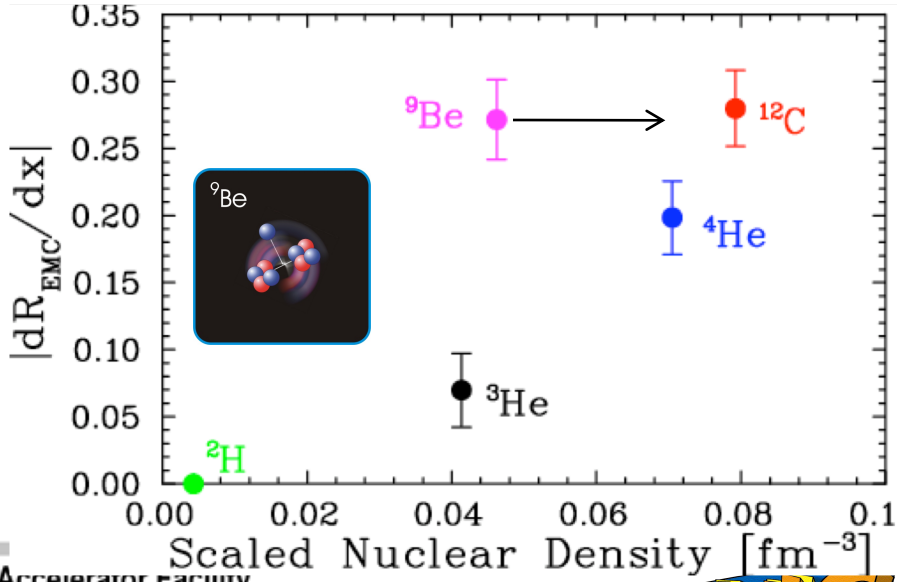
- 0.1<x<0.9
- Up to $Q^2 \approx 15 GeV^2$
- Light nuclei: ^{1}H, ^{2}H, ^{3}He, ^{4}He, $^{6,7}Li$, 9Be, $^{10,11}B$, $_{12}C$
- Medium/Heavy nuclei: Al, $^{40,48}Ca$, Ti, ^{54}Fe, Ni, Cu, Ag, Sn, Au, Th



Early 2018 ran ^{9}Be, $^{10,11}B$, ^{12}C

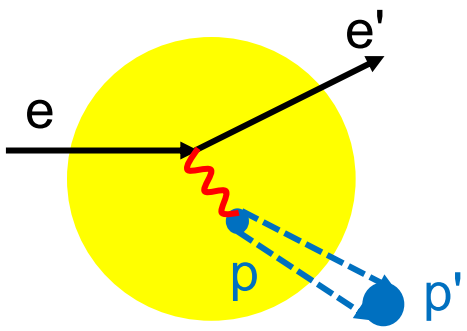
- Examine single nucleon differences

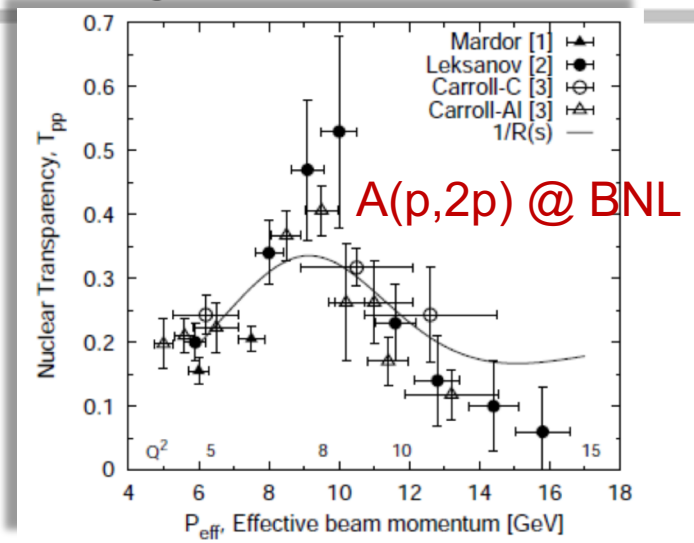




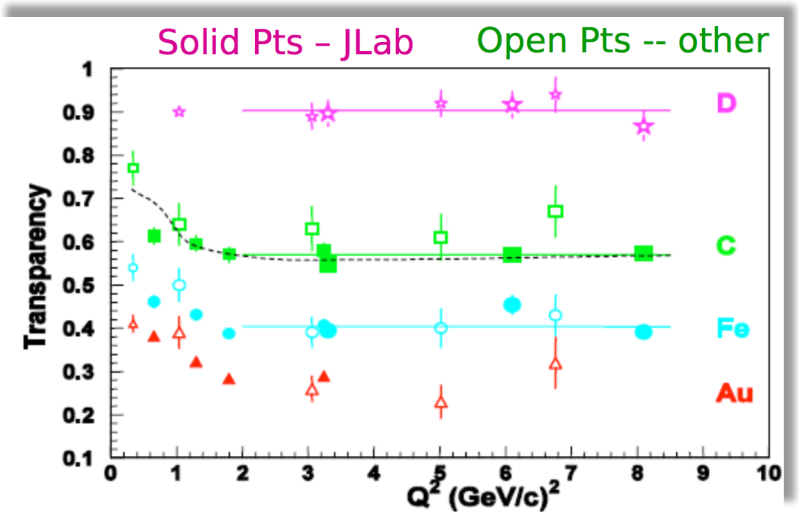
Color Transparency

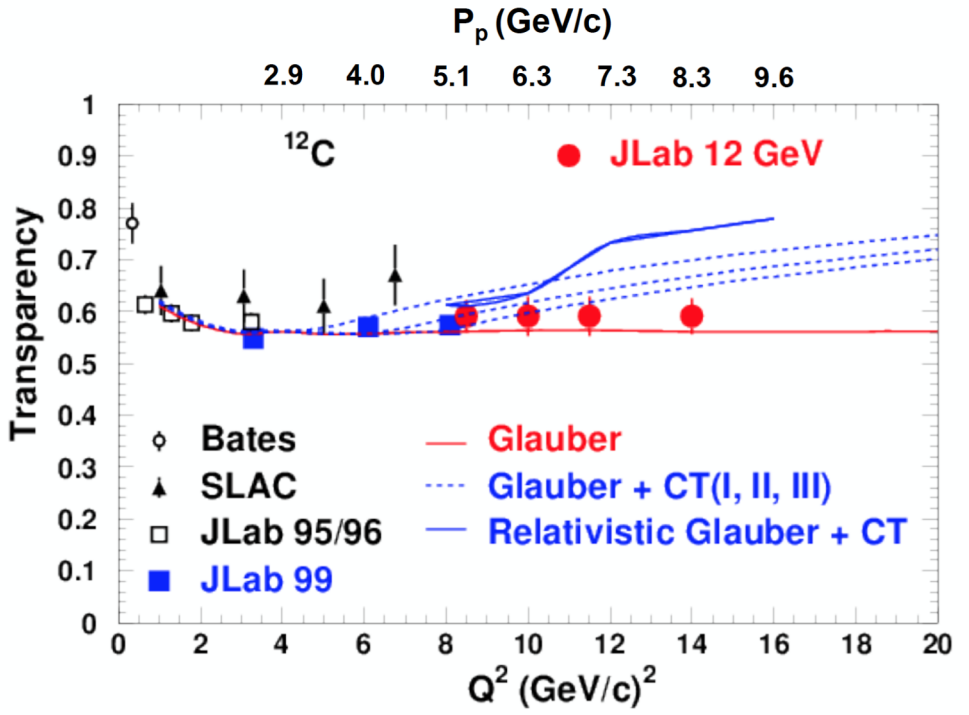
$$T_A = \frac{\sigma_{A(e,e'p)}}{Z\,\sigma_{p(e,e'p)}}$$





A(p,2p) @ BNL





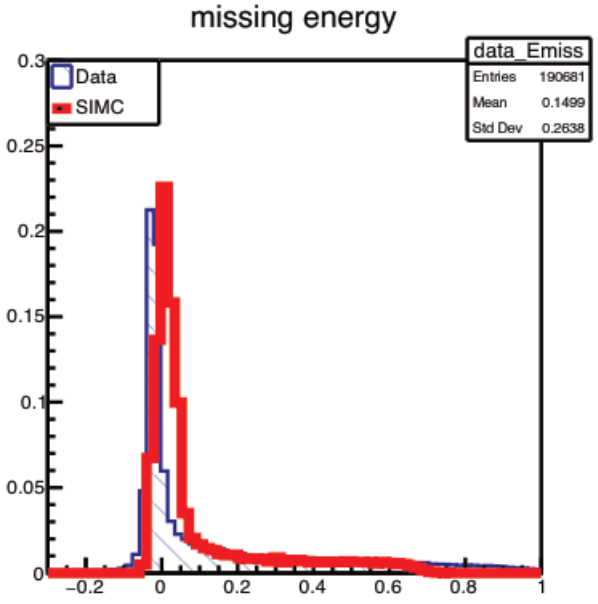
Deuteron Electro-Disintegration at Very High Missing Momenta (E10-003)

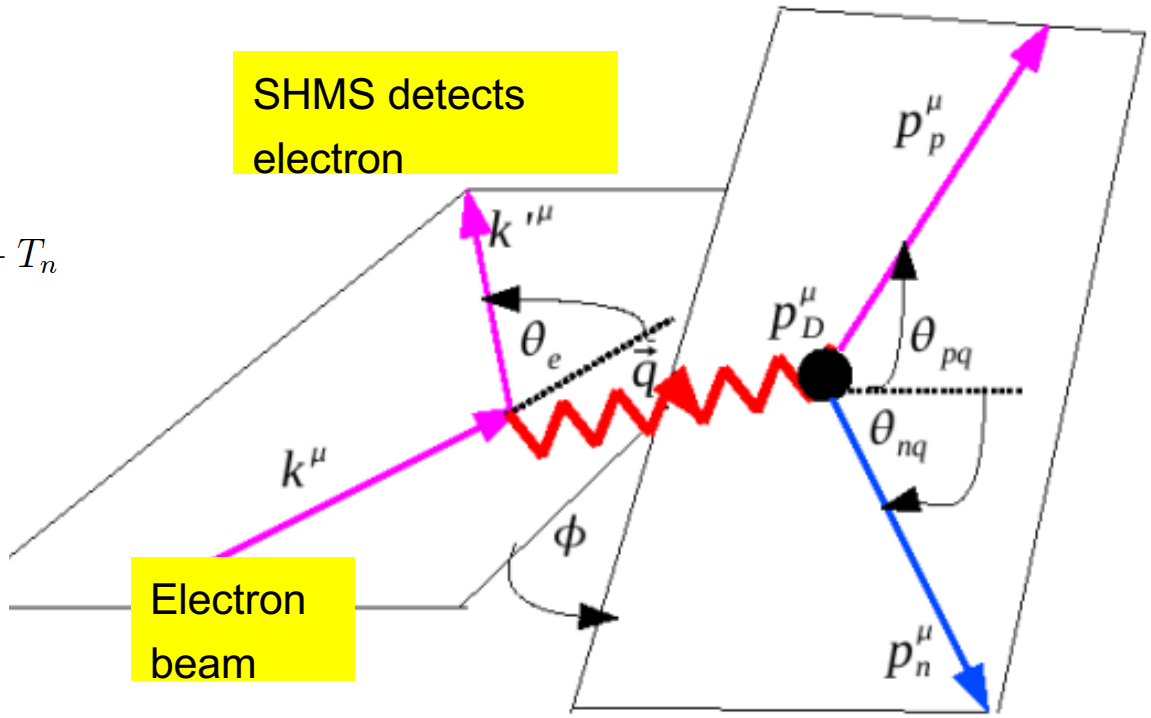
D(e,e'p)n exclusive reaction by using cut on missing energy with the neutron energy and angle reconstructed

$$\vec{p}_m = \vec{q} - \vec{p}_p.$$

$$\cos\theta_{nq} = \frac{q - p_p \cos\theta_{pq}}{\sqrt{q^2 + p_p^2 - 2qp_p\cos\theta_{pq}}},$$

$$E_{miss} = M_d - M_p - M_n = \omega - T_p - T_n$$

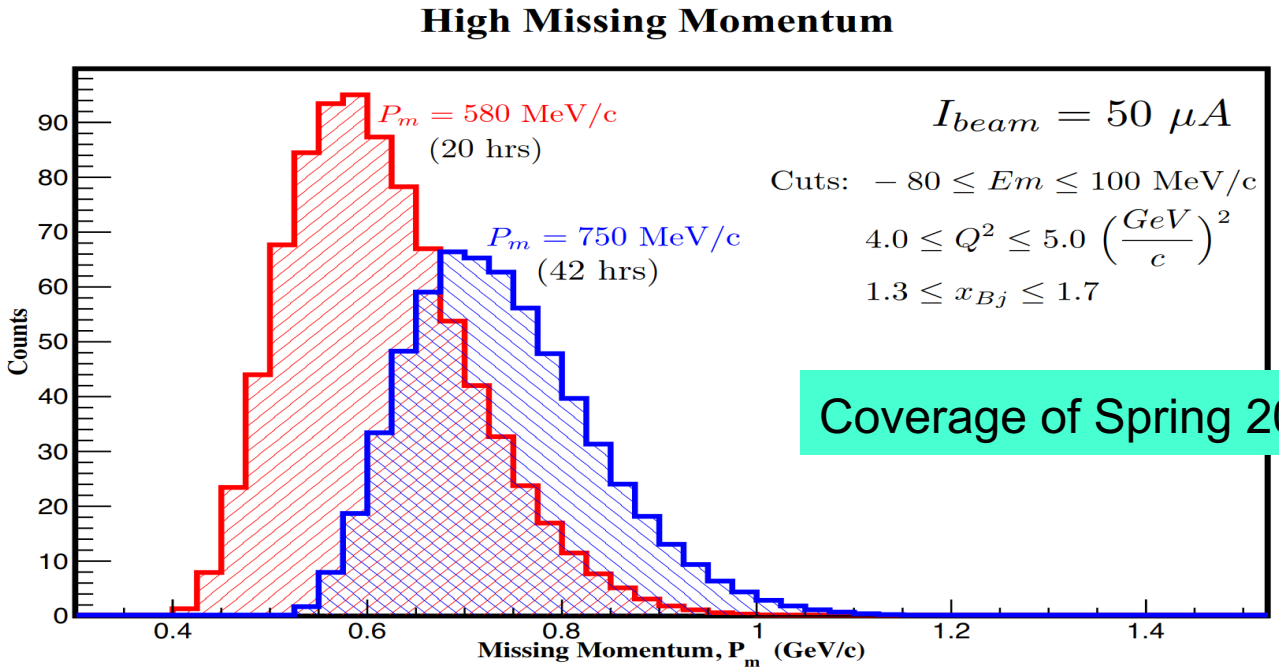




d(e,e'p)

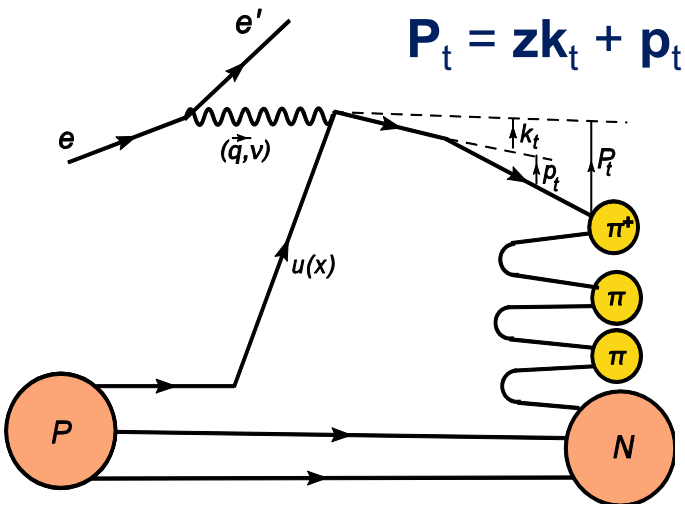
Motivation:

- Explore a new kinematical region of the 2-nucleon system above p_m> 500
- No Deuteron data exist at these kinematics!
- Short range correlation studies cover similar region on missing momenta
- Models are able to reproduce the present data with 20%.
- Signs of a dependence on NN potential at highest missing momentum
- Measure at well defined kinematic settings, selected to minimize contributions from FSI and delta at Q^2 = 4.25



Coverage of Spring 2018 run

P_t dependence of Semi-inclusive DIS – p/d(e,e′π±)X



$P_t = zk_t + p_t$

$\sigma_{SIDIS} = \sigma_{DIS} \cdot \sum e_i^2 [q_i(x,Q^2) D_i(z)] \cdot$
$b\, e^{-bp_T^2} \{1 + A\cos(\varphi) + B\cos(2\varphi)\}$

High energy factorization

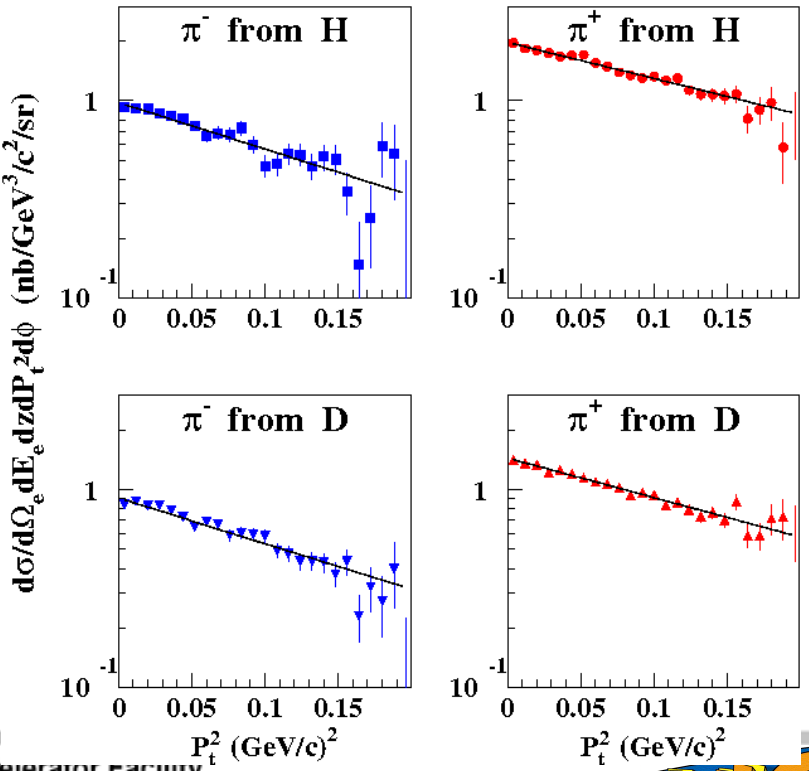
Seemed to work at pre upgrade JLab

Assume the quark and fragmentation functions widths are Gaussian in k_t and p_t and $\langle P_t^2 \rangle = \langle z^2 k_t^2 \rangle + \langle p_t^2 \rangle$

Allow separate widths for u and d quarks, and separate widths for D^+ and D^-

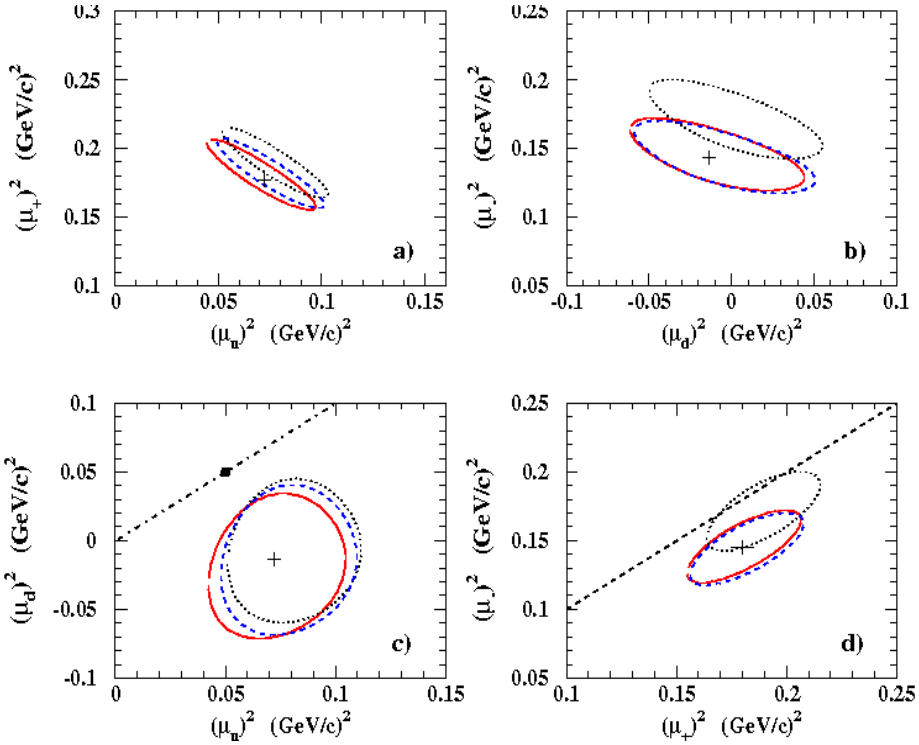
$\sigma_{SIDIS} \sim \sigma_{DIS}\, (dN/dz)\, b \exp(-bP_t^2)$

$b^{\pm}_u = (z^2\mu_u^2 + \mu_{\pm}^2)^{-1}$ and $b^{\pm}_d = (z^2\mu_d^2 + \mu_{\pm}^2)^{-1}$



Quarks & Fragmentation Function Transverse Momentum

$\sigma_{SIDIS} \sim \sigma_{DIS}\,(dN/dz)\; b \exp(-bP_t^2)$ ➡ $b \rightarrow b^{\pm}_q\,(b^{\pm}_u \,\&\, b^{\pm}_d)$, and $b^{\pm}_q = (z^2\mu_q^2 + \mu_{\pm}^2)^{-1}$



$\sigma_p^{\pi^+} = C[4c_1 \cdot \exp(-b^+_u P_t^2) + (d/u)(D^-/D^+)c_2 \cdot \exp(-b^-_d P_t^2)]$

$\sigma_p^{\pi^-} = C[4(D^-/D^+)c_3 \cdot \exp(-b^-_u P_t^2) + (d/u)c_4 \cdot \exp(-b^+_d P_t^2)]$

$\sigma_n^{\pi^+} = C[4(d/u)c_4 \cdot \exp(-b^+_d P_t^2) + (D^-/D^+)c_3 \cdot \exp(-b^-_u P_t^2)]$

$\sigma_n^{\pi^-} = C[4(d/u)(D^-/D^+)c_2 \cdot \exp(-b^-_d P_t^2) + c_1 \cdot \exp(-b^+_u P_t^2)]$

Fit values:

- $D^-/D^+ = 0.43 \pm 0.01$; $d/u = 0.39 \pm 0.03$
- $\mu_u^2 = 0.07 \pm 0.03$ GeV^2 $\mu_d^2 = -0.01 \pm 0.05$ GeV^2
- $\mu_+^2 = 0.18 \pm 0.02$ GeV^2 $\mu_-^2 = 0.14 \pm 0.02$ GeV^2

Fit results for agree with HERMES D^-/D^+ (0.42), and LO GRV d/u ratio with (0.40)

Fit tends to larger k_t width for u quarks than for d ($\mu_d^2 \sim 0$)

Fragmentation width μ_+ and μ_- are similar (as predicted by Anselmino)

E12-09-017 TMD of SIDIS at 12 GeV

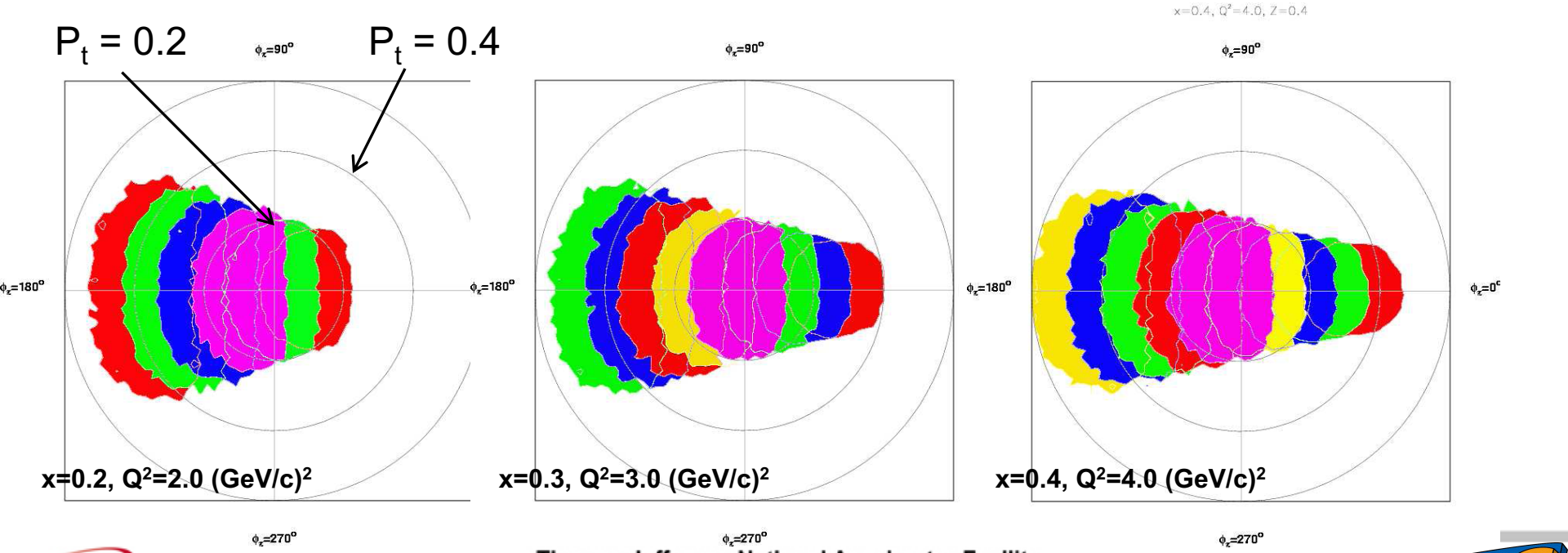
Map transverse momentum dependence of (e,e′π) over range:

$0.2 < x < 0.5$, $2 < Q^2 < 5$ GeV^2, $0.3 < z < 0.5$ and $P_t < 0.5$ GeV

Combine with CLAS12 data to constrain transverse widths of u/d quarks and fragmentation functions

Obtain some statistics on transverse momentum dependence of (e,e′K)

~60% of data acquired, remainder in late 2018.



E12-09-002 Charge Symmetry Violation Test with SIDIS

Charge Symmetry:

$m_p \sim m_n$

Energy levels mirror nuclei

p vs n scattering lengths

Charge Symmetry is assumed in parton distribution functions:

$u^p(x) = d^n(x)$

If Charge Symmetry, then $d(e,e'\pi^+)/d(e,e'\pi^-)$ depends only on fragmentation functions not PDFs

Precision $N\pi^+/N\pi^-$ ratio gives $C(x) = \delta d(x) - \delta u(x)$ where:

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

Experiment E12-09-002:

Measure $d(e,e'\pi^-)/d(e,e'\pi^+)$ to 1% over range of kinematics

$p(e,e'\pi^+)$, $p(e,e'\pi^-)$ for further factorization tests

Requires careful control of π^+ π^- detection efficiency, radiative corrections

E12-09-002 Charge Symmetry Violation Test with SIDIS

Measure d(e,e′π^-) and d(e,e′π^+) yields Y^{π^-} and Y^{π^+}

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

$$D(z)\left(\frac{5}{2} + R^D_{meas}\right) + CSV(x) = B(x,z)$$

D(z) ~ from ratio of favored to unfavored fragmentation functions.

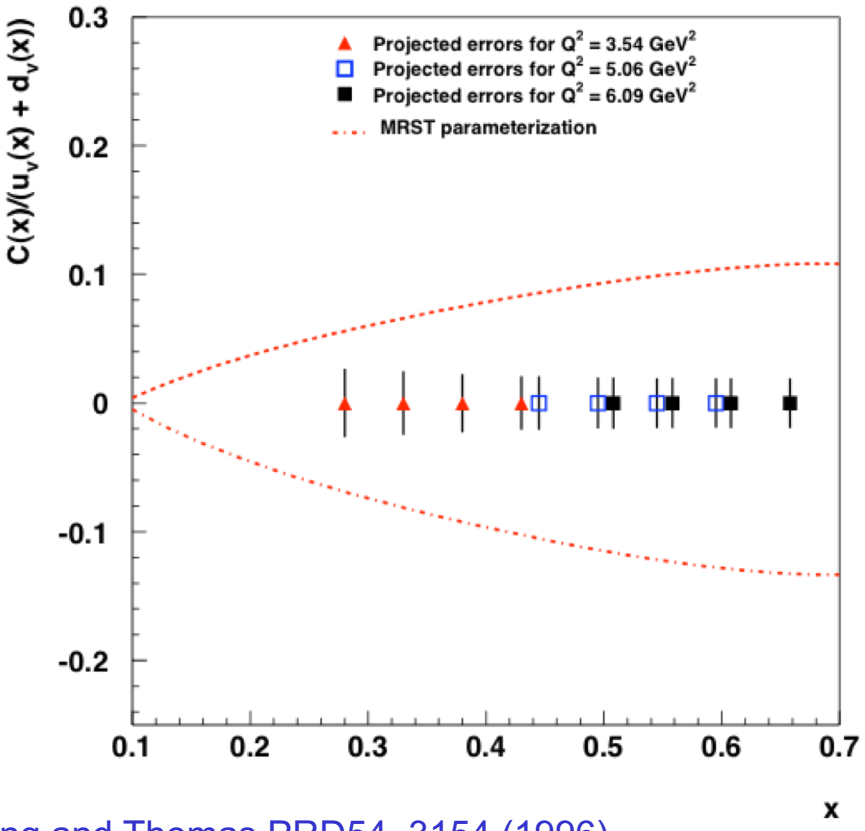
B(x,y) calculated from sea quark PDFs

$$CSV(x) = \frac{-4(\delta d - \delta u)}{3(u_v - d_v)}$$

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

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

Measure R(x,z) over a grid in x and z to extract D(z) and CSV(x).



Formalism of Londergan, Pang and Thomas PRD54, 3154 (1996)

Neutral (e.g. π^0/γ) detector facility in Hall C

- Augment Hall C spectrometers with capability for precision measurements with neutral final states. (L/T separations)

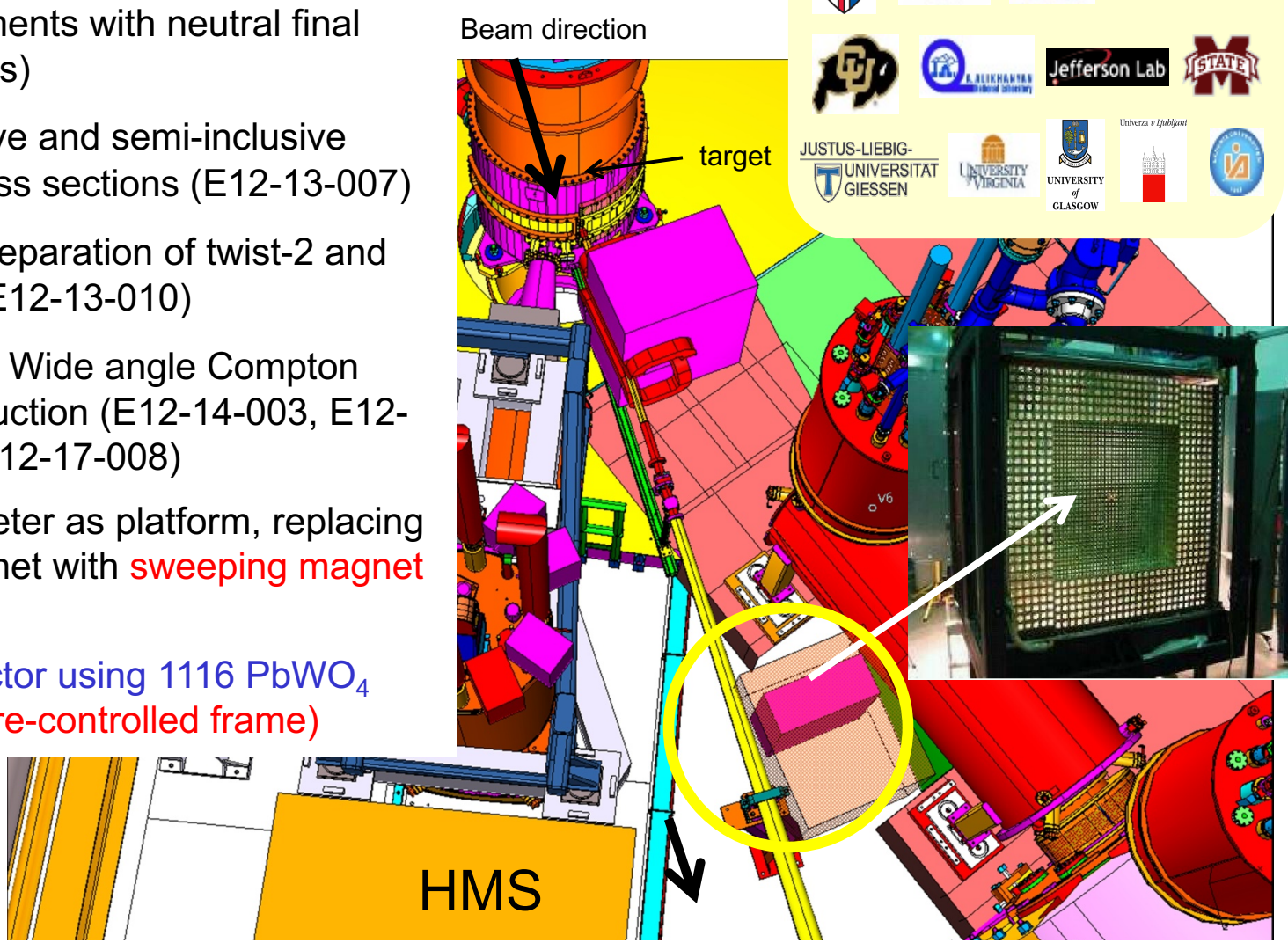
  $p(e,e'\pi^0)$ exclusive and semi-inclusive L/T separated cross sections (E12-13-007)

  $p(e,e'\gamma)$ DVCS (separation of twist-2 and twist-3 contributions) (E12-13-010)

  $p(\gamma,\gamma)p$, $p(\gamma,\pi^0)p$ Wide angle Compton scattering and π^0 production (E12-14-003, E12-14-005, E12-14-006, C12-17-008)

- Use SHMS spectrometer as platform, replacing first spectrometer magnet with sweeping magnet before calorimeter

- Add 25 msr π^0/γ detector using 1116 $PbWO_4$ blocks (with temperature-controlled frame)



Summary

Recent Hall C results from ”6 GeV” Era

- Qweak, Hypernuclear, Kaon Form Factor
- Spin Asymmetries on the Nucleon (g_1^p, g_2^p, d_2^p) arXiv 1805.08835
- Proton/Deuteron F_L structure function – Phys. Rev. C 97, 045204 (2018)

“12 GeV” Era data taking started – Productive first run

- Proton Color Transparency, p/d F_2 at high x, EMC, deuteron electrodisintegration
- Semi-inclusive DIS: Transverse momentum distributions

Future

- SIDIS, CSV, Exclusive K^+ production/FF, Pion FF, Pion σ_L σ_T scaling
- LHCb pentaquark [$P^+_c(4450)$] photoproduction – detect J/ψ → e^+e^-
- Neutron spin structure (A_1^n, g_2^n/d_2^n) with polarized ^{3}He
- Neutral Particle Spectrometer, SIDIS with π^0, DVCS, Wide Angle Compton Scat.
- + more

Super High Momentum Spectrometer