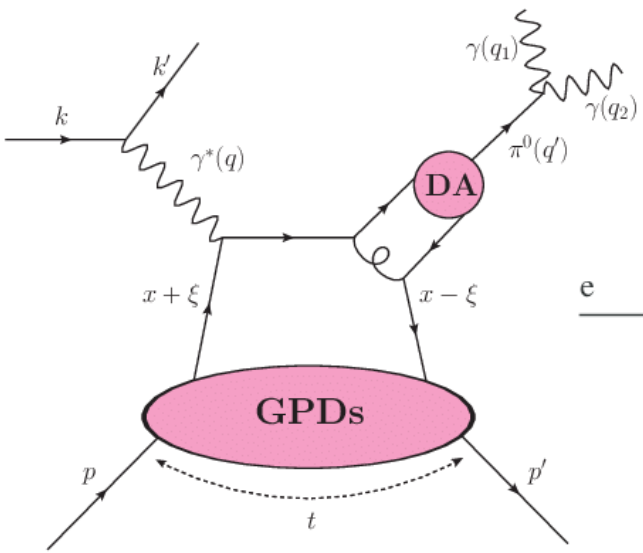
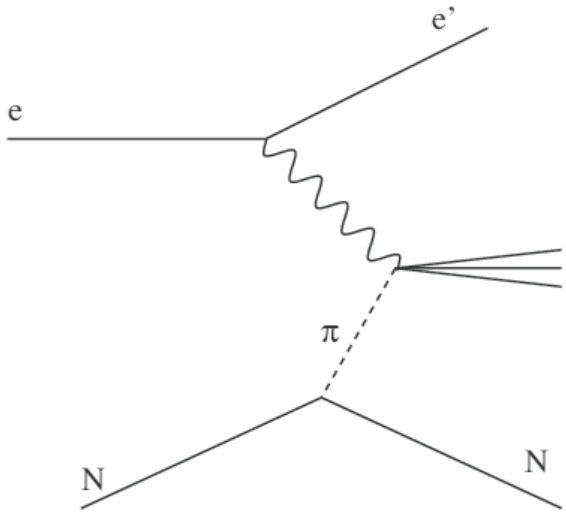
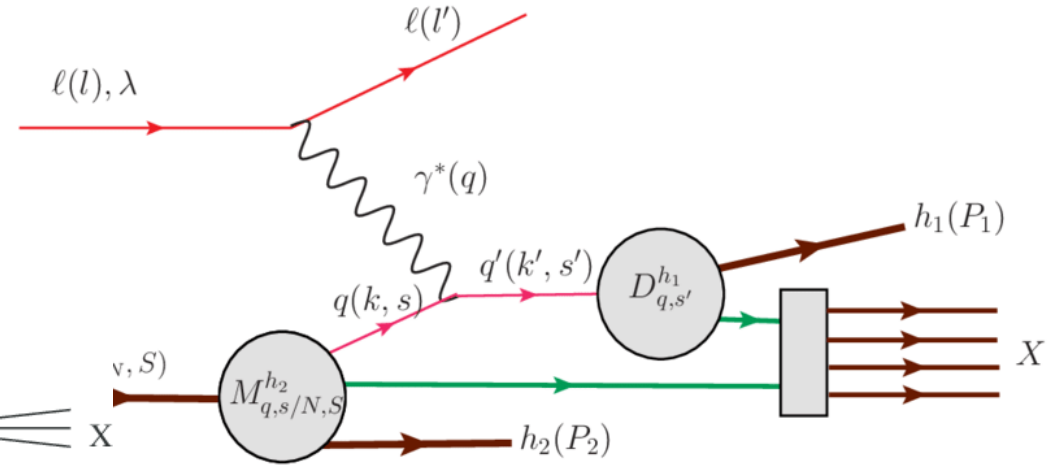
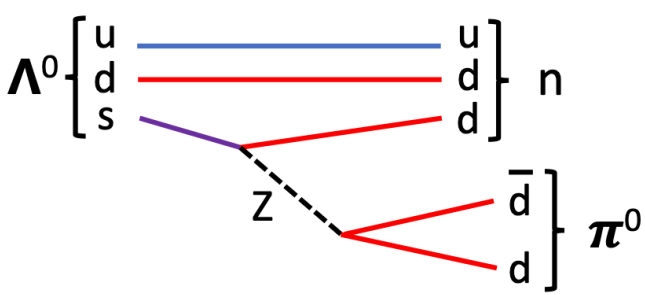
The Jefferson Lab Hall C Program: Physics at the Luminosity Frontier

Edward R. Kinney, University of Colorado at Boulder
On behalf of the **Hall C Futures Task Force**









- Overview and Focus
- Hall C Tools
- Experimental Physics Program
- Summary and Recommendation

Preliminaries

- Thanks to Arun Tadepalli, Tanja Horn, Mark Jones, Thia Keppel and many others for sharing their slides from previous talks.
- Thanks to the Hall C Task Force for allowing me to join the discussion and learn from them!
- My apologies in advance to the Hall C Task Force for any mis-statements or misrepresentations I may make; they are my mistakes, not yours!

The Hall C Futures Task Force

Chairs: Cynthia Keppel, Steve Wood, Mark Jones,Dave Mack

Jay Benesch (JLab)
V. Berdnikov (CUA)
P. Brindza (JLab)
S. Covrig Dusa (JLab)
Eric Christy (Hampton U.)
Dipangkar Dutta (Mississippi State U.)
David Gaskell (JLab)
T. Gogami (Kyoto U)
J.M. Grames (Jlab)
David Hamilton (U.Glasgow)
D. Higinbotham(JLab)
Or Hen (MIT)
Tanja Horn (CUA)
Garth Huber (U. Regina)
C. Keith (JLab)
Ed Kinney (U. Colorado)
Wenliang Li (W&M)
Nilanga Liyanage (UVa)
Ellie Long (New Hampshire)
B. Metzger (Jlab)
Carlos Munoz-Camacho (IJCLab-Orsay)
S.N. Nakamura (Tohoku U)
Brad Sawatzky (JLab)
Karl Slifer (New Hampshire)
Holly Szumila-Vance (JLab)
Arun Tadepalli (JLab)
Bogdan Wojtsekhowski (JLab)

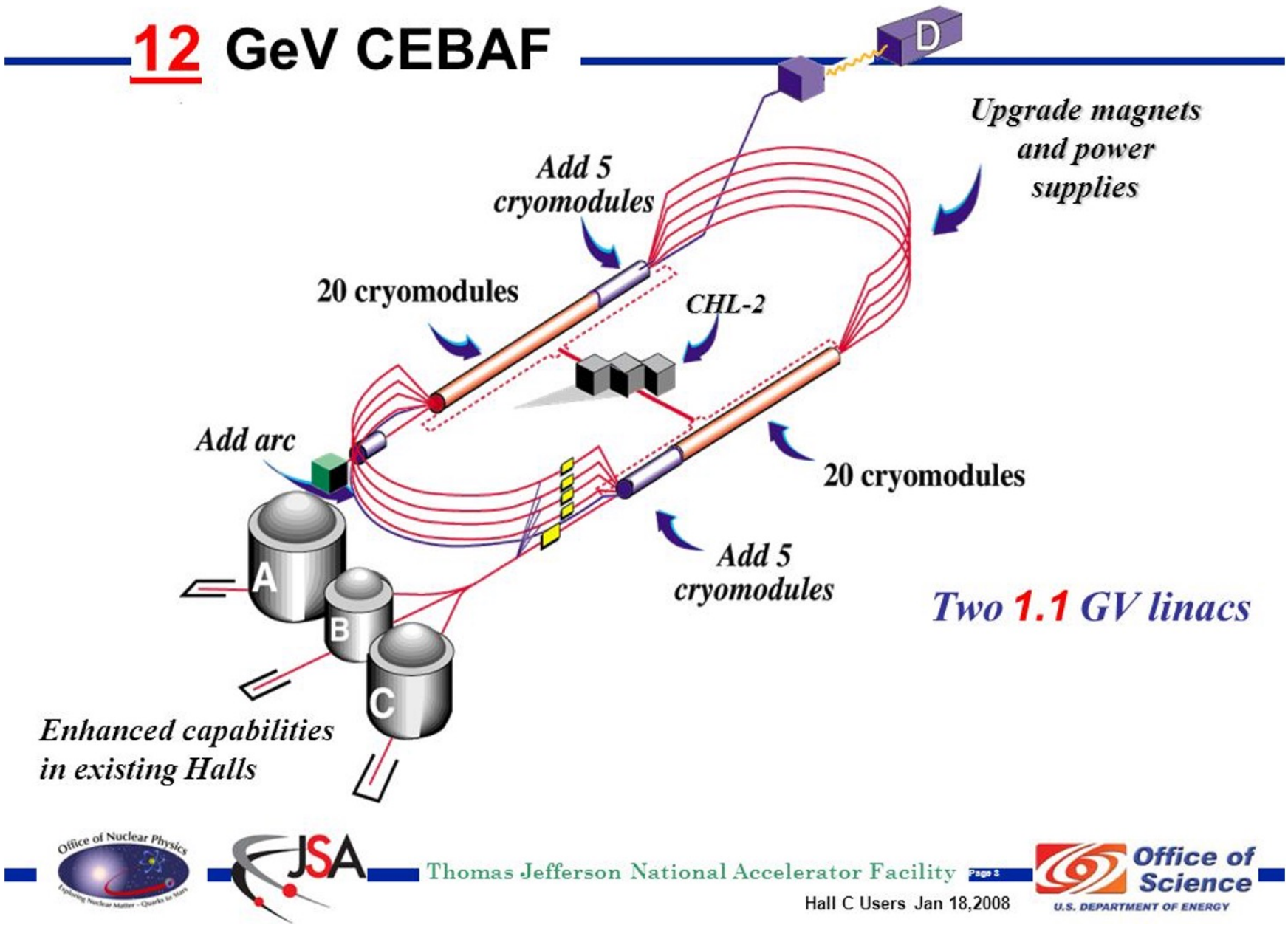
Futures Task Force Overview

- First Meeting of Hall C Futures Task Force convened February 2021 by Thia Keppel
- Charged to think about the future of measurements in Hall C beyond presently approved experiments into the EIC era
- Focus on strengths and complementarity of experiments in Hall C relative to other Jefferson Lab halls and the EIC
- Develop a white paper to express these ideas to the wider nuclear physics community
- White paper to be posted on arxiv shortly; available now at https://hallcweb.jlab.org/doc-public/ShowDocument?docid=1189

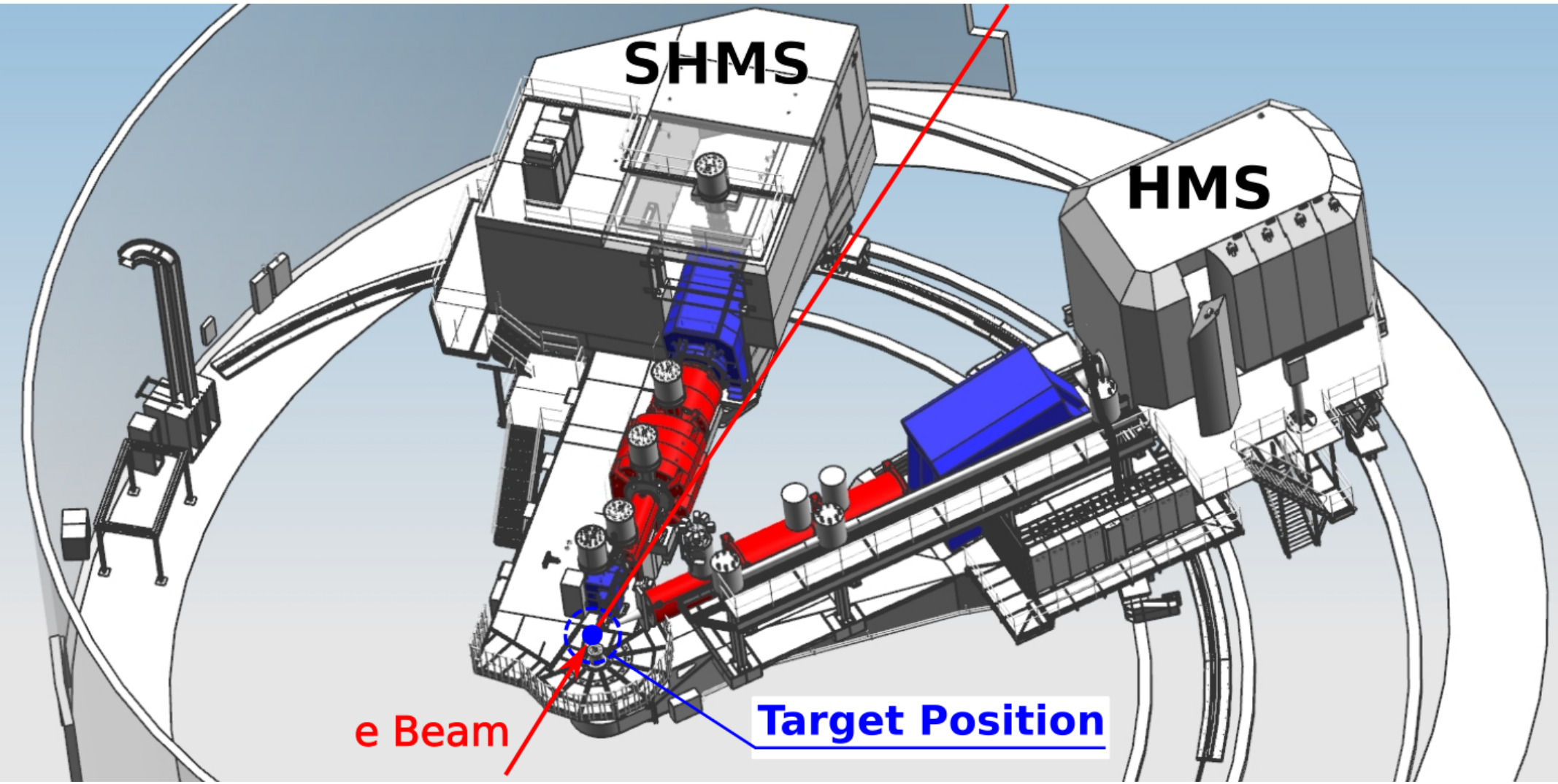
Outline of White Paper

- Focus on basic questions about QCD and Hadrons
- Questions guide us to measurements!
- Existing equipment and future conceptual ideas described
- A sampling of future measurements are described showing the breadth of the program
- How positrons and higher beam energy augment the program at 12 GeV

Jefferson Lab: Polarized CW Electrons up 12 GeV

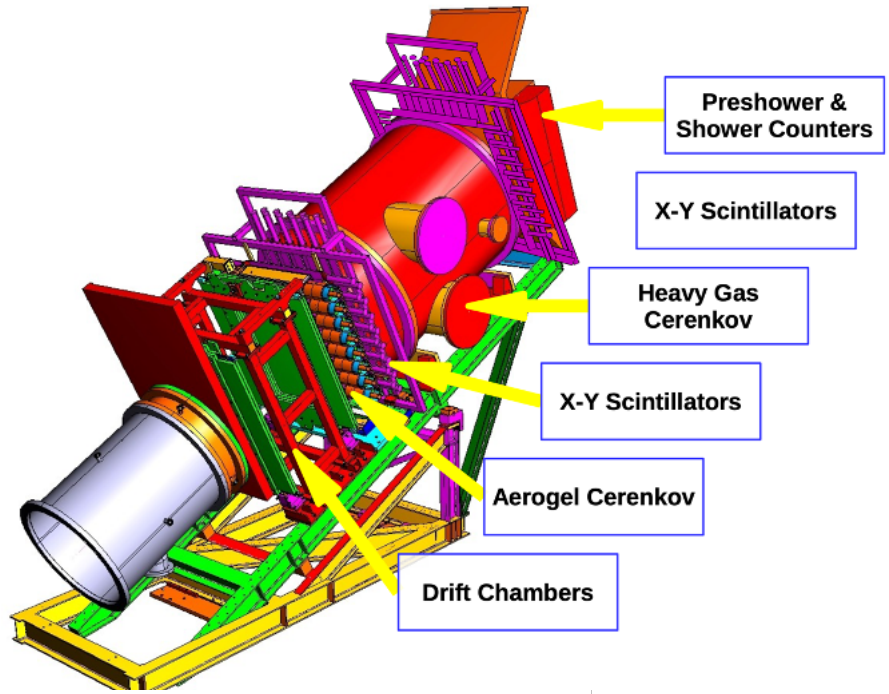


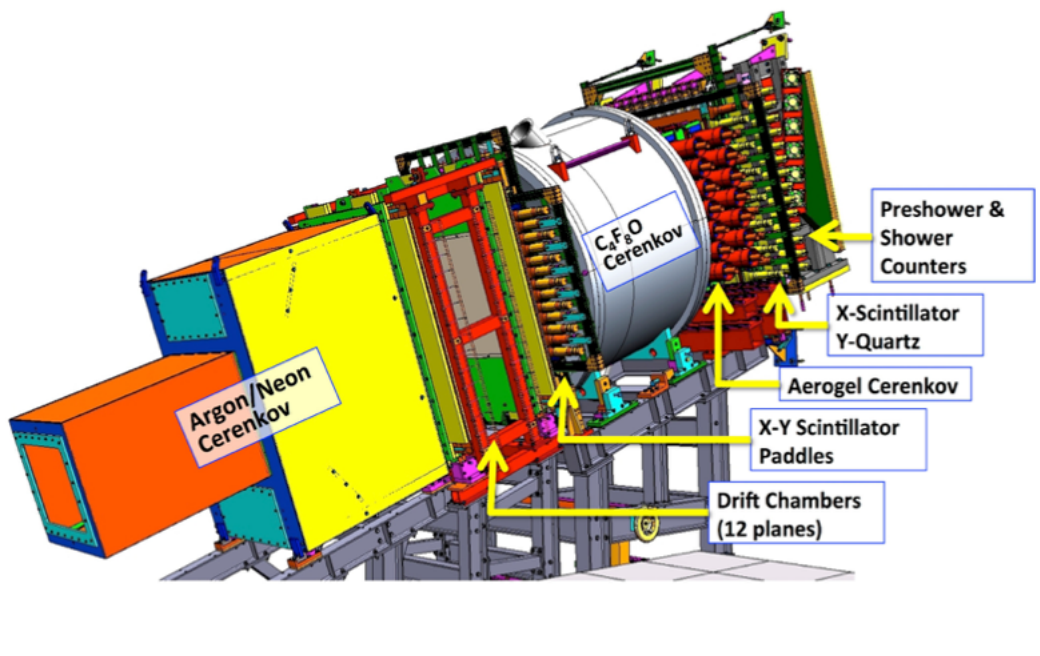
The tools available in Hall C



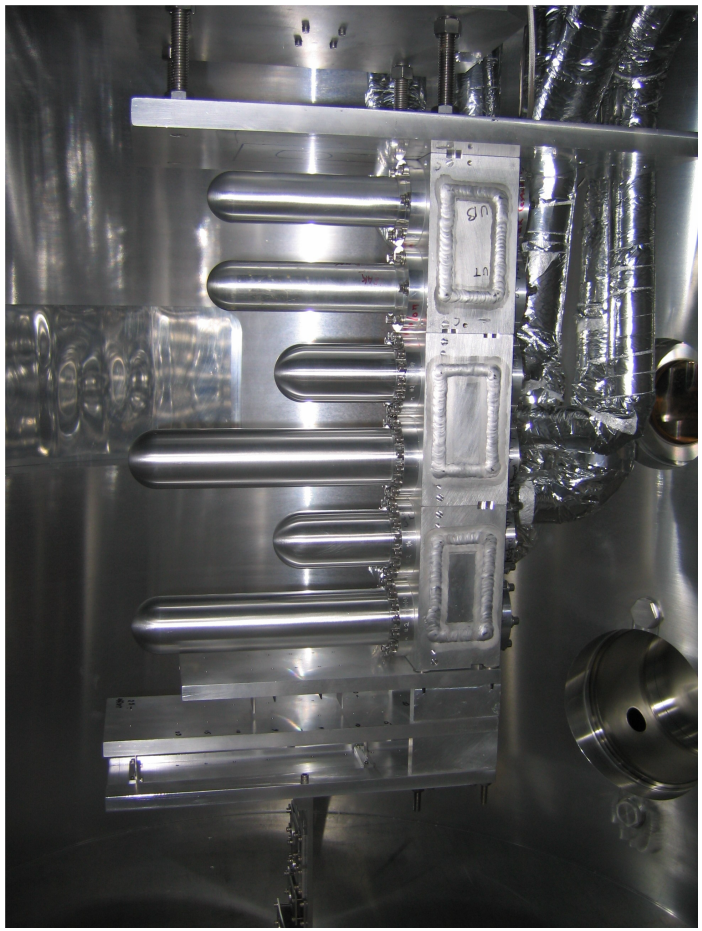
HMS and SHMS: Base Spectrometers

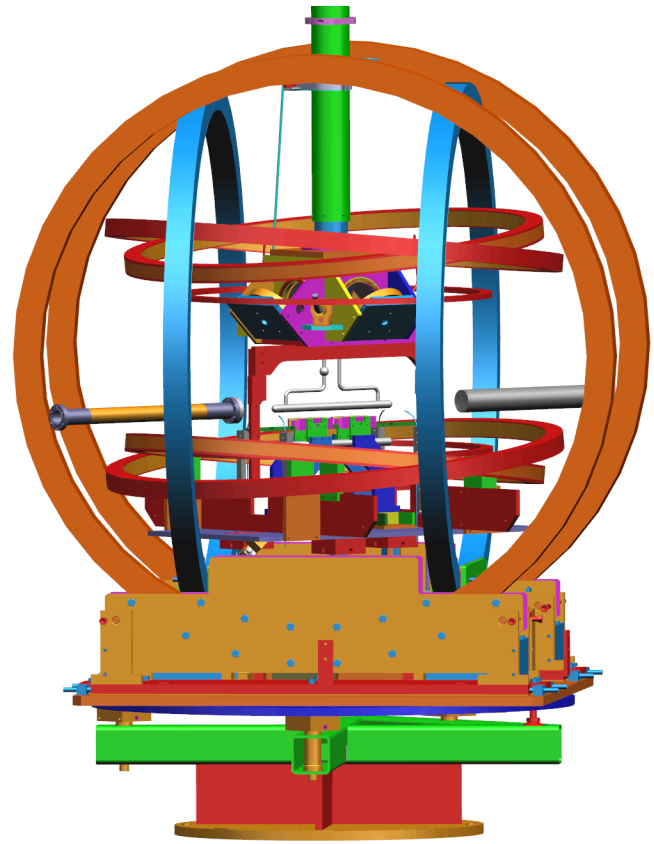
- HMS and SHMS that can reach 6+ and 11+ GeV/c with 10% momentum bites (single and coincidence mode)
- 0.1% reconstruction efficiency easily demonstrated
- Excellent PID
- Cerenkov and lead glass shower counters
- Can go up to 5.5 and 10.5 deg with sub-mrad pointing accuracy





High Power Unpolarized and Polarized Targets



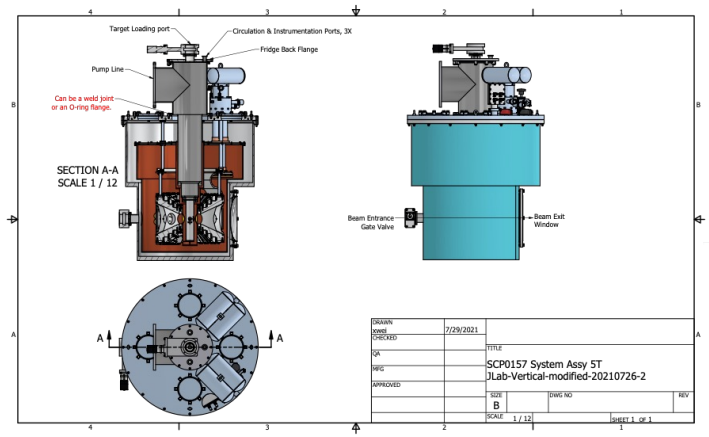


- Luminosities up to 10^{38}
- Unpolarized target changes in a few minutes

Transversely Polarized H and D Targets

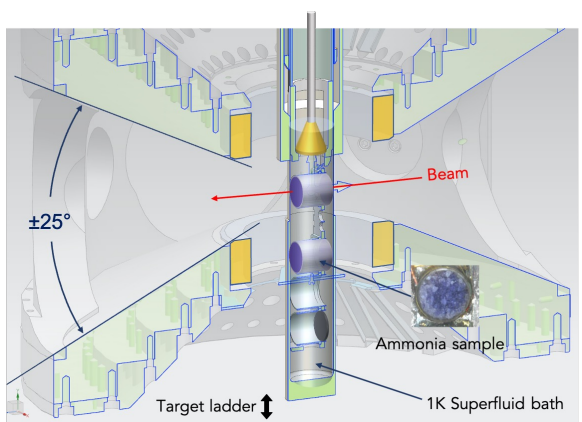
Transversely polarized target development

Jefferson Lab Target Group

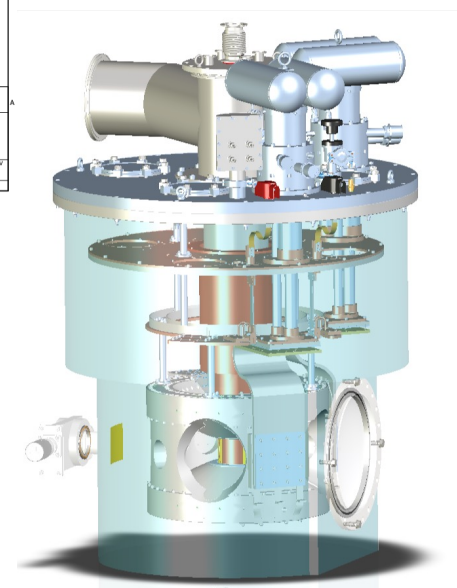


Custom vacuum chamber for target.

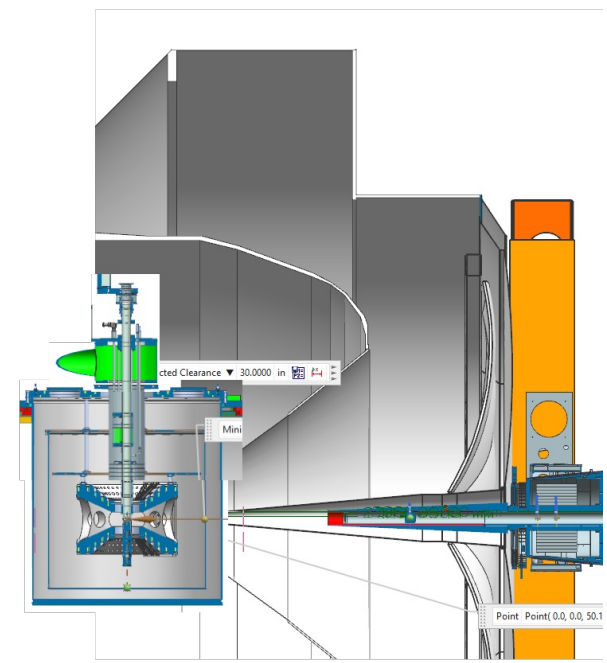
Target development for Hall C benefits also CLAS12



Vertical target ladder with multiple target samples.



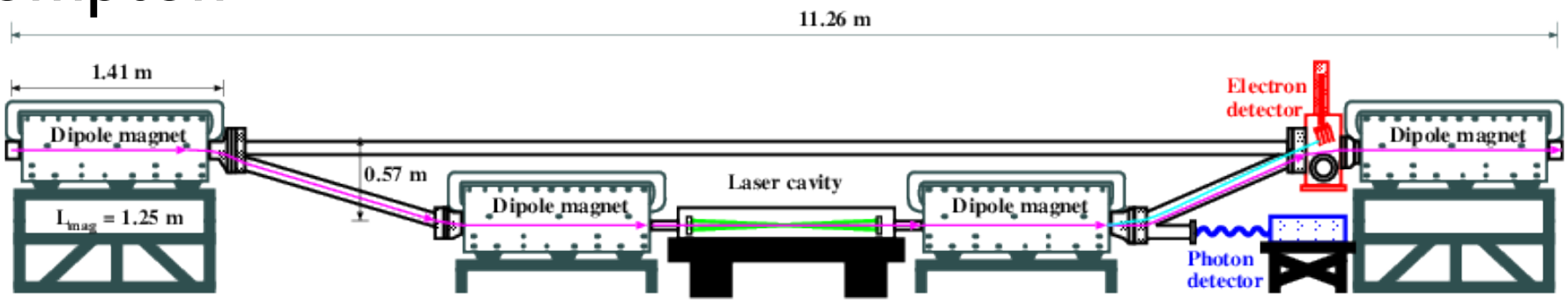
Compact 1 K refrigerator for sample cooling.



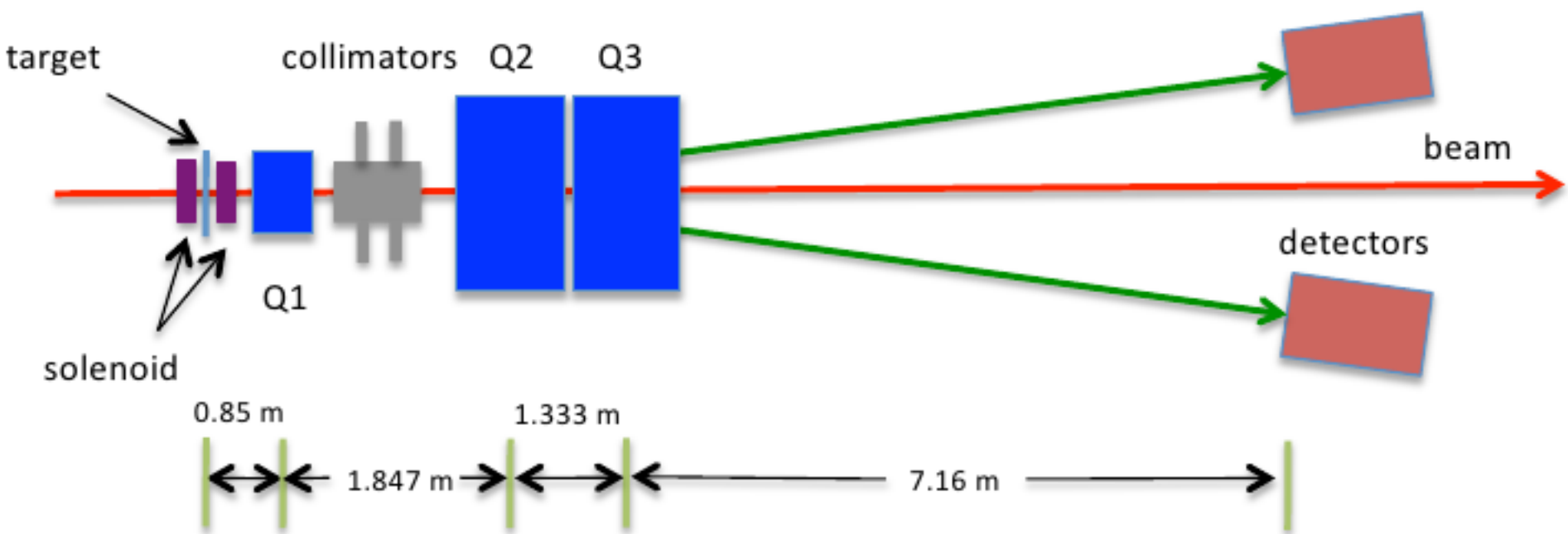
Conceptual design inside CLAS12 FD.

Precision Beam Polarimetry

Compton



Moller



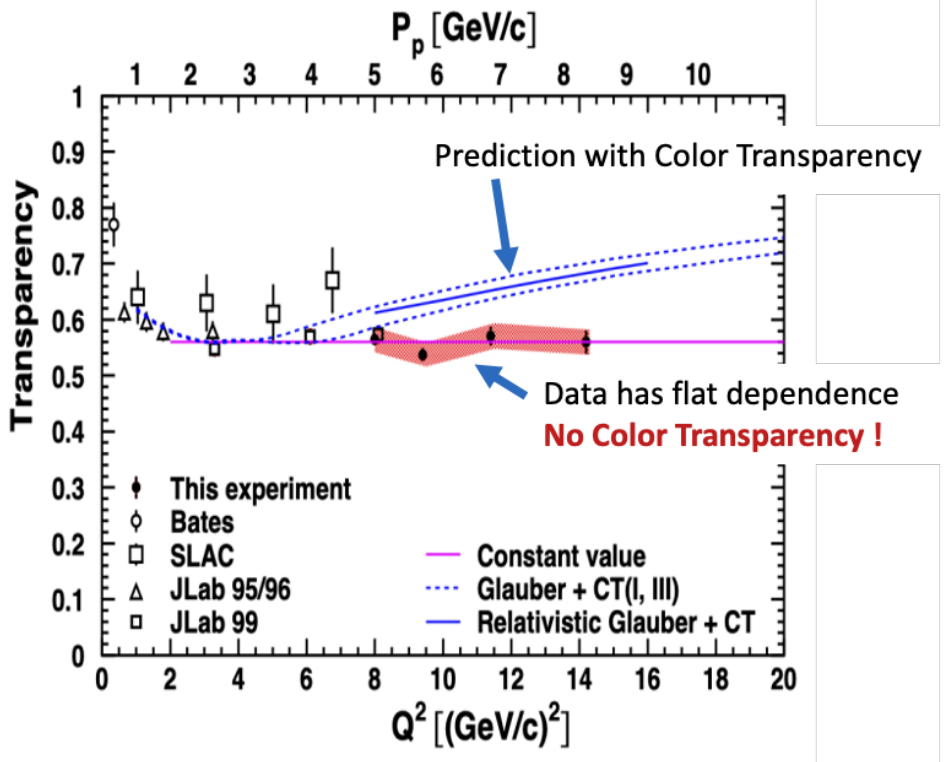
Achievements since 2015 Long Range Plan

- Super High Momentum Spectrometer (SHMS) installed and commissioned
- Active experimental program of new measurements using two spectrometers
- Already a queue of highly rated experiments waiting to be performed

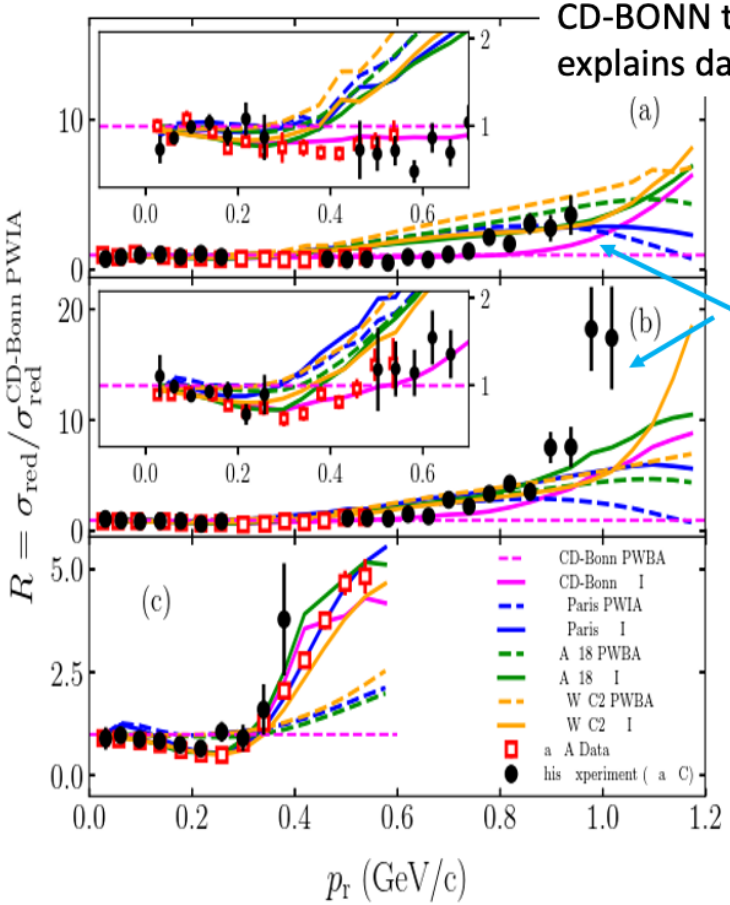
Hall C Results: CT & SR Deuteron Structure

First PRLs with data using new SHMS in 12 GeV Era

PRL 126 *"Ruling out color transparency in quasi-elastic 12C(e,ep) up to Q^2 of 14.2 (GeV/c)2"*

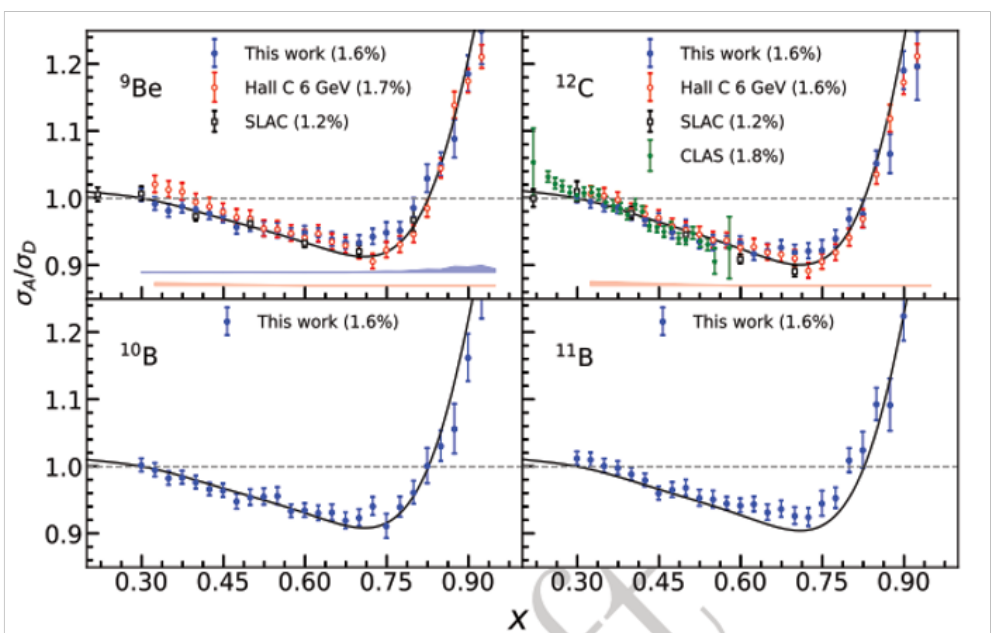


PRL 125 *"Probing the Deuteron at Very Large Internal Momenta"*



Hall C Results: EMC Effect in ^{10}B and ^{11}B

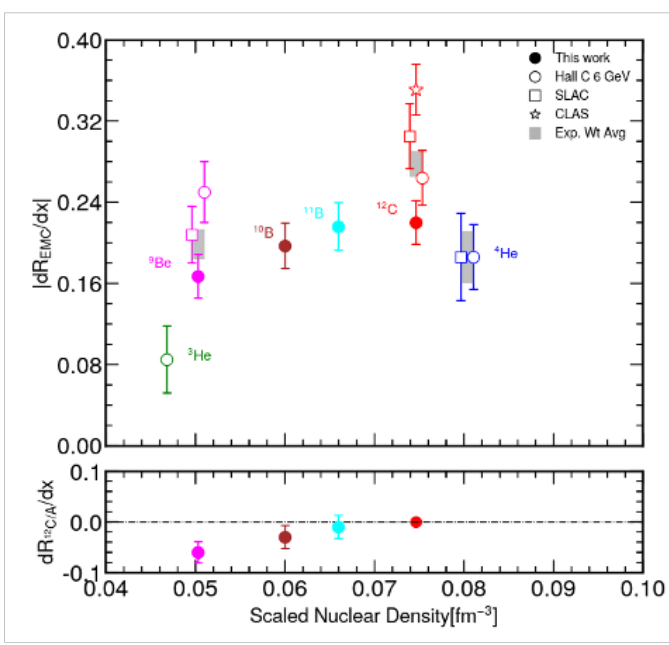
- Previous experiments on 9Be found that the EMC slope for 9Be was similar to 4He.
  - 9Be has α-cluster component to nuclear structure, local density effect?
- Correlation between EMC effect and SRC.
  - Two theories: Local density or highly virtual nucleons in correlated pair.
- Part of E12-10-008 on 9Be, 10B, 11B, 12C was completed as one of the SHMS commissioning experiments.
- An additional test of local density effect, since 10B and 11B are nuclei with α-cluster component.
- Submitting publication for PRL this week.
- Completion of E12-10-008 starts in Aug 2022



- Error bars on points are statistical and point-to-point systematic in quadrature
- Percentage in parenthesis is the normalization error
- Black line is A-dependent fit from SLAC E139

^{10}B and ^{11}B similar slope to ^{9}Be, ^{12}C, ^{4}He

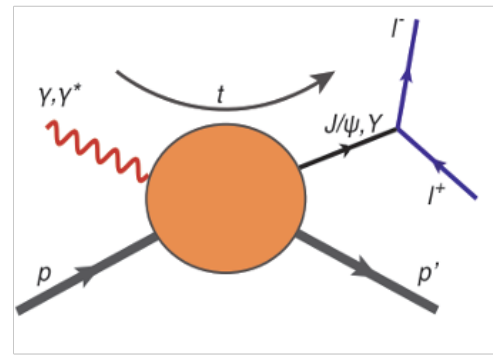
Slope of line fitted to σ_A/σ_D between $0.3 < x < 0.7$



Hall C Results: Photoproduction of J/Ψ

At DNP 2021: Released of final results of the E12-16-007 "A Search for the LHCb Charmed "Pentaquark" using Photoproduction of J/ψ at Threshold in Hall C at Jefferson Lab"

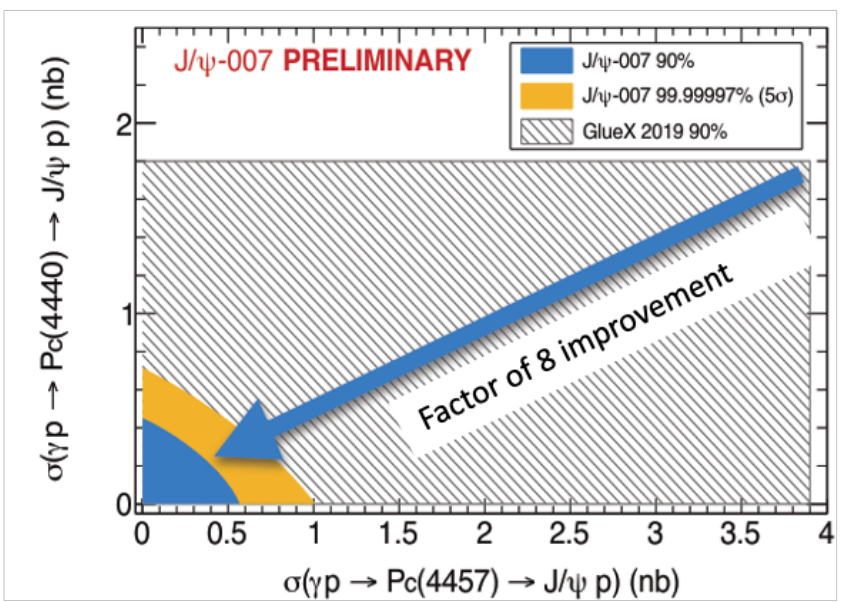
CERN LHCb found 3 narrow hidden charm states: Pc(4312), Pc(4440) and Pc(4457)
Pentaquark states? Molecular states?

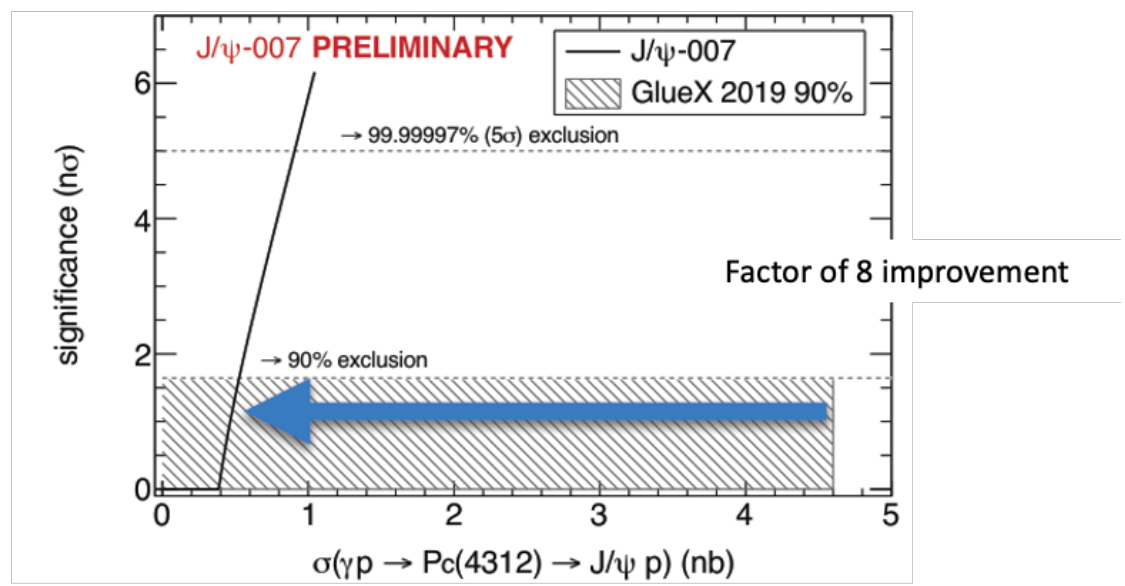


Photoproduction of J/ψ is excellent way to search for pentaquark

- Hall D GlueX published results in 2019 (grey box in figure)
- Hall C (J/ψ-007) measured 5x more statistics

New results are inconsistent with reasonable assumptions for true 5-quark states.

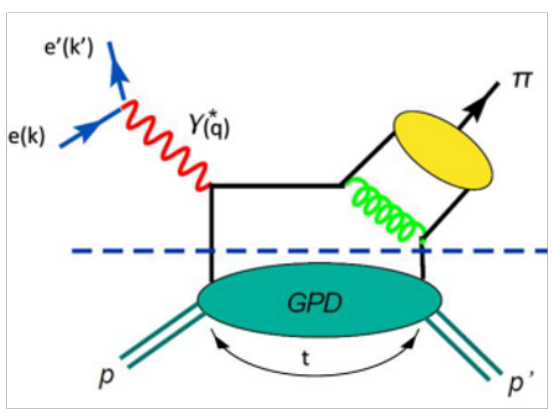




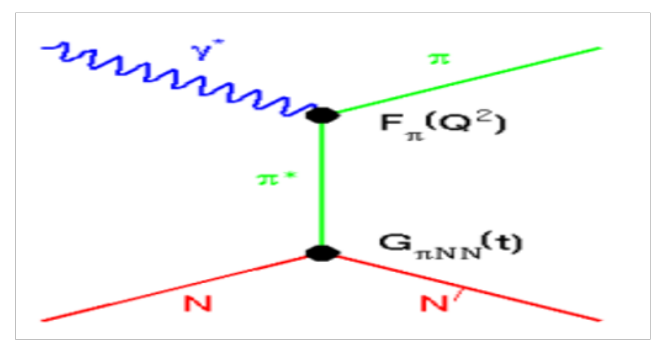
Hall C: Longitudinal/Transverse Separated Pion Electroproduction Cross Sections

E12-19-006 : *Study of the L–T Separated Pion Electroproduction Cross Section at 11 GeV*
and
Measurement of the Charged Pion Form Factor to High Q^2

- Scaling study at fixed x_{bj} = 0.31, 0.40 and 0.55
- In Hard Scattering regime
  - σ_L scales at $1/Q^6$
  - σ_T scales at $1/Q^8$
- Study hard/soft factorization for GPD extraction
  - Does σ_L or σ_T dominate?



- Indirectly measure F_π using the pion cloud in p(e,e'π^+)n
- Need to isolate the σ_L at low t
- Measure F_π to Q^2 = 8.5



Data collection completed Sept 2022!

See contribution from Tanja Horn

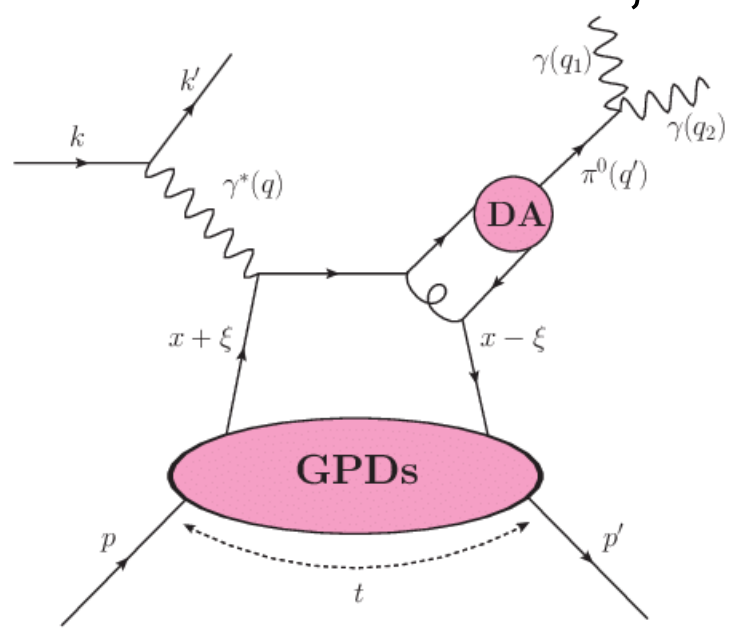
Future Science at Hall C -1-

Question: What is the spatial distribution of quarks inside the nucleon and nuclei?

Measurements: Elastic and hard exclusive process cross-sections, Parity Violating DIS

Requirements: High luminosity, excellent resolution, polarized beam and targets, Compact Photon Source, positrons, L/T Separation

Goals: Generalized Parton Distributions and Transition Amplitudes



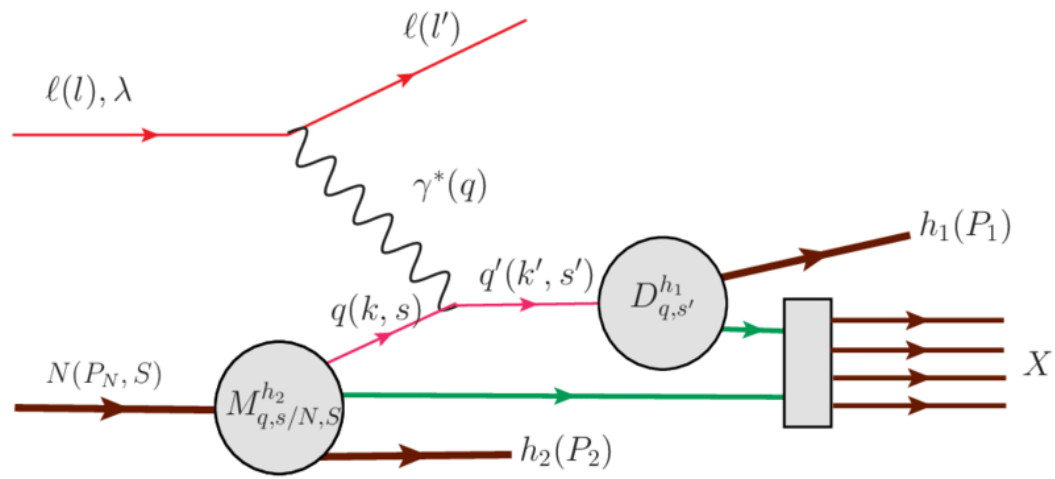
Future Science at Hall C -2-

Question: What is the quark structure of nucleons and nuclei in momentum space? High x and Q^2 emphasis

Measurements: Inclusive and semi-inclusive cross-sections

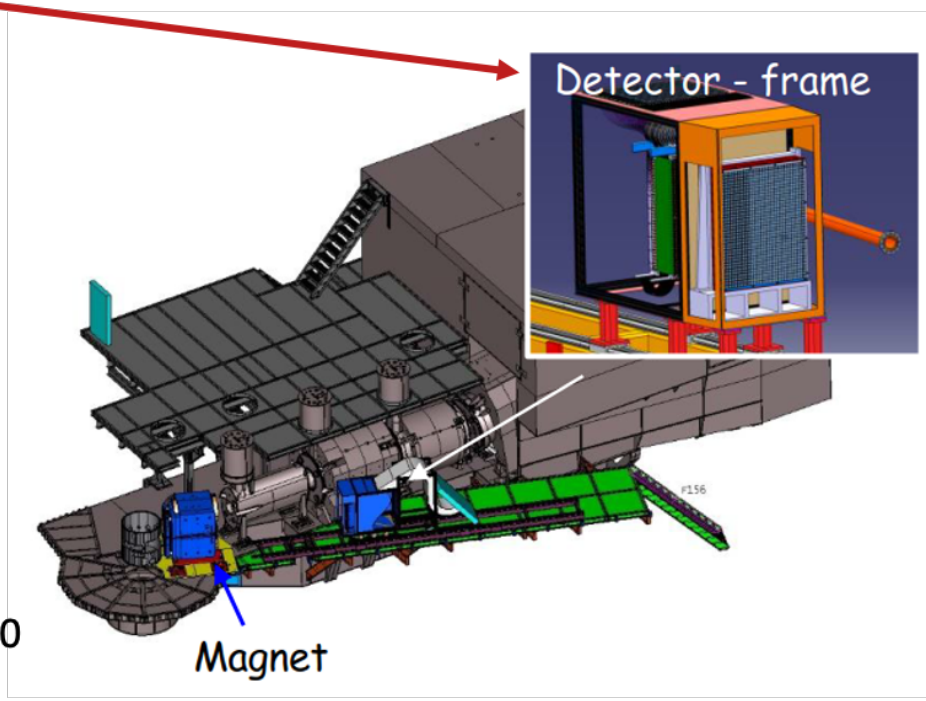
Requirements: L-T separations, good resolution

Goals: Transverse Momentum Dependent Parton and Fragmentation Functions



Hall C Neutral Particle Spectrometer (NPS) experiments

- Install Neutral Particle Spectrometer (NPS) during March 2023 to July 2023 down
- Magnet with calorimeter
  - 1080 Lead-Tungstate blocks in Calorimeter to detect γ and π^0
  - Remove the SHMS HB magnet



- Experiments
  - E12-13-010 is two concurrent experiments
    - Exclusive Deeply Virtual Compton on proton
    - SIDIS p(e,e',π^0) cross section. Map the transverse momentum dependence.
    - 53 PAC days.
  - E12-06-114 is completion of Hall A DVCS experiment
    - 35 PAC days.
  - *Note new proposal for Neutron DVCS could change*
  - Two experiments with photon beam running concurrently
    - E12-14-003 : Wide-angle Compton Scattering at 8 and 10 GeV Photon Energies (18 PAC days)
    - E12-14-005 :Wide Angle Exclusive Photoproduction of pi-zero Mesons

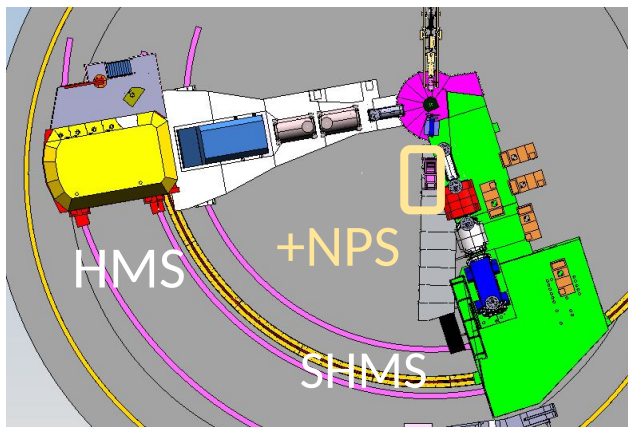
8

See later talk today by Tanja Horn

Flexibility for Additional Detectors

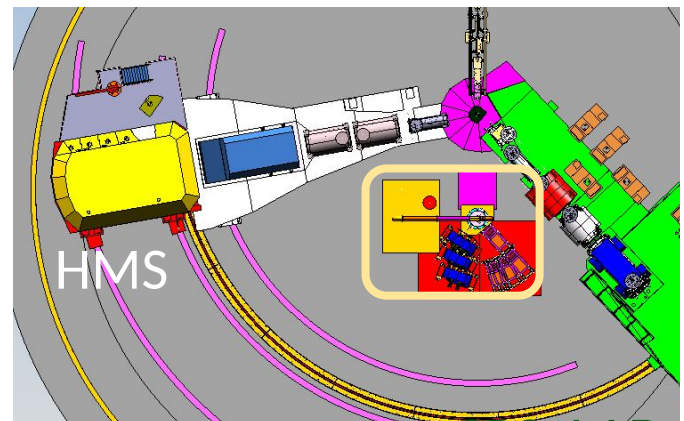
Two pivot configurations

Spectrometers with standard pivot



- Spectrometers provide control over systematic uncertainties (important for L/T separations)
  - ➢ Fixed pivot, precision kinematics, well-shielded detectors
- NPS adds neutral particle detection

Pivot moved downstream



+CPS, LAD, polarized target, etc.

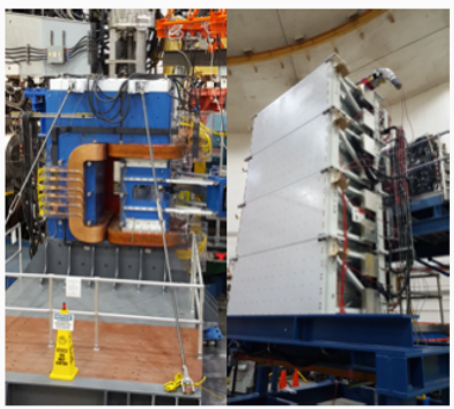
- Polarized targets downstream in combination with large acceptance detection
  - LAD or BigBite add large acceptance (backward) detection
- CPS adds high intensity photons

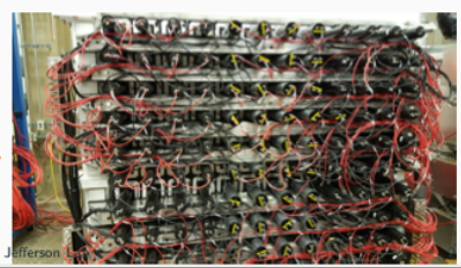
Slide from Tanja Horn

Large Acceptance Hadron Detectors
SBS+HCAL

HCal Overview

- Design based on COMPASS HCAL1 (Vlasov *et al.* 2006).
- Segmented calorimeter designed to detect multiple GeV protons and neutrons.
  - 288 PMT modules (24×12).
  - LED fiber optics system.
- SBS dipole magnet separates scattered hadrons by charge.
- High time resolution (0.5 ns).
- High position resolution (3-4 cm at 8 GeV).
- Neutron to proton detection efficiency ratio 0.985 at 8 GeV.
- Energy resolution ≈30%.

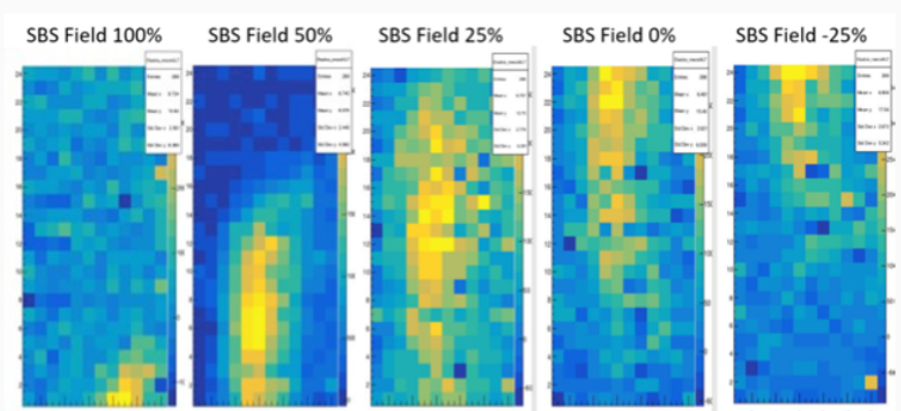




Scott Barcus Jefferson

Proton Sweep

- Using a LH_2 target sweep the magnetic field to illuminate all of HCal with elastic protons.
- These elastics are well understood and can be used for calibrations and detector characterization.



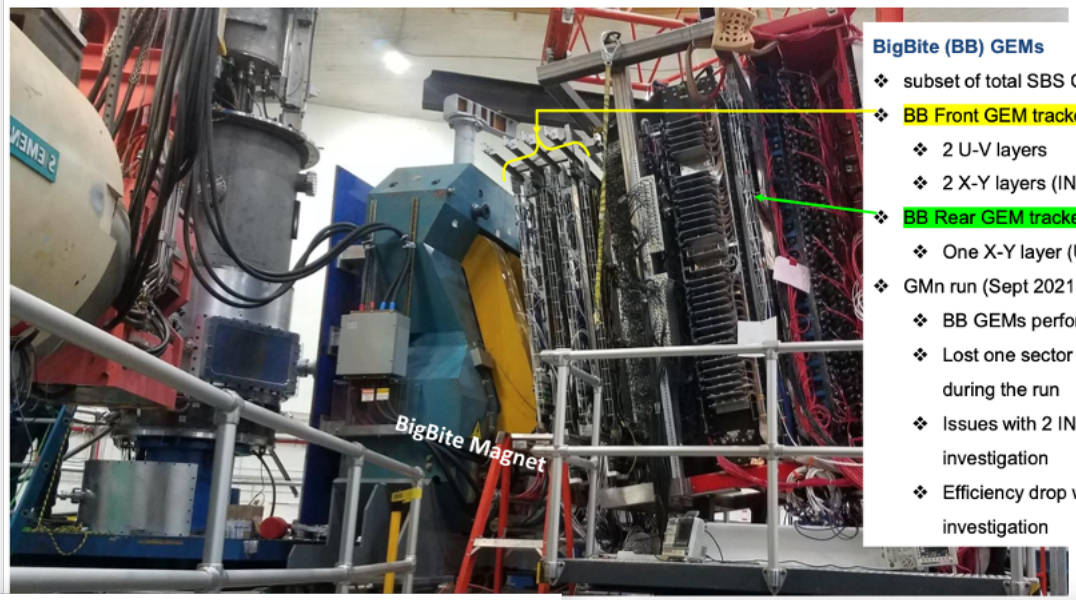
Scott Barcus Jefferson Lab 7

Slides taken from Scott Bacrus's talk at Hall A Collaboration meeting (Feb 11th, 2022)

Hall A BigBite Spectrometer

GEM trackers in BigBite Spectrometer

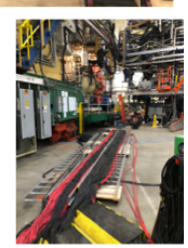
Jefferson Lab
Exploring the Nature of Matter



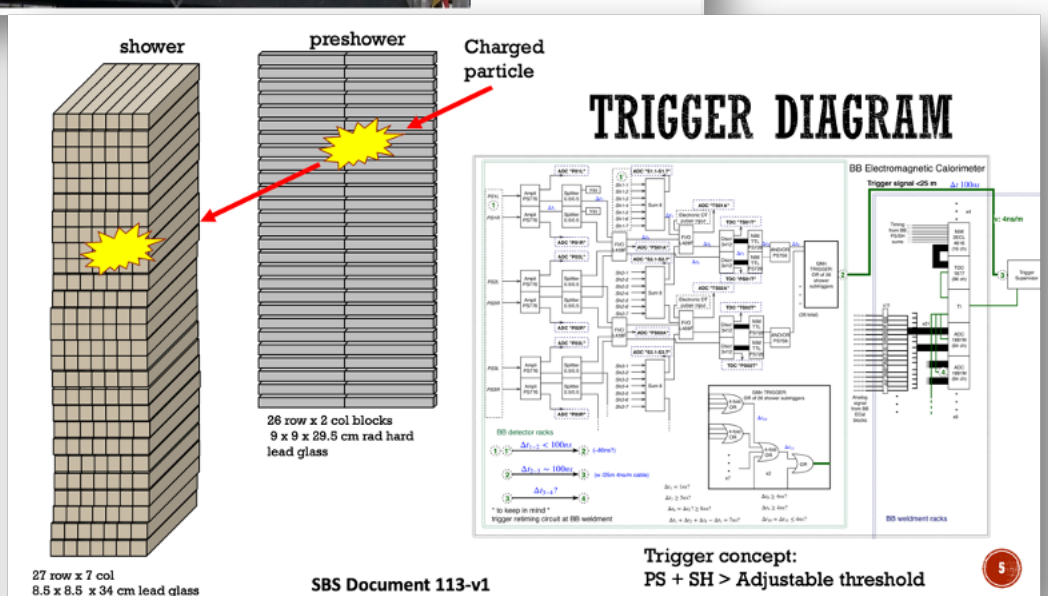
BigBite (BB) GEMs

- subset of total SBS GEM layers (5 out of 17)
- BB Front GEM tracker (150cm × 40cm):
  - 2 U-V layers
  - 2 X-Y layers (INFN)
- BB Rear GEM tracker (200cm × 50cm):
  - One X-Y layer (UVa)
- GMn run (Sept 2021 - Feb 2022)
  - BB GEMs performing very well
  - Lost one sector each in 2 U-V layers during the run
  - Issues with 2 INFN layers under investigation
  - Efficiency drop with high rates → under investigation

BIGBITE CALORIMETER MOVE TO THE HALL



Cabling up the calorimeter, front end electronics, and DAQ in the hall

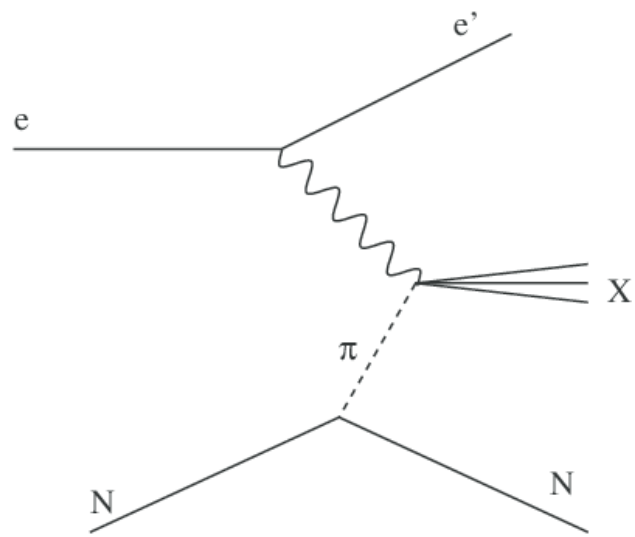


Future Science at Hall C -3-

Question: What is the origin of hadronic mass?

Measurements: Pion structure function via Sullivan process; π+, K+ form factors

Requirements: Low-energy forward hadron detection; L-T separation, high momentum hadron detection at very forward angle



Future Science at Hall C -4-

Question: Where does the hard/soft QCD factorization regime begin?

Measurements: Factorization tests in both t- and u-channel hard exclusive processes

Requirements: L-T separation, high momentum hadron detection at very forward and backward angles

Future Science at Hall C -5-

Question: What is the nature of confinement/hadronization?

Measurements: (e,e'p) cross-sections, A_{LT}, SIDIS fragmentation functions, Hyperon decays

Requirements: Polarized beams, Focal Plane Polarimeter, low energy hadron detection, triple coincidence

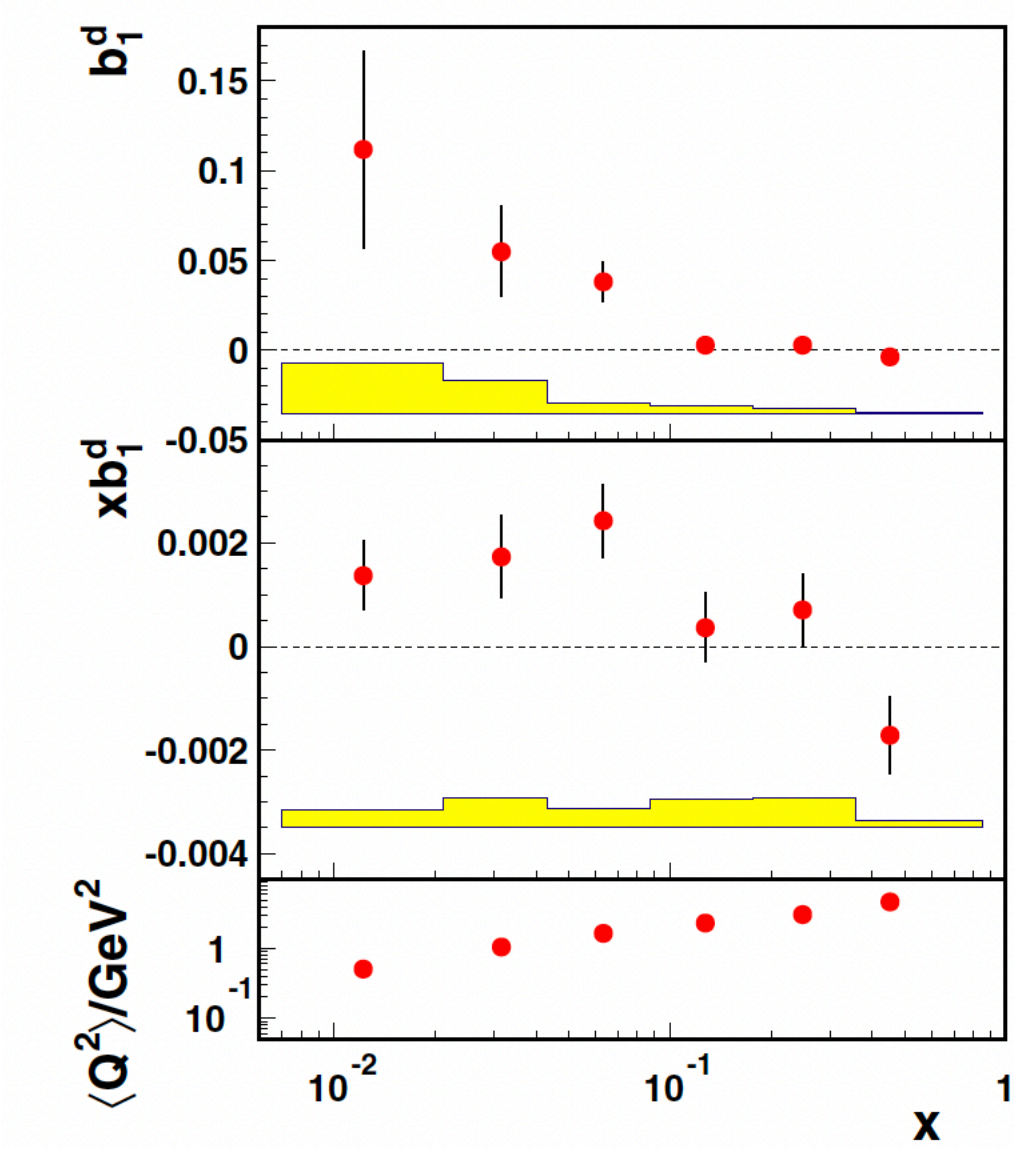
Question: How does the spin of the nucleon arise from the spin of quarks and their orbital angular momenta?

Measurements: Structure functions g_2 and b_1

Requirements: Transverse and *tensor* polarized targets

Tensor Structure Function b_1

- Tensor polarized deuteron target will allow the measurement of the b_1 structure function
- Sensitive to quark-gluon correlations; the only multiparticle inclusive structure function



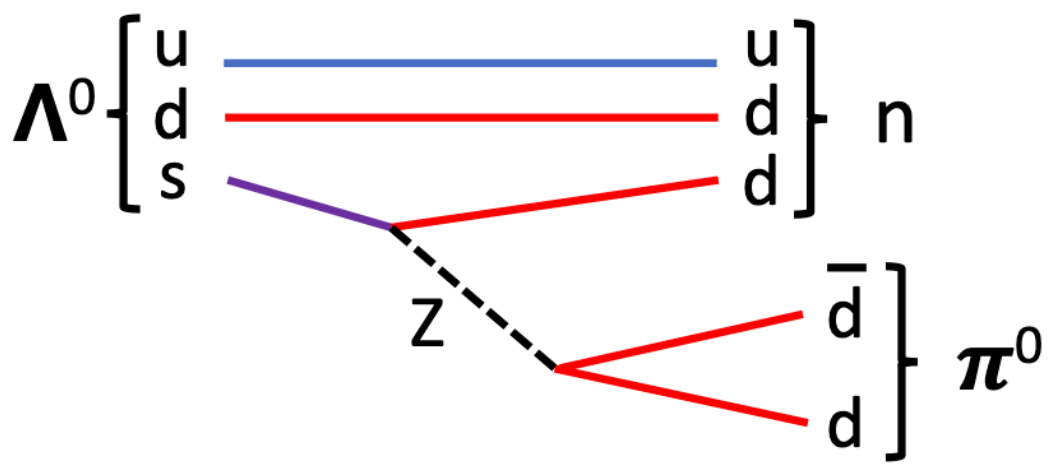
Hermes, PRL 95, 242001 (2005)

Future Science at Hall C -6-

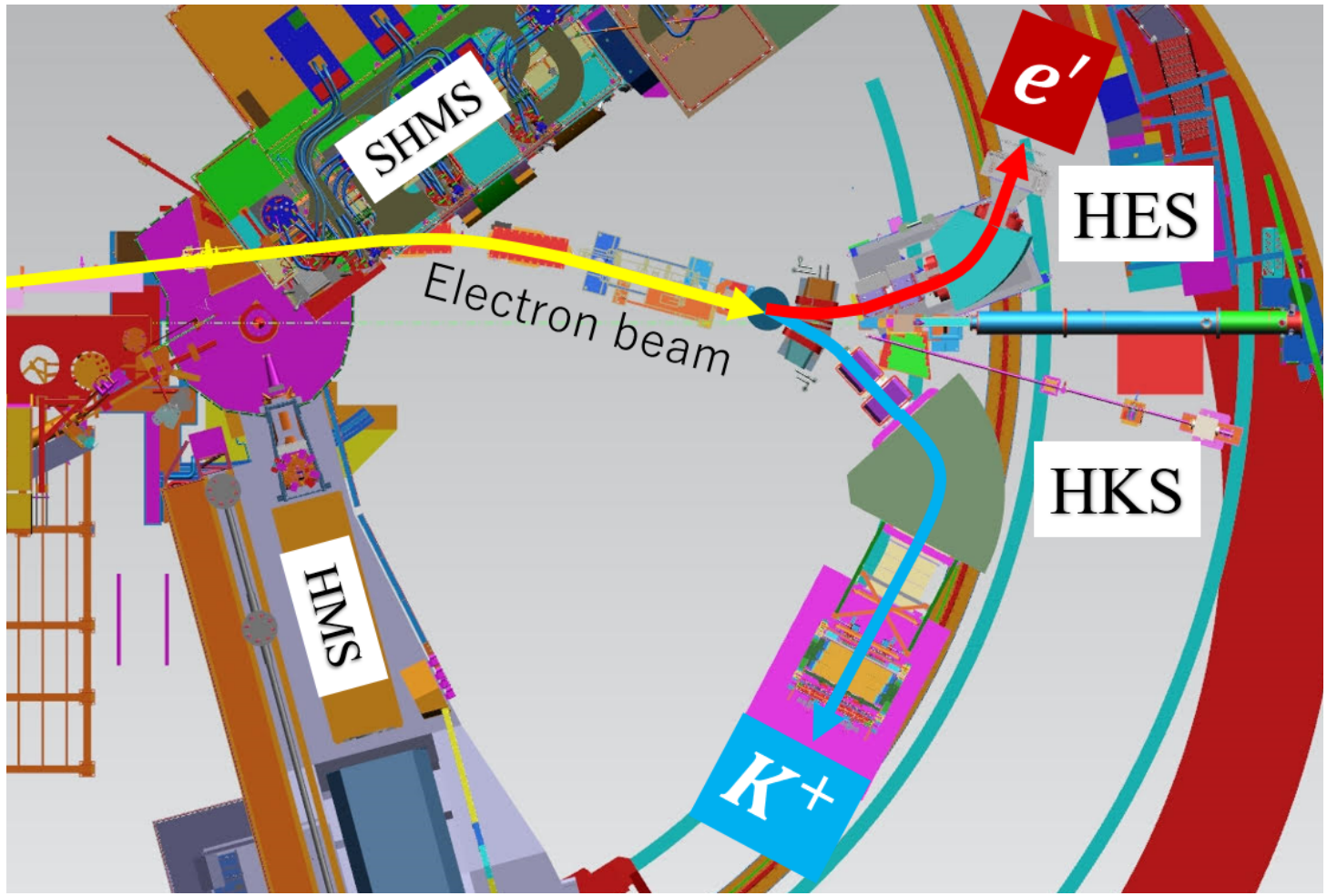
Question: What is the nature of the strong/nuclear force?

Measurements: Hyper-nuclear cross-sections, Short range correlations, Hyperon decays

Requirements: HMS, SHMS, NPS, polarized beam, backwards detection, triple coincidence



Hypernuclear Setup



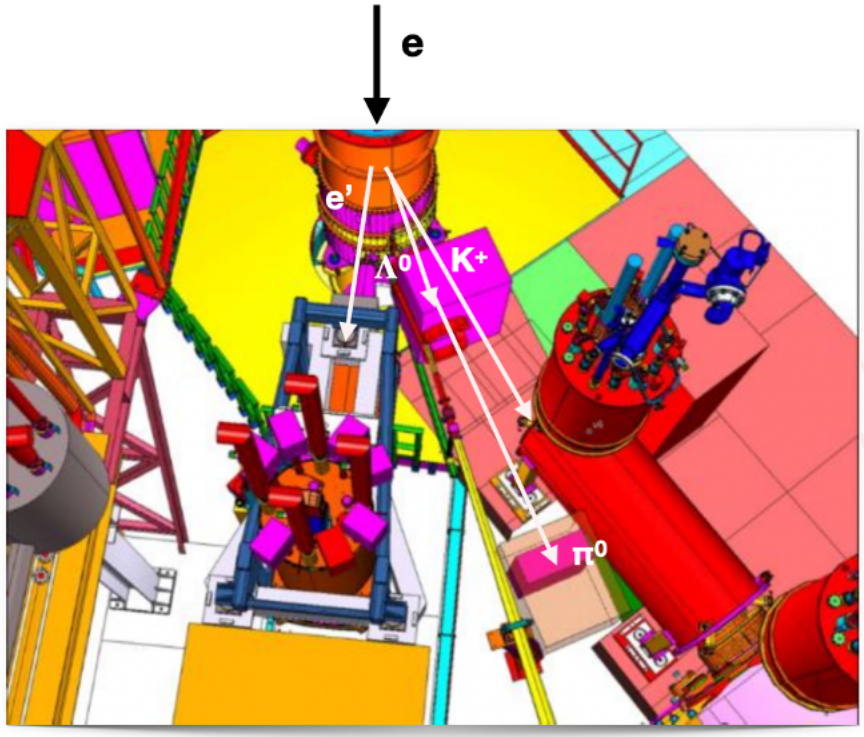
Hall C with SHMS+NMS can provide a new unique window into Λ^0 polarization.

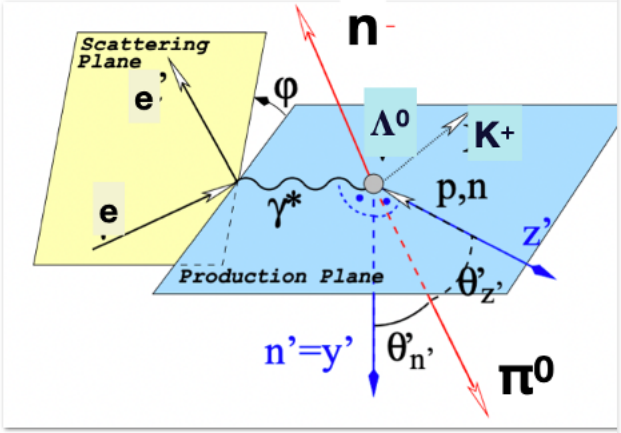
$p(\vec{e}, e' K^+ \pi^0)n$ ($\vec{\Lambda}^0$ decay) e' in HMS, K^+ in SHMS and π^0/γ in NMS, invariant mass of (n/Λ^0)

$p(\vec{e}, e' K^+ \gamma)\Lambda^0$ ($\vec{\Sigma}^0$ decay)

$n(\vec{e}, e' \vec{p}\, \pi^0)K^-$ ($\vec{\Sigma}^+$ decay) e' in HMS, $\vec{p}$ in SHMS and π^0 in NMS

$p(\vec{e}, e' \vec{p}\, \pi^0)K^0$ ($\vec{\Sigma}^+$ decay)





Hyperon rest frame (RF)

induced (self) polarization

transferred polarization

$$\frac{dN^{\pm}}{d\cos\theta^{RF}_{\pi^0}} = N[1 + \alpha(P^0 \pm P_b P')\cos\theta^{RF}_{\pi^0}],$$

beam polarization

analyzing power
(parity violating decay parameter)

Slide from Dipangker Dutta

Strong Hall C Capabilities

- Hall C is at the high luminosity frontier, precisely measuring small cross sections and performing longitudinal/transverse separations are our bread and butter.
- The ability to rapidly switch between different targets can greatly reduce systematic uncertainties, and a wide choice of nuclei is possible
- High luminosity measurements with polarized beams and targets are well established capabilities at Jefferson Lab
- Flexibility to change experimental layout (spectrometers, calorimeters, compact photon source) allows for optimized measurements with precision.
- The program of setting up widely varying experimental equipment provides an incredible learning experience for young scientists.

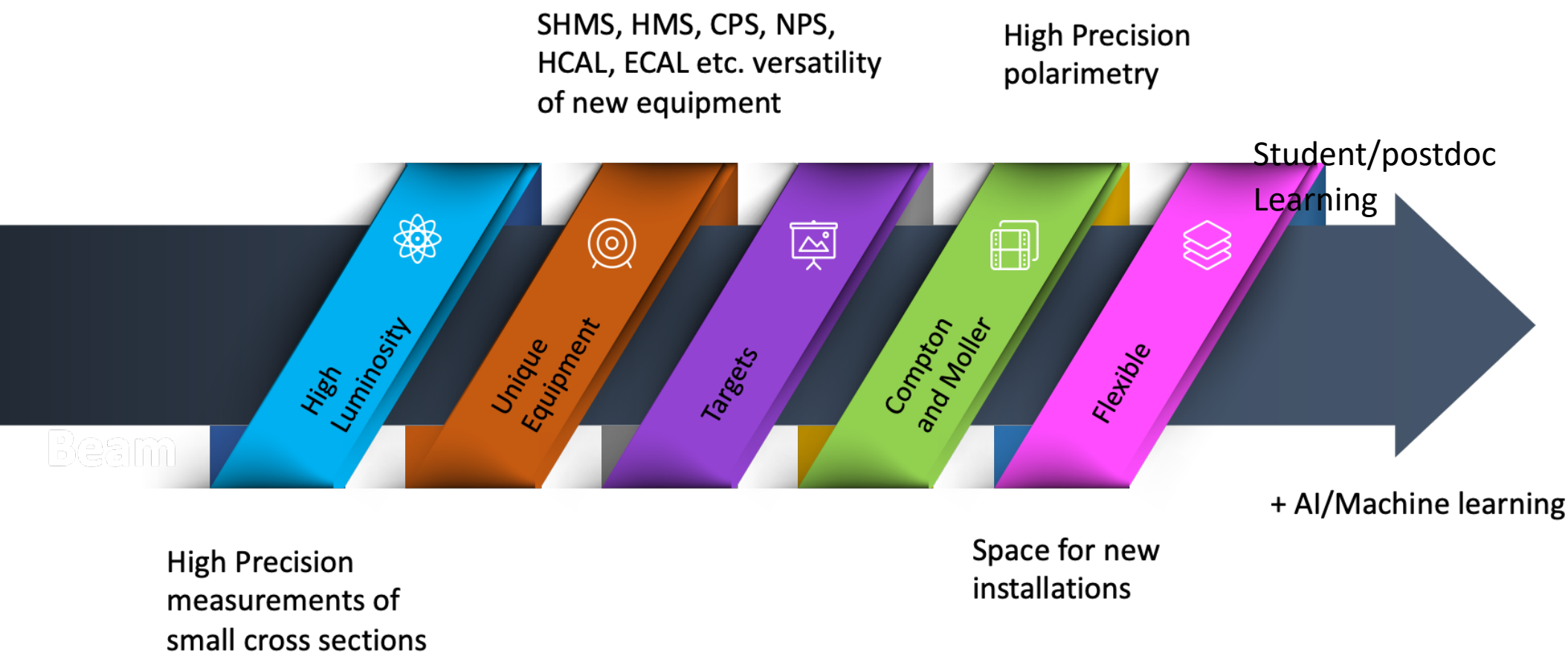
Recommendation for LRP (my opinion!)

Recommend the continued support of CEBAF operation and the Hall C program of physics measurements which take advantage of the high luminosity capability, the ability to perform precise longitudinal/ transverse separated exclusive and semi-inclusive cross section measurements, the wide variety of unpolarized and polarized targets available, the ability to detect neutral pions and photons, and the flexibility to install multiple spectrometers to study multiple hadron final states. This measurement program will furthermore provide a nearly unparalleled opportunity for the training of young scientists in accelerator based experimental physics.

See LRP Recommendations presented yesterday by Muñoz Camacho, later by Napolitano and Keppel, as well as other Jefferson Lab programs

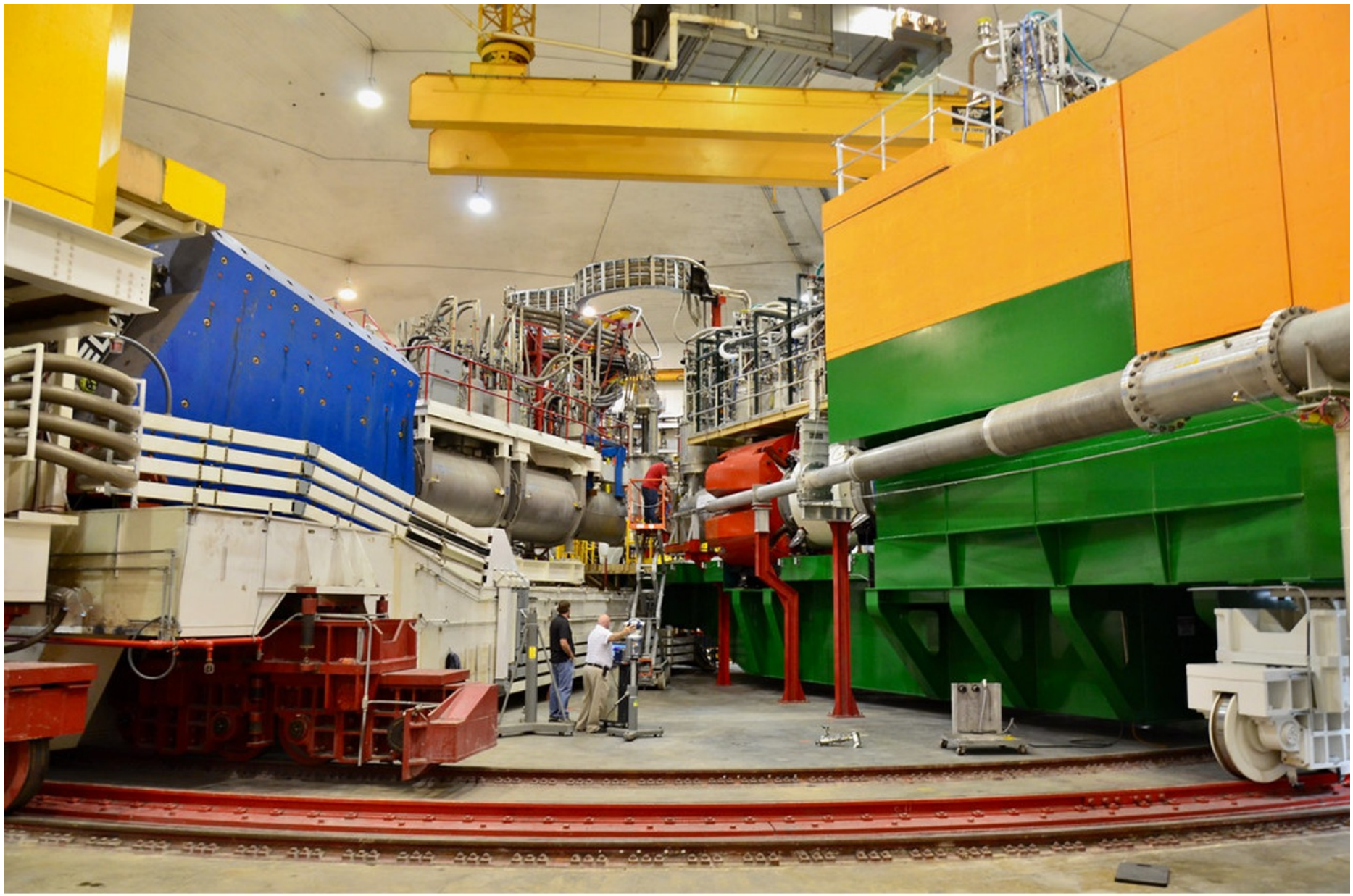
Backup

Hall C: Future Physics at the Luminosity Frontier



Graphic from Arun Tadepalli

Experimental Hall C



Hall C Kinematic Reach

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

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

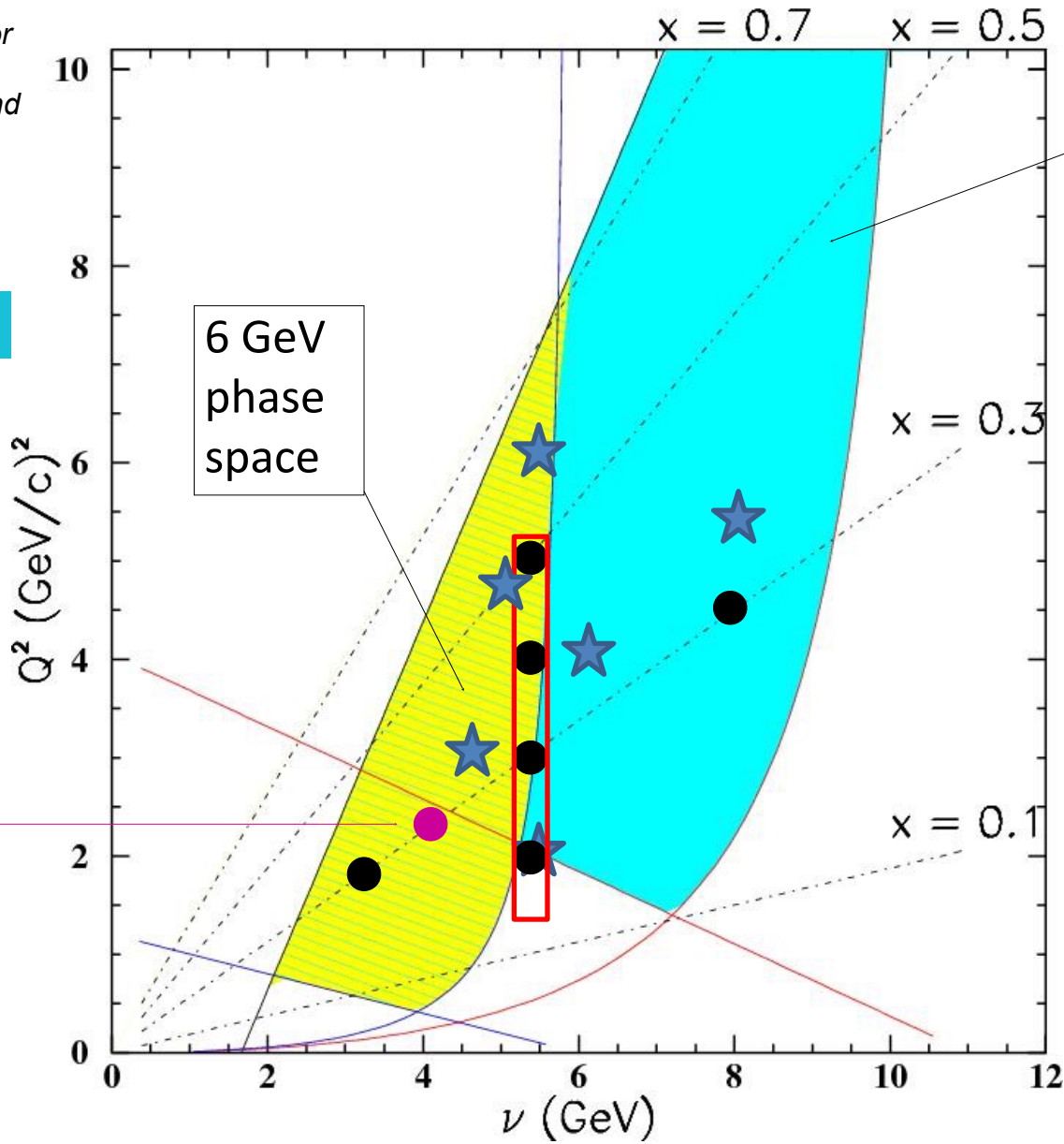
E12-13-007

★ Neutral pions:

Scan in (x,z,P_T)

Overlap with E12-09-017

E00-108 (6 GeV)



Charged pions:

E12-06-104

L/T scan in (z,P_T)

No scan in Q^2 at fixed x: $R_{DIS}(Q^2)$ known

● E12-09-017

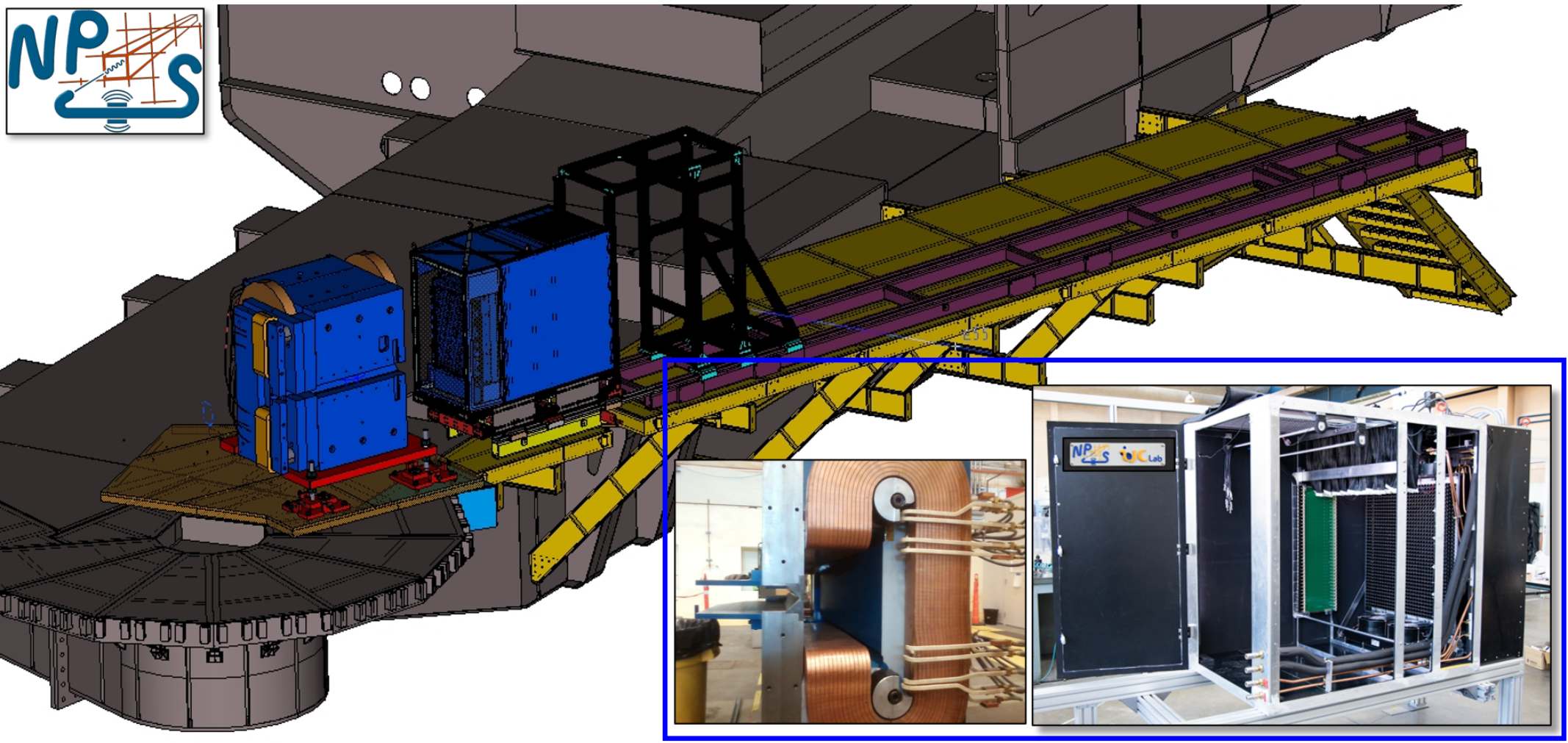
Scan in (x,z,P_T)

+ scan in Q^2 at fixed x

Hall C Work during Shutdown

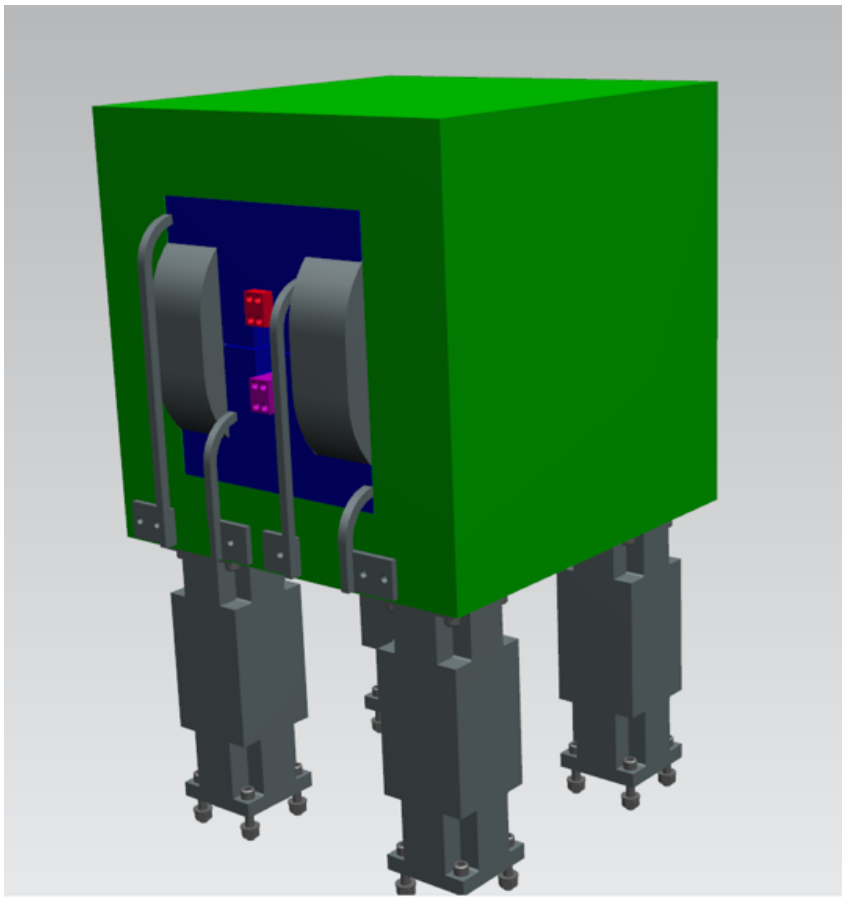
- Test installation of the NPS platform and rails.
- Deinstalled NPS platform and stored
- Established SHMS to 5.5 degrees

Neutral Pion Spectrometer



Compact Photon Source

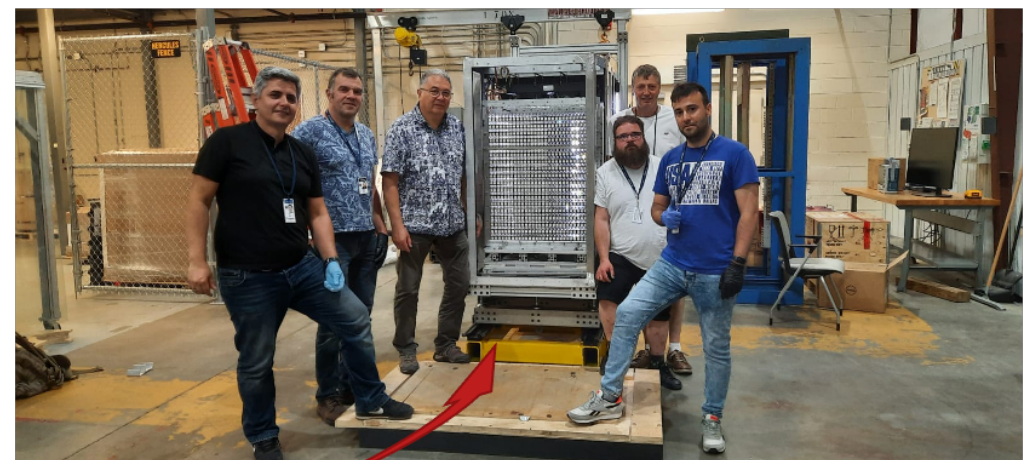
The compact photon source is designed to provide high intensity and narrow Bremsstrahlung beam for study of exclusive photon-induced reactions, e.g., Wide Angle Compton Scattering



NPS Preparation

- All 1080 blocks have been inspected and tested.
- In month of May all blocks wrapped.
- Stored in EEL108 for installation.

- French CNRS-IN2P3 group built calorimeter frame which was shipped to USA.
- From May 31st to June 16th, the French group was at JLab to assemble the calorimeter.
- *Completed assembly!*

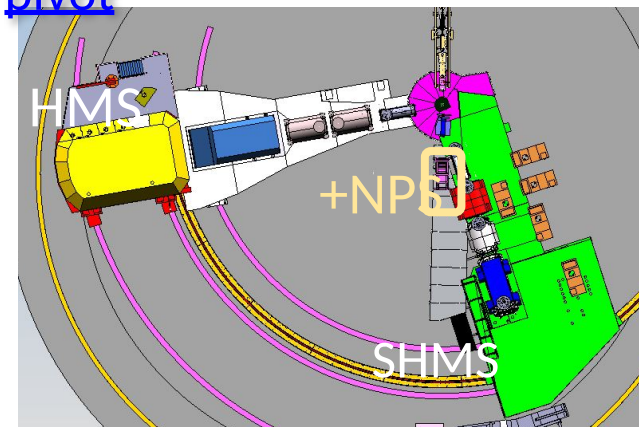


- Test installation of NPS platform and rails was done in Hall C during Feb-June 2022 down.
- Has been disassembled and stored.

Two pivot configurations

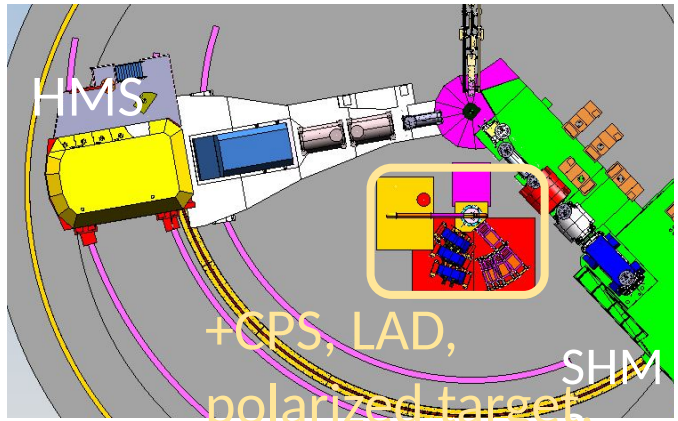
Slide from Tanja

Spectrometers with standard pivot



- F_2 at x>1
- Pion Form Factor
- Reaction Mechanism validation – Kaon FF, GPD and TMD
- Precision EMC
- DVCS and p^0 cross sections
- .....

Pivot moved downstream



- Polarized WACS
- 2N-SRC
- Tagging processes
- TCS
- ....

A New Solenoidal Spectrometer

A high luminosity spectrometer based on a compact 7T Solenoid magnet for DVCS, DVMP, TDIS and more

Nilanga Liyanage, Paul Souder, Weizhi Xiong