The Neutral Particle Spectrometer (NPS) and its Science Program in Hall C

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For the NPS Collaboration

THE CATHOLIC UNIVERSITY OF AMERICA

Jefferson Lab

Towards improved hadron femtography with hard exclusive reactions, Aug 7-11, 2023, Jefferson Lab

NPS Collaboration (since 2012)

Collaboration and meetings open to All!

The NPS collaboration consists of members active in the construction and commissioning of the instrument (listed below) and additional collaborators on the individual NPS experiments.

1. Ibrahim Albayrak (Akdeniz Univ/Turkey)
2. Salina Ali (UVA)
3. Tristan Anderson (VTech)
4. Moskov Amaryan (ODU)
5. Vladimir Berdnikov (JLab)
6. Peter Bosted (W&M)
7. William J. Briscoe (GWU)
8. John R.M. Annand (U Glasgow)
9. Arshak Asaturyan (JLab)
10. Vincenzo Bellini (INFN-Catania)
11. Kai Brinkmann (Giessen U.)
12. Marie Boer (VTech)
13. Alex Camsonne (JLab)
14. Marco Carmignotto
15. Josh Crafts (CUA)
16. Donal Day (UVa)
17. Maxime Defurne (CEA)
18. Bhesha Devkota (MSU)
19. Rolf Ent (JLab)
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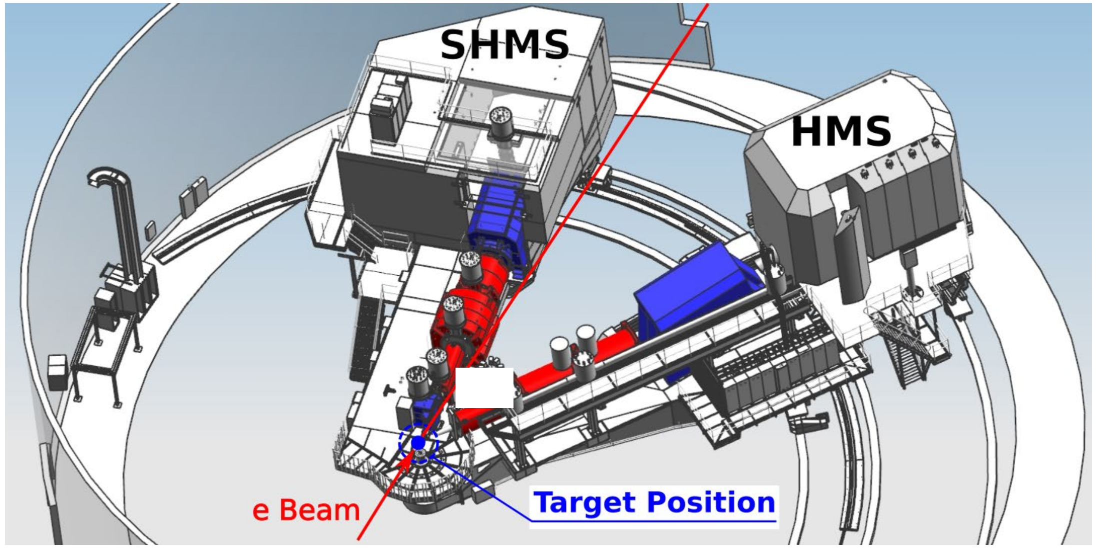
21. Michel Guidal (IJCLab-Orsay)
22. Wassim Hamdi (U. of Monastir)
23. David J. Hamilton (U Glasgow)
24. Tanja Horn (CUA)
25. Zheng Huang (UIC)
26. Charles Hyde (Old Dominion University)
27. Oliver Jevons (U Glasgow)
28. Greg Kalicy (CUA)
29. Dustin Keller (UVa)
30. Cynthia Keppel (JLab)
31. Mitchell Kerver (ODU)
32. Paul King (Ohio University)
33. Edward Kinney (U. of Colorado)
34. Mark Mattison (Ohio University)
35. Malek Mazouz (U. of Monastir)
36. Arthur Mkrtchyan (AANL, YerPhI)
37. Hamlet Mkrtchyan (AANL, YerPhI)
38. Rachel Montgomery (U. Glasgow)
39. Carlos Munoz-Camacho (IJCLab-Orsay)
40. Jacob Murphy (Ohio University)
41. Pawel Nadel-Turonski (Stonybrook)
42. Gabriel Niculescu (James Madison U.)
43. Rainer Novotny (Giessen U.)
44. Rafayel Paremuzyan (JLab)
45. Ian Pegg (CUA)
46. Pierre Pichard (U. Nantes/Ohio University)
47. Christine Ploen (Old Dominion University)
48. Hashir Rashad (Old Dominion University)
49. Riley Reedy (Ohio University)
50. Julie Roche (Ohio University)
51. Oscar Rondon (UVa)
52. Simon Sirca (U Ljubljana)
53. Alex Somov (JLab)
54. Igor Strakovsky (GWU)
55. Vardan Tadevosyan (AANL, YerPhI)
56. Richard Trotta (CUA)
57. Hakob Voskanyan (AANL, YerPhI)
58. Erik Wrightson (MSU)
59. Bogdan Wojtsekhowski (JLab)
60. Steve Wood (JLab)
61. Zhenyu Ye (UIC)
62. Zhihong Ye (Tsinghua University, Beijing, China)
63. Carlos Yero (JLab)
64. Simon Zhamkochyan (AANL, YerPhI)
65. Yao Peng Zhang (Tsinghua University, Beijing, China)
66. Carl Zorn (JLab)
67. Jixie Zhang (UVa)

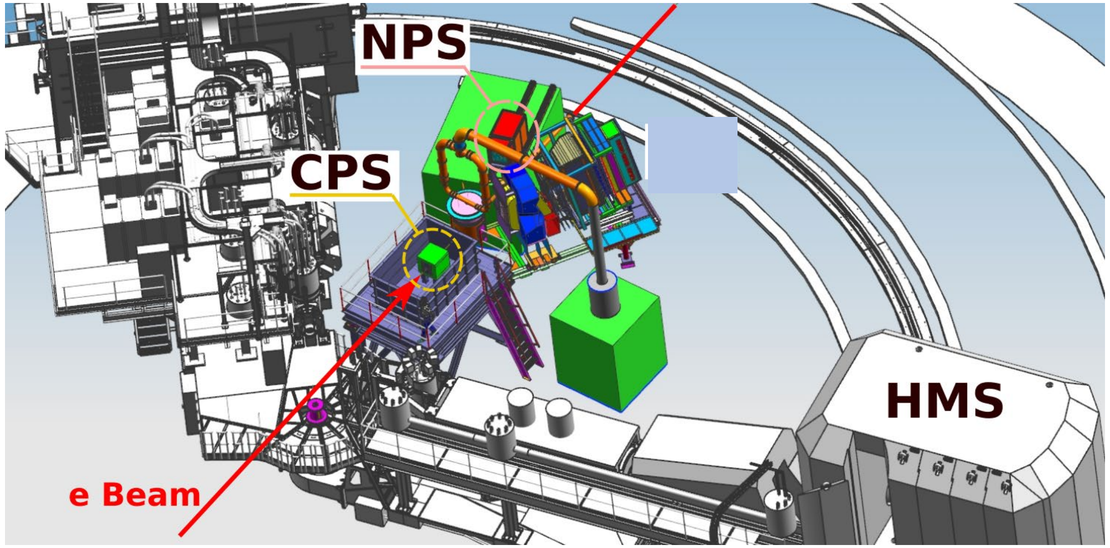
More info in the NPS Wiki: https://wiki.jlab.org/cuawiki/index.php/Main_Page

NPS in Hall C - Overview

Got ideas for experiments – join our meetings!

- ❑ Neutral Particle Spectrometer replaces one of the Hall C focusing spectrometers in the experiments
  - ➢ Angle reach between 5.5 and 60 degrees
  - ➢ allows for precision (coincidence) cross section measurements of neutral particles (γ and π^0).
- ❑ HMS (existing 6 GeV era)
  - ➢ Has been recommissioned for 12 GeV
- ❑ Beam line and beam line instrumentation
- ❑ Cryogenic liquid hydrogen and solid targets
- ❑ Data acquisition, counting house, computing





More in Jefferson Lab Hall C: Precision Physics at the Luminosity Frontier (Hall C White Paper); D. Mack et al. arXiv 2209.11838

NPS Science Program

- The NPS Science program currently includes 10 approved experiments divided into two run groups. The first phase (run group 1) is scheduled for running in 2023/24.

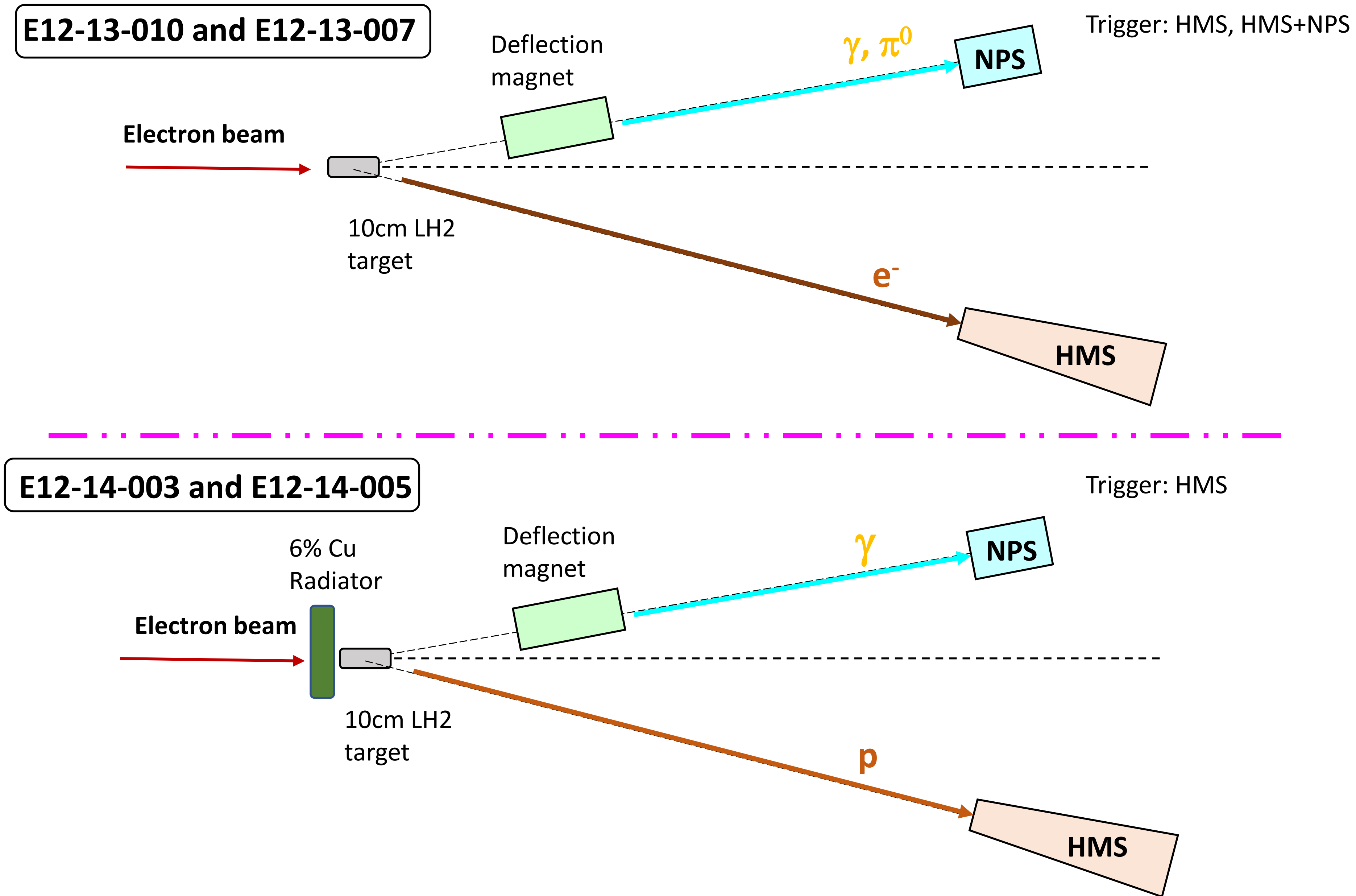
Experiment Number	Title	Beam	Target	Run Group	PAC Days	Rating
E12-13-010	DVCS and exclusive π^0	$\vec{e}^-$	LH_2	1	53	A
E12-13-007	SIDIS π^0	$\vec{e}^-$	LH_2	1	(26)	A-
E12-06-114 (days moved to Hall C)	*Measurements of the electron-helicity dependent cross-sections DVCS*	$\vec{e}^-$	*LH_2*	*1*	*35*	*A*
E12-23-014	Measurement of R in SIDIS π^0	$\vec{e}^-$	LH_2, LD_2	1	7	A-
E12-14-003	Wide-Angle Compton scattering (WACS)	e^-,γ	LH_2	2		A-
E12-14-005	Wide-Angle Exclusive π^0 photoproduction	e^-,γ	LH_2	2		B
E12-22-006	DVCS off the neutron with the NPS	$\vec{e}^-$	LD_2	1	44	A
E12-17-008	Polarization observables in WACS at high s, t, u	CPS: γ	$N\vec{H}_3$			A-
E12-23-006 (C1)	DVCS using positron beam in Hall C	e^+	LH_2		77	A-
E12-23-004	Search for nonzero strange proton FF	$\vec{e}^-$	LH_2		45	A-

ERR 2019

- Two new LOIs submitted to PAC51 (LOI-12-23-003, LOI-12-23-014)
- A proposal on Time-like Compton Scattering off transversely polarized proton is in preparation – previously submitted as C12-18-005

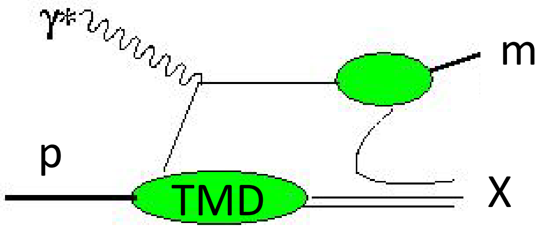
Experimental Techniques

The Neutral Particle Spectrometer (NPS) is a new facility in Hall C. Utilizing the well-understood HMS/SHMS infrastructure, it allows for **precision (coincidence) cross section measurements of neutral particles (γ and π^0).**



E12-13-007 – SIDIS basic (e,e'π^0) cross sections

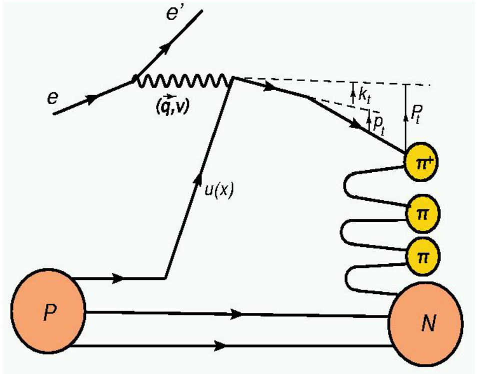
Linked to framework of *Transverse Momentum Dependent Parton Distributions*



$TMD^q(x,k_T)$

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

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



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

E12-13-007 goal: Measure the basic SIDIS cross sections of π^o production off the proton, including a map of the P_T dependence ($P_T \sim \Lambda < 0.5$ GeV), to validate(*) flavor decomposition and the k_T dependence of (unpolarized) up and down quarks

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

Requires new ~25 msr Neutral-Particle Spectrometer

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

- Many experimental and theoretical advantages to validate understanding of SIDIS with neutral pions
- Can verify: $\sigma^{\pi^0}(x,z) = ½ (\sigma^{\pi^+}(x,z) + \sigma^{\pi^-}(x,z))$
- Confirms understanding of flavor decomposition/k_T dependence

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

E12-13-010: precision DVCS/π^0 cross sections

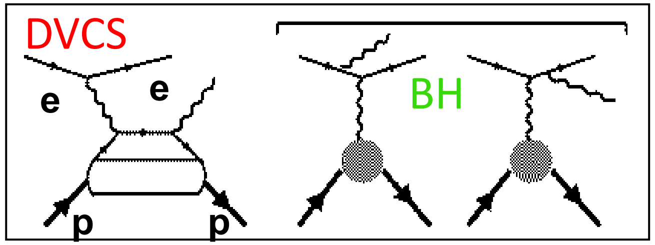
Simplest process: **e + p → e' + p + γ (DVCS)**

E12-13-010 DVCS measurements follow up on measurements in Hall A:

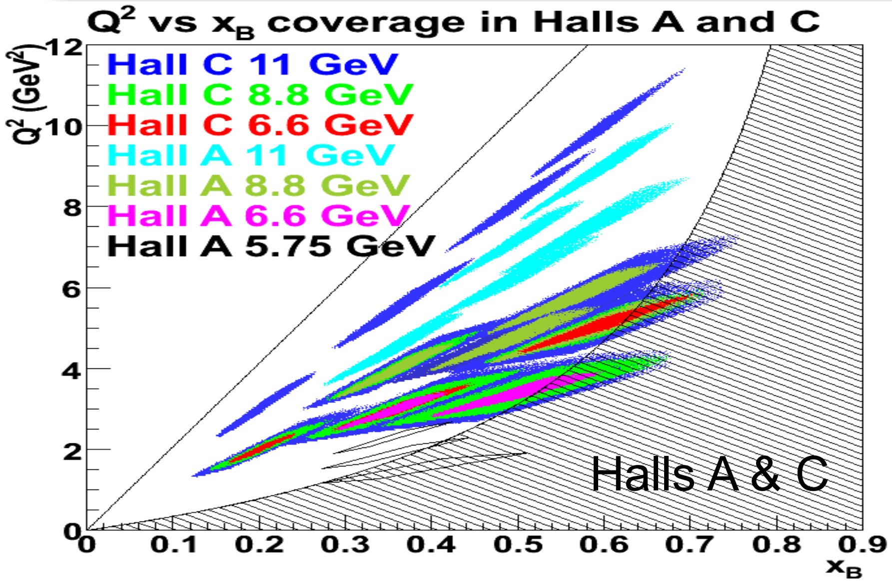
- Scaling of the Compton Form Factor
- Rosenbluth-like separation of DVCS:

$$\sigma = |BH|^2 + \mathrm{Re}\left[DVCS^{\perp}\ BH\right] + |DVCS|^2$$
$$\sim E^2_{beam} \qquad \sim E^3_{beam}$$

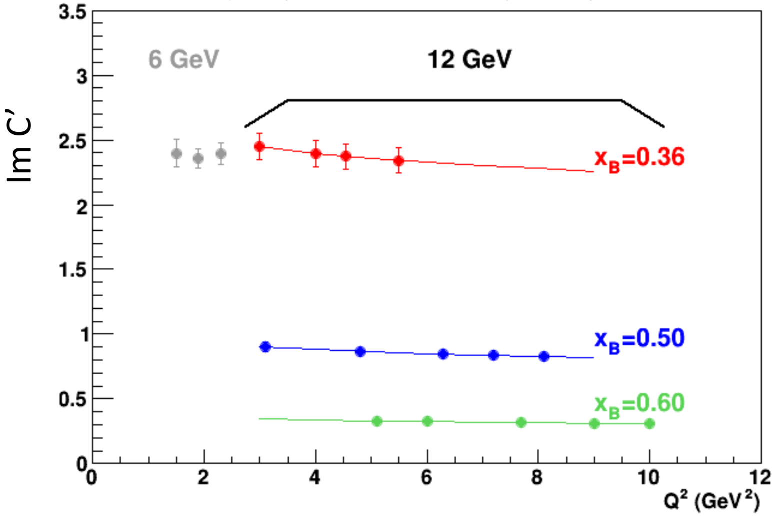
- L/T separation of π^0 production



Hall A data for Compton form factor (over *limited* Q^2 range) agree with hard-scattering

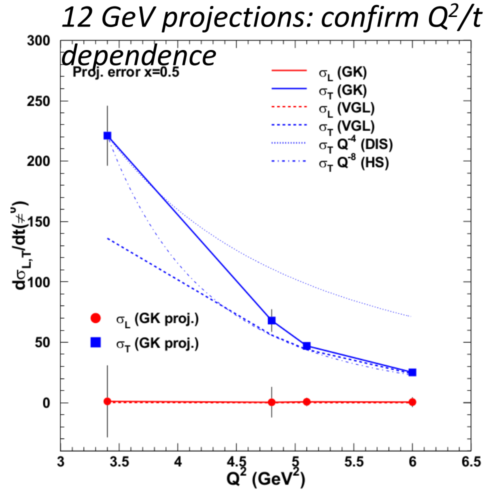


12 GeV projections: confirm formalism



π^0 Exclusive Cross Sections

- Relative L/T contribution to π^0 cross section important in probing transversity
- Results from Hall A at 6 GeV Jlab suggest that the longitudinal cross section in π^0 production is non-zero up to Q^2=2 GeV^2

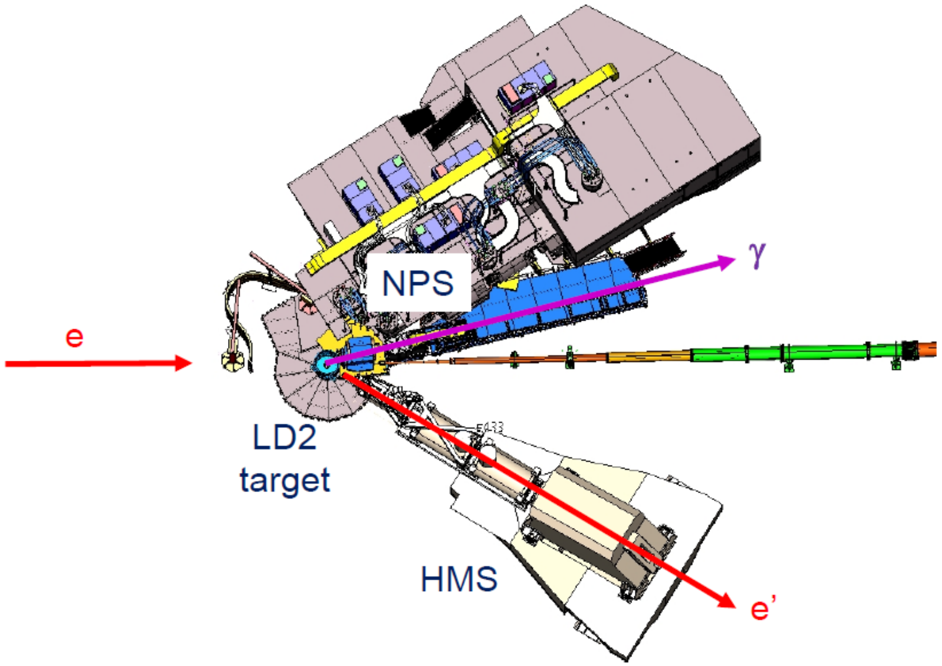


E12-13-010 provides also data on σ_T and σ_L at higher Q^2 for reliable interpretation of 12 GeV GPD data

Extracting the real part of CFFs from DVCS requires measuring the cross section at multiple beam energies (DVCS^2–Interference separation)

E12-22-006: DVCS off the Neutron

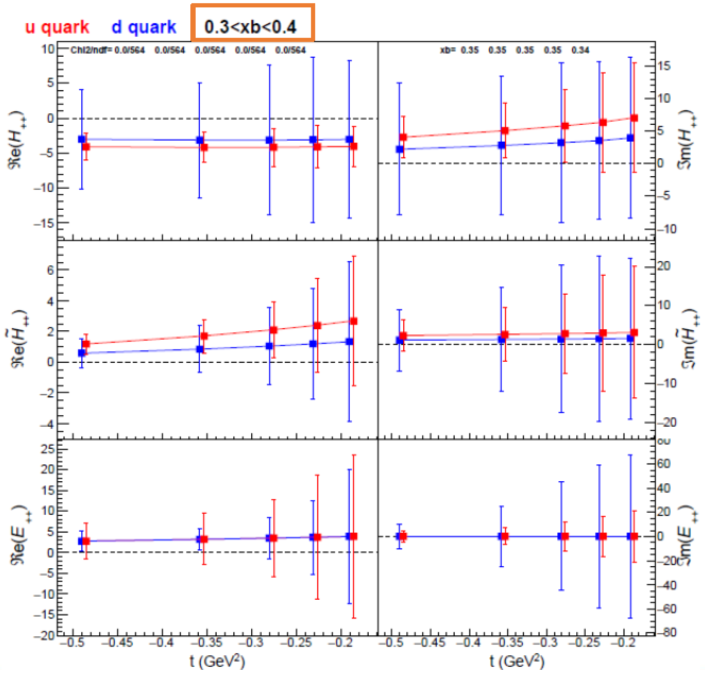
Probe flavor dependence of GPDs with precision nDVCS cross sections
Measurement of the $N \to e'\gamma X$ reaction (N=p, n, d) using an LD_2 target in Hall C

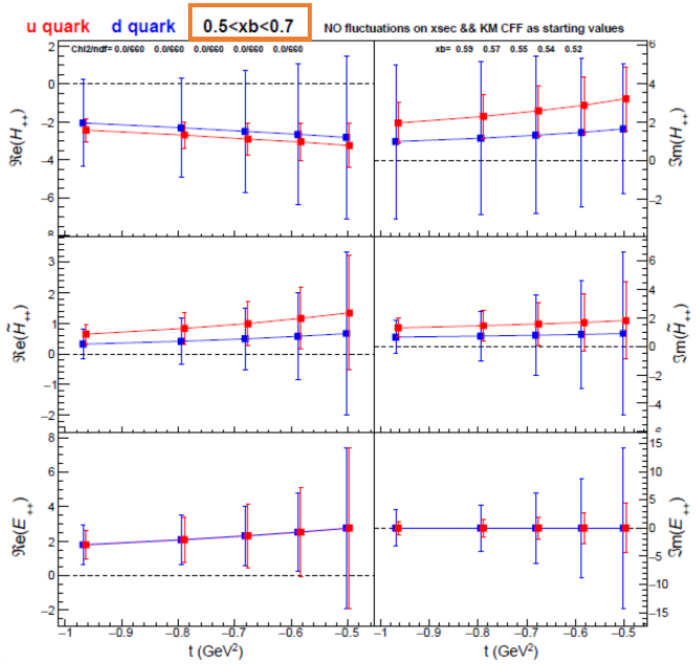


With NPS and HMS in Hall C reach ~x2-12 better nDVCS & dDVCS separation than previous 6 GeV experiment

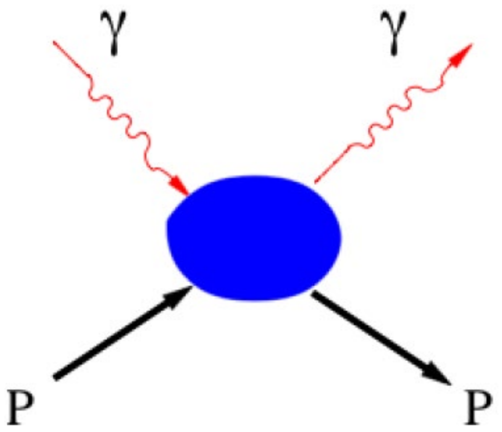
Projected Impact on flavor dependence of CFFs

- *Simultaneous fit of E12-13-010 (p) and E12-22-006 (n)*
- *Real and imaginary parts of CFFs H and $\widetilde{H}$ and E (u & d) as free parameters (nDVCS not sensitive to $\tilde{E}$)*

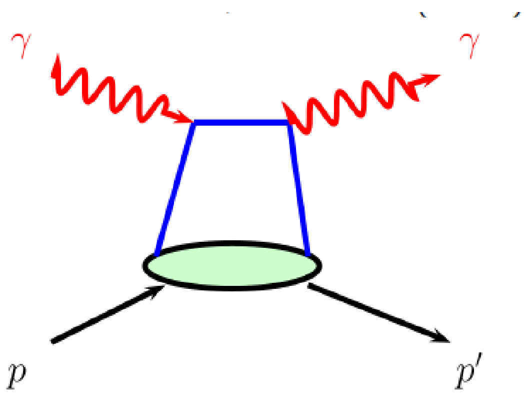




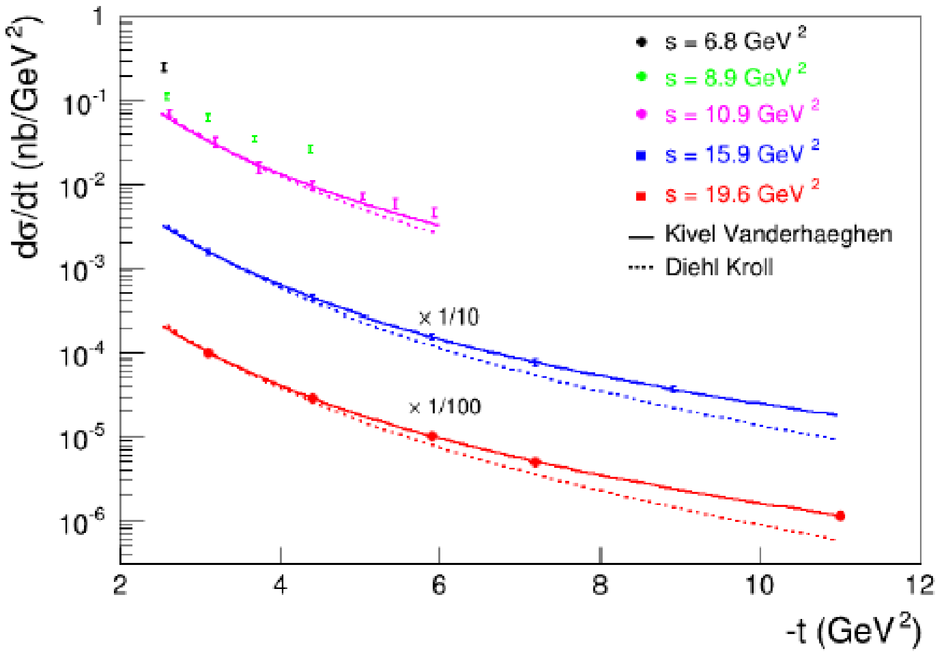
E12-14-003: Wide Angle Compton Scattering



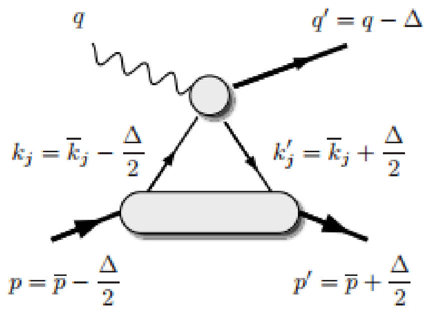
- ❑ Arguably the least understood of the fundamental reactions in the several-GeV regime
- ❑ Wide-Angle Compton Scattering cross section behavior was a foundation leading to the GPD formalism
- ❑ Reaction mechanism intrinsically intertwined with basics of hard scattering process (handbag diagram), yet also sensitivity to transverse structure like high-Q^2 form factors



- ➢ Perhaps (6-GeV data) factorization valid for *s, -t, -u > 2.5 GeV*^{2}
- ➢ 12-GeV data for *–u > 2.5* and *–t* up to *~ 10, s* up to *~ 20* GeV^2



E12-14-005: Wide angle exclusive photo-production of π^0 mesons

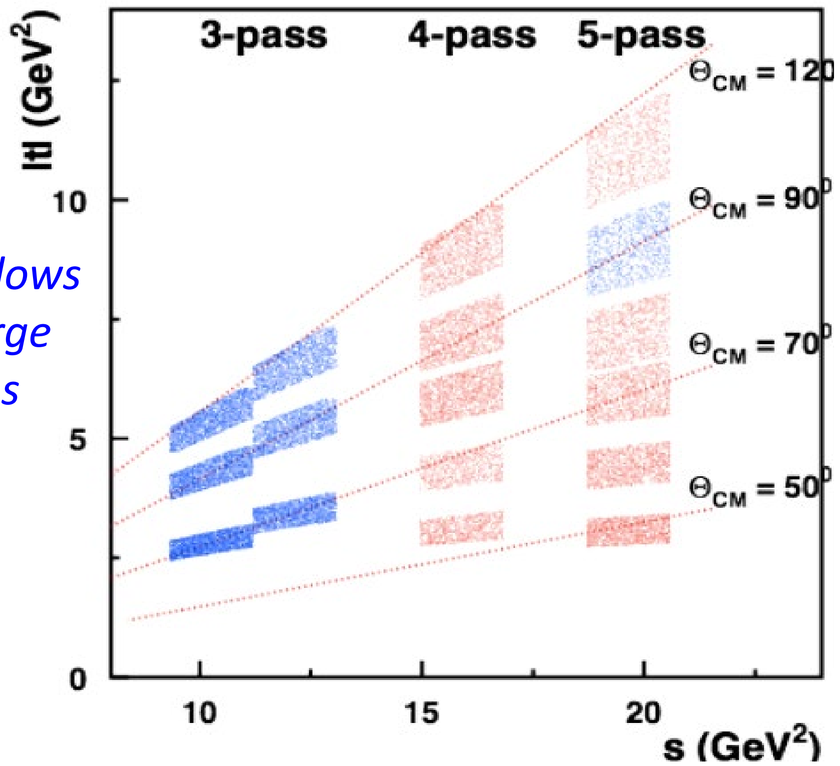


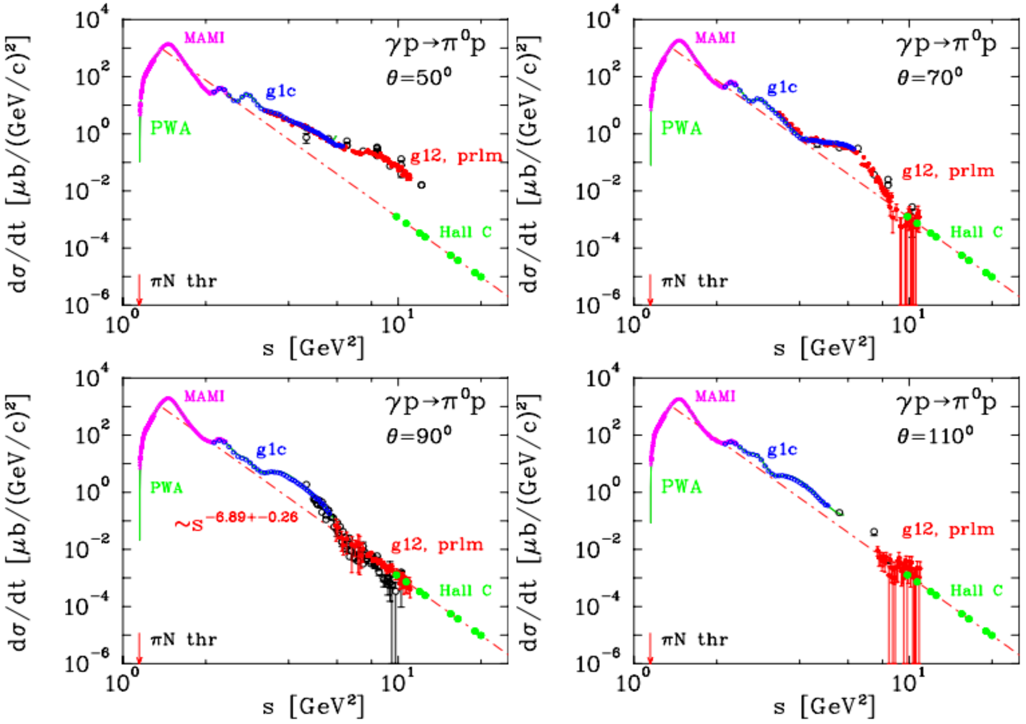
The next simplest reaction after Compton scattering.

But model prediction disagree with data by orders of magnitude!

E12-14-005 projections

Using the NPS allows for covering a large range in |t| and s

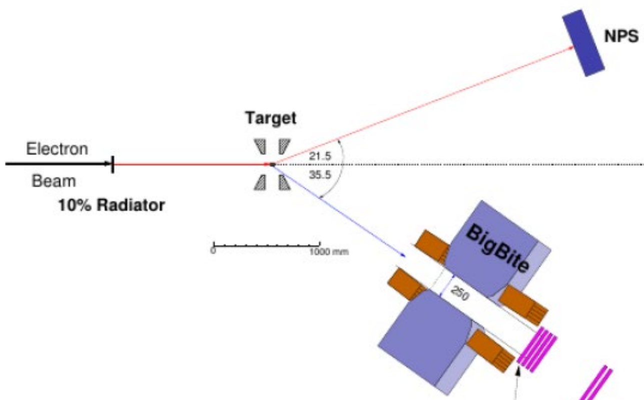


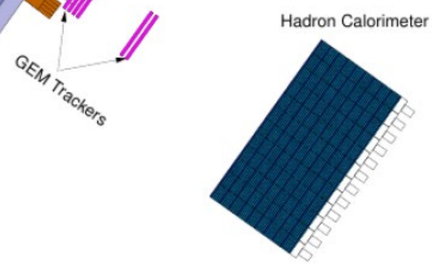


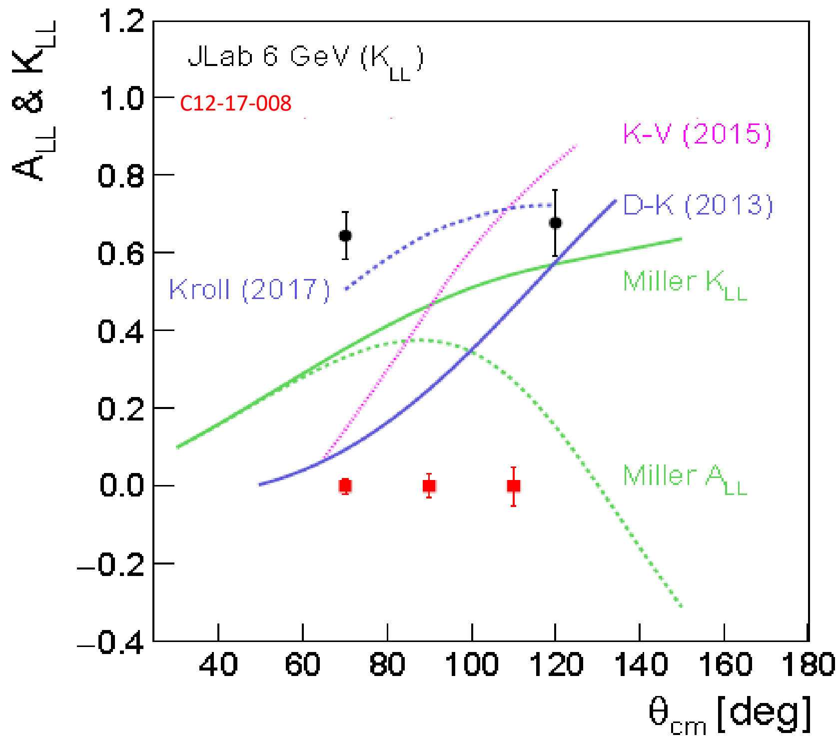
NPS data will help confirm scaling and provide wide angular coverage for testing models based on the dominance of handbag mechanism. Also help extract Regge trajectories.

E12-17-008: Polarization Observables in WACS

Versatility – combine NPS with other equipment in Hall C







Combining NPS with CPS and BigBite gives a considerably improved Figure-of-Merit over all previous experiments and opens up a new range of polarized physics opportunities at Lab

- ❑ Make an explicit, model-independent test of factorization by measuring the s-dependence of the polarization observables at fixed centre of mass angle, t, and verify that target mass corrections and higher twist effects are small
- ❑ Measurement of A_{LL} at large angles allowed for tests of relevant degrees of freedom in hard exclusive reactions
- ❑ Also extract the Axial and Pauli form factors - constrain GPDs $\widetilde{H}$ and E at high –t

More on CPS design: A Conceptual Design Study of a CPS for Jefferson Lab; D. Day et al., Nucl. Instrum. Meth. A 957 (2020) 163429

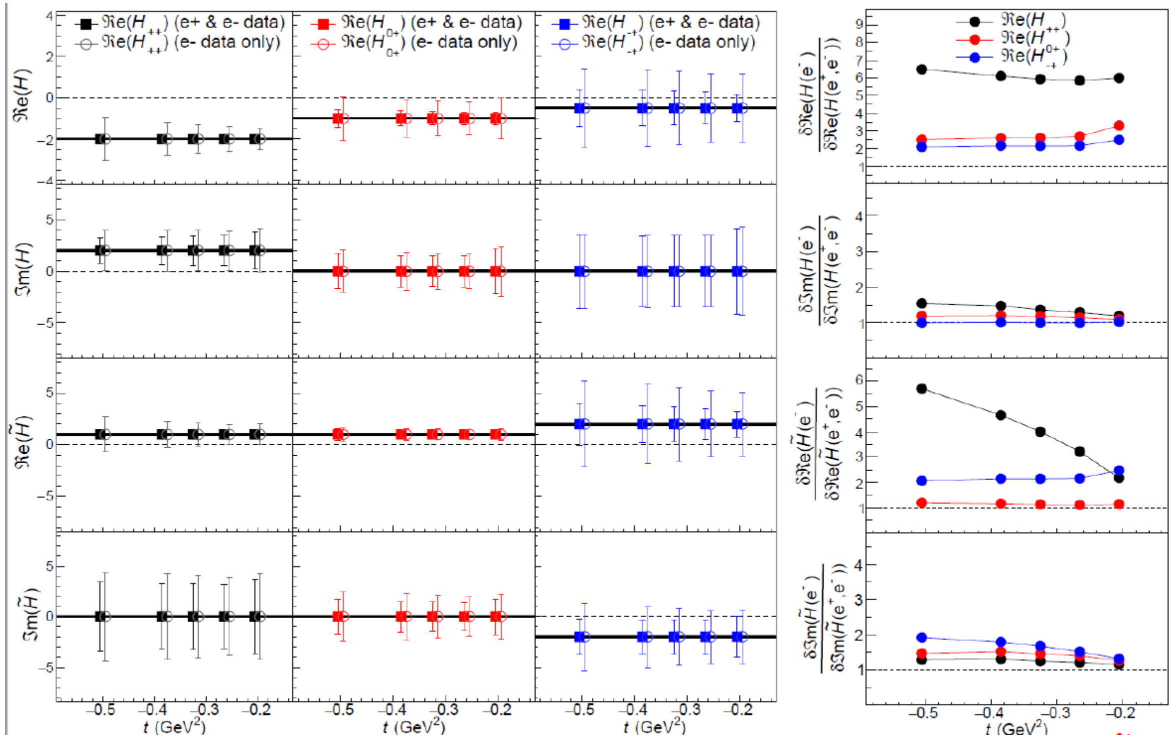
E12-23-006: DVCS using a positron beam in HC

Versatility – combine NPS and a positron beam in Hall C

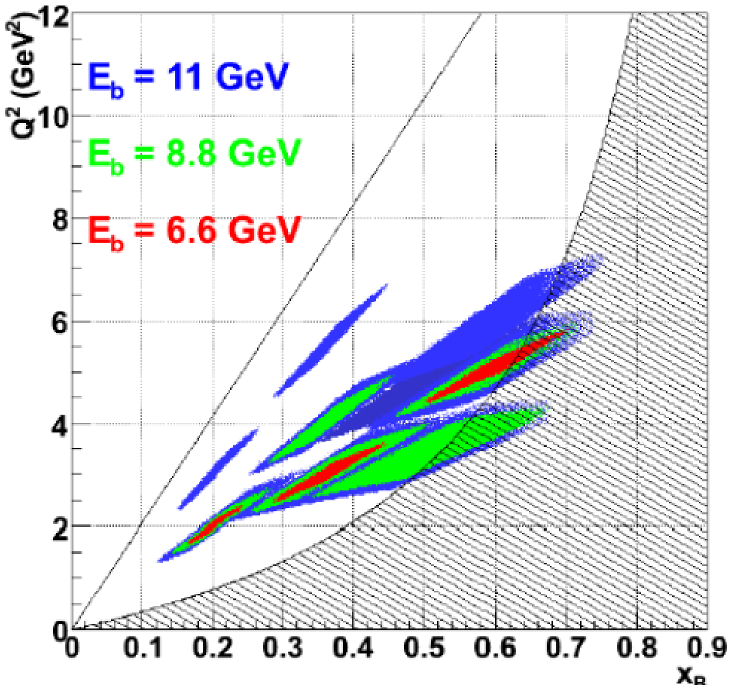
$$|\mathcal{T}(\pm ep \to \pm ep\gamma)|^2 = |\mathcal{T}^{BH}|^2 + |\mathcal{T}^{DVCS}|^2 \mp \mathcal{I}$$

Opposite sign for e- & e+

Impact on Compton Form Factors (CFFs) extraction



A factor of 4-6 improvement in the extraction of LO/LT CFFs Re(H) and Re($\widetilde{H}$), factor of ~2 for HT/NLO

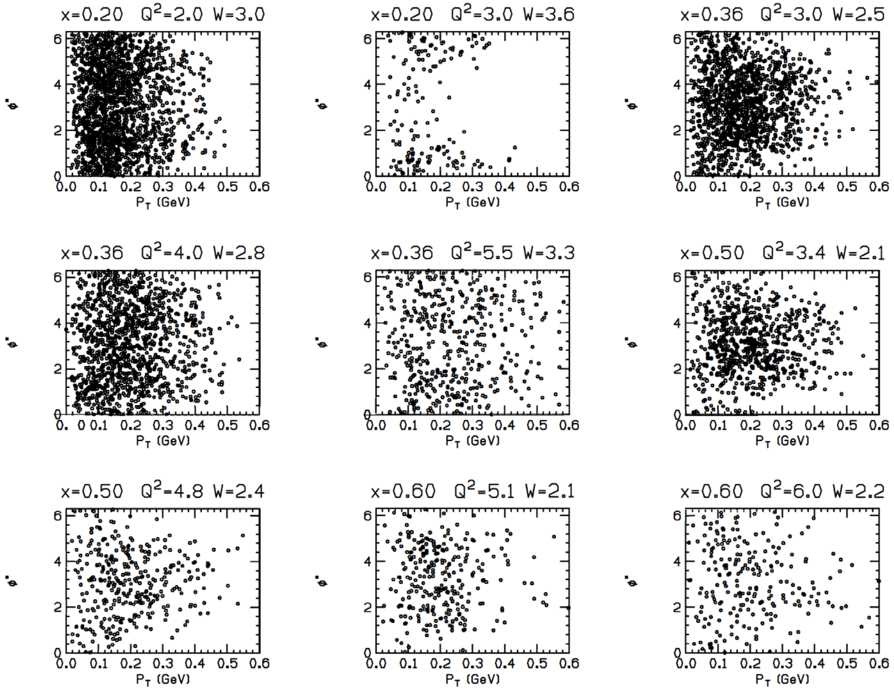


Physics Goals and motivation:

- Precise determination of the absolute photon electroproduction cross section
- Clean model-independent separation of DVCS^2 and DVCS-BH interference
- More stringent constraints on CFFs by combining e^+/e^- data

PR12-23-014: SIDIS basic $(e,e'\pi^0)$ cross sections

Angles for which NPS has good acceptance in (z,p_T)

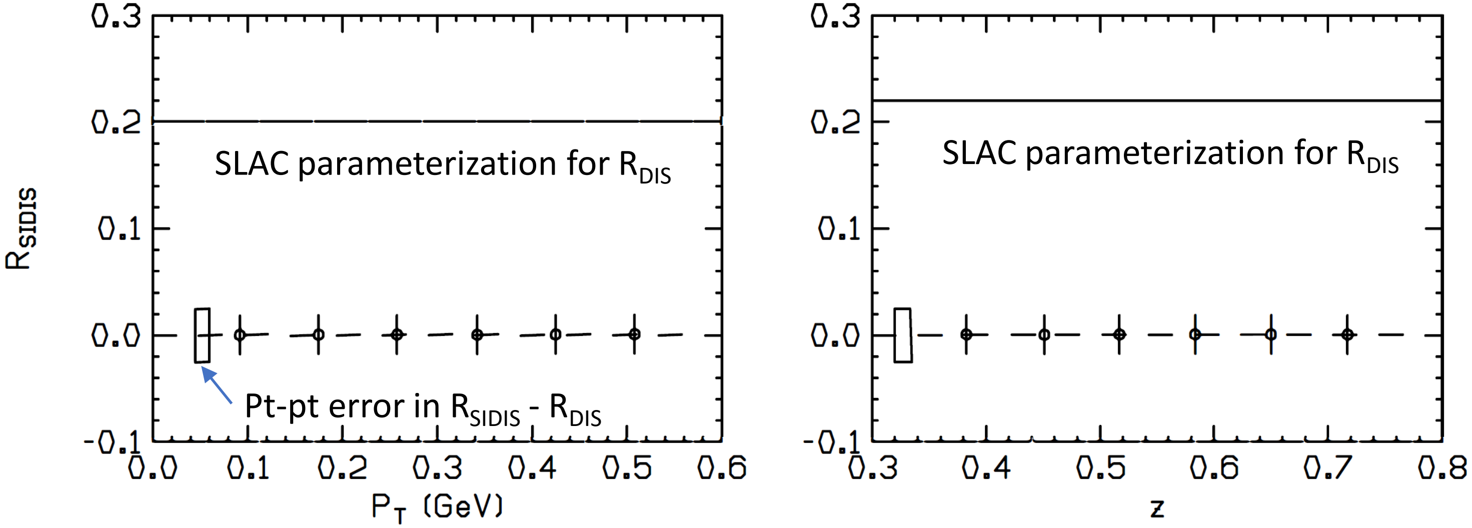


Set	x	Q^2	W	E	ϵ	E'	θ_e	θ_π	d	I	D_p	D_d
		GeV^2	GeV	GeV		GeV	deg	deg	m	μA	day	day
Ib	0.20	2.0	3.0	8.5	0.64	3.17	15.7	8.9	4	50	0.1	0.1
IIIa	0.36	3.0	2.5	6.4	0.51	1.96	28.3	11.2	3	28	0.1	0.1
IVb	0.36	4.0	2.8	8.5	0.52	2.58	24.7	9.9	4	40	0.1	0.1
V	0.36	5.5	3.3	10.6	0.41	2.46	26.6	7.5	4	40	0.3	0.3
VIIIa	0.60	5.1	2.1	6.4	0.46	1.87	38.1	13.2	3	28	0.3	0.3
VIa	0.50	3.4	2.1	6.4	0.67	2.78	25.3	16.9	6	28	0.1	0.1

Run Group addition approved at PAC51 (P. Bosted, E. Kinney, H. Mkrtchyan, V. Tadevosyan, R. Ent, T. Horn, et al.)

Measure $R_{LT} = \sigma_L/\sigma_T$, the ratios of d/u cross sections, the transverse momentum dependence of the cross section, and the spin-independent and beam-spin-dependant modulations of the cross section

Projections for R_{LT} SIDIS as function of p_T and z

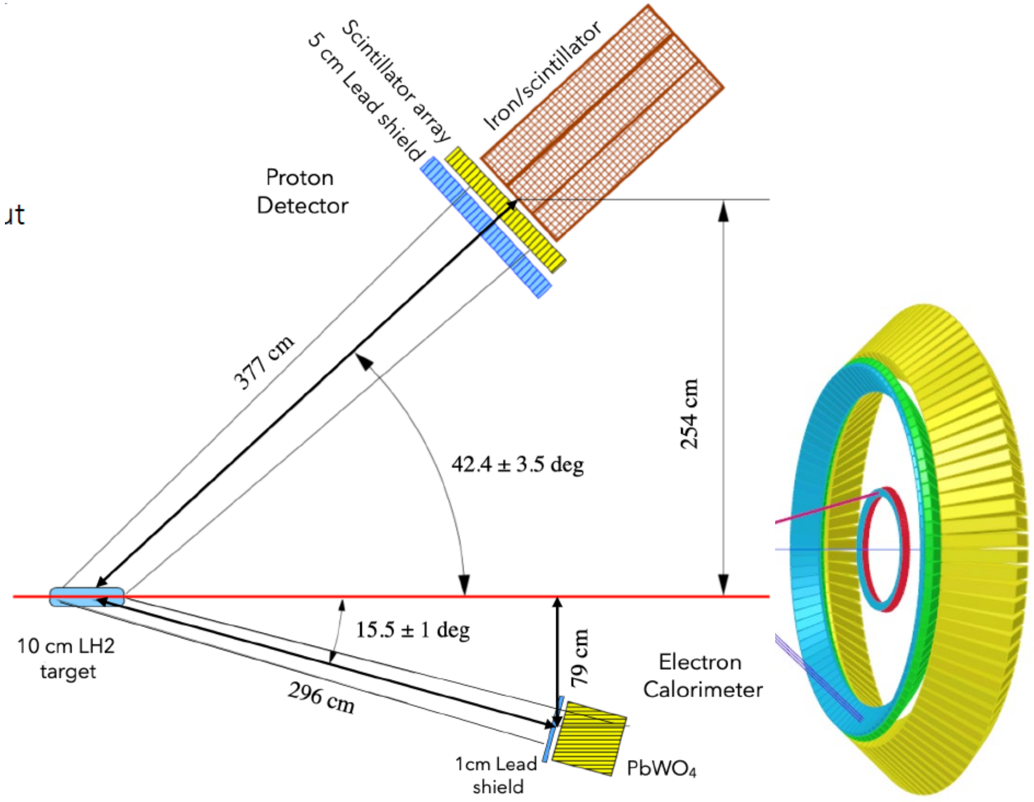


Physics goals are driven by the need to more fully understand the production processes that enter SIDIS for better understanding of the 3D nucleon structure

- Dynamic and target higher twist, deep-exclusive processes, VM, CSV

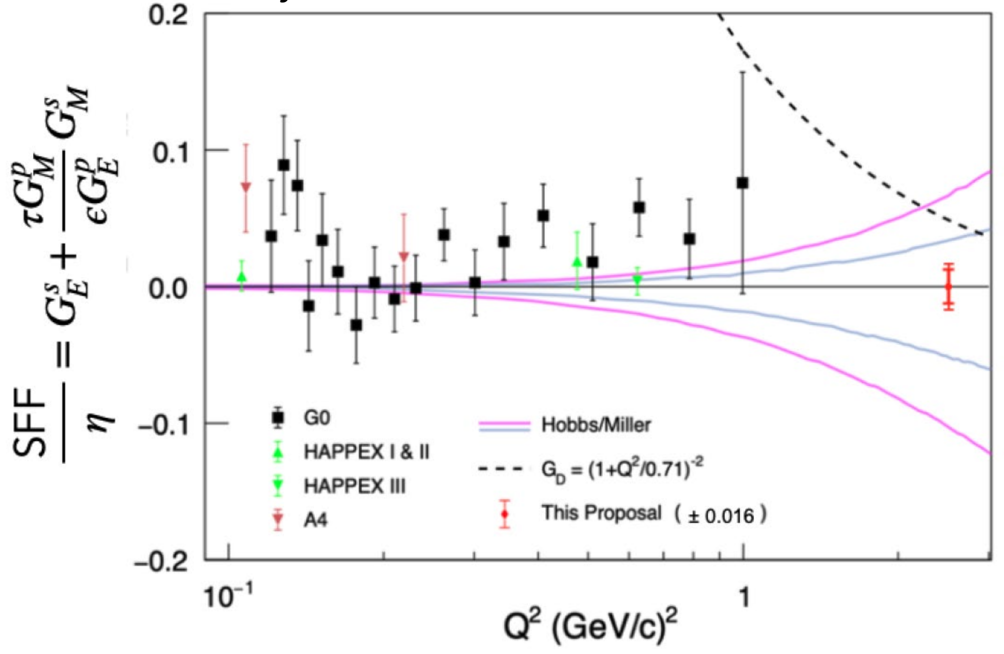
New Physics with NPS: Search for a Nonzero G_S at 2.5 GeV^2

Versatility – NPS as precision EMCal – reconfigure and use with other equipment in Hall C



Measure the PVA for elastic e-p using a highly segmented NPS-type EMCal as electron arm and an iron-scintillator-based HCal as proton arm in coincidence mode

Projections



New proposal approved at PAC51 (B. Wojtsekhowski, C. Palatchi, K. Paschke, et al.)

Science questions:

- How large is the contribution of $s\bar{s}$ quark pairs to the hadron current at x_B=1
- Is the lattice prediction of the almost zero values of G_S consistent with experiment

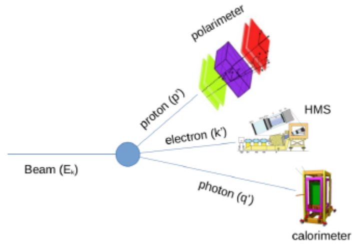
New Physics with NPS: New DVCS Observables

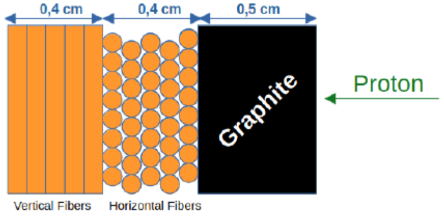
Versatility – NPS as precision EMCal – reconfigure and use with other equipment in Hall C

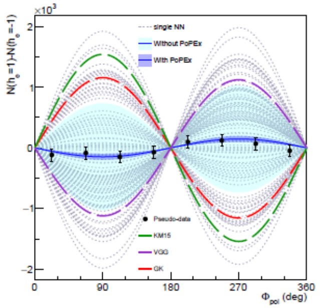
New DVCS observable: the recoil proton polarization

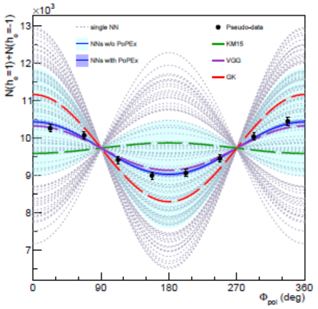
- Can only be done at JLab with NPS,
- Simultaneous access to E and $\widetilde{H}$ through the two transverse polarization of the recoil proton,
- Large polarimeter on the ground made of Scintillating Fibers.
- π^0-electroproduction done simultaneously.
- More details in LOI 12-23-014.

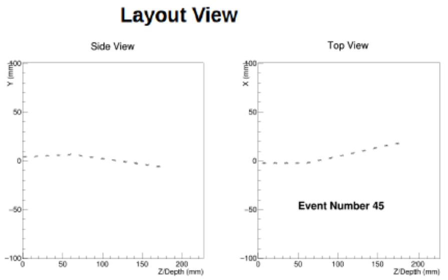
Bessidskaia Bylund *et al.*, Phys. Rev. D 107, 014020





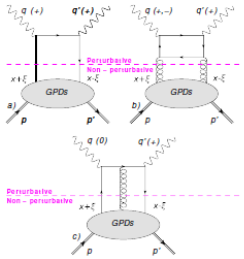


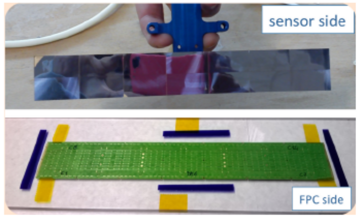




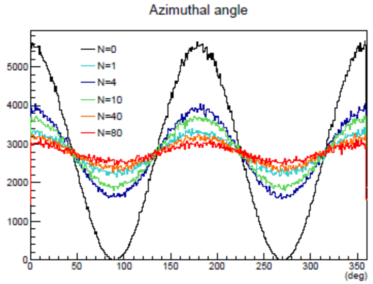
New DVCS observable: Linear polarization of DVCS photon

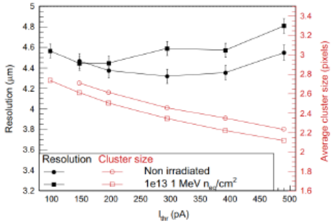
- Can only be done at JLab with NPS,
- Direct access to gluon transversity GPDs,
- Pair polarimeter composed of light MAPS planes.
- Figure-of-merit being optimized (anlyzing power vs efficiency).
- May need SBS as electron arm to increase acceptance.
- More details in LOI 12-23-003.





Below, reconstruction of azimuthal angle as lepton pair goes through layers of 0.05% of radiation length spaced by 0.5 mm.



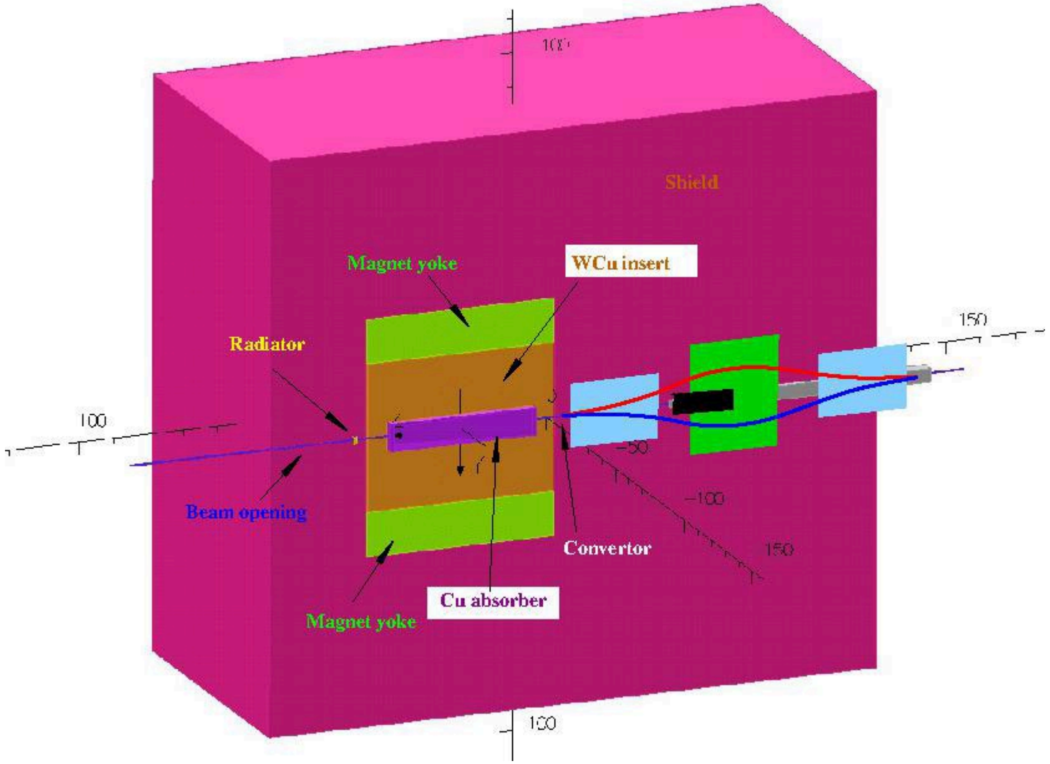


New LOIs to PAC51 (M. Defurne)

Other new physics ideas with NPS

CPS as a positron source

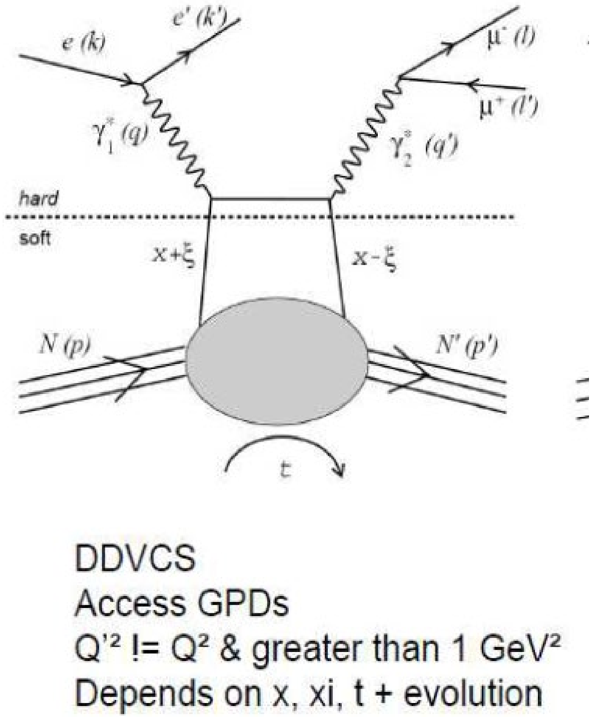
- TPE effects
- Dark photon search



More in Jefferson Lab Hall C: Precision Physics at the Luminosity Frontier (Hall C White Paper); [D. Mack et al. arXiv 2209.11838]

Beyond DVCS and TCS

- DDVCS (access to ERBL region)
- J/Psi on transversely polarized target

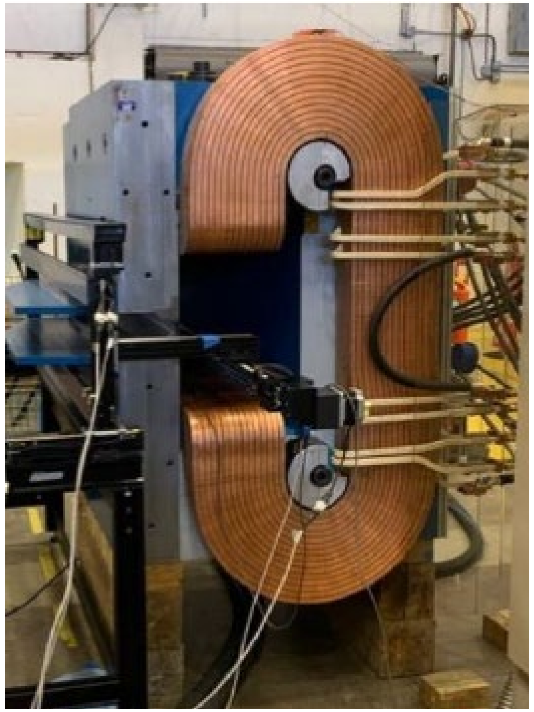


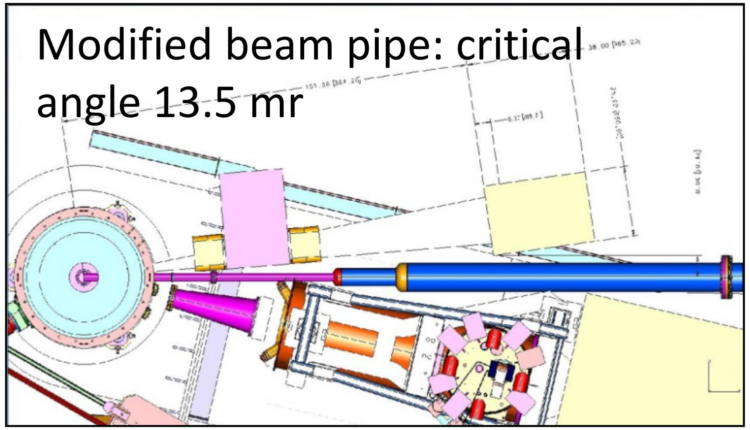
Marie Boer et al. – 2022 NPS Collaboration Meeting

NPS General Design Concept

NSF MRI PHY-1530874

- a ~25 msr neutral particle detector consisting of up to 1116 **$PbWO_4$ crystals** in a temperature-controlled frame including gain monitoring and curing systems
- HV distribution bases with built-in amplifiers for operation in a high-rate environment
- Essentially deadtime-less digitizing electronics to independently sample the entire pulse form for each crystal – JLab-developed Flash ADCs
- A new 0.3Tm sweeping magnet allowing for small-angle and large angle operation at 0.6 TM. The magnet is compatible with existing JLab power supplies.
- Cantelevered platforms off the SHMS carriage to allow for remote rotation (in the small angle range), and platforms to be on the SHMS carriage (in the large angle range)
- A beam pipe with as large critical angle as possible to reduce beamline-associated backgrounds





More on PWO crystal studies: Scintillating Crystals for the NPS in Hall C at JLab; [T. Horn et al., Nucl. Instrum. Meth. A 956 (2020) 163375]

NPS Examples of Preparation Tasks - Complete

Reflector shaping/crystal wrapping

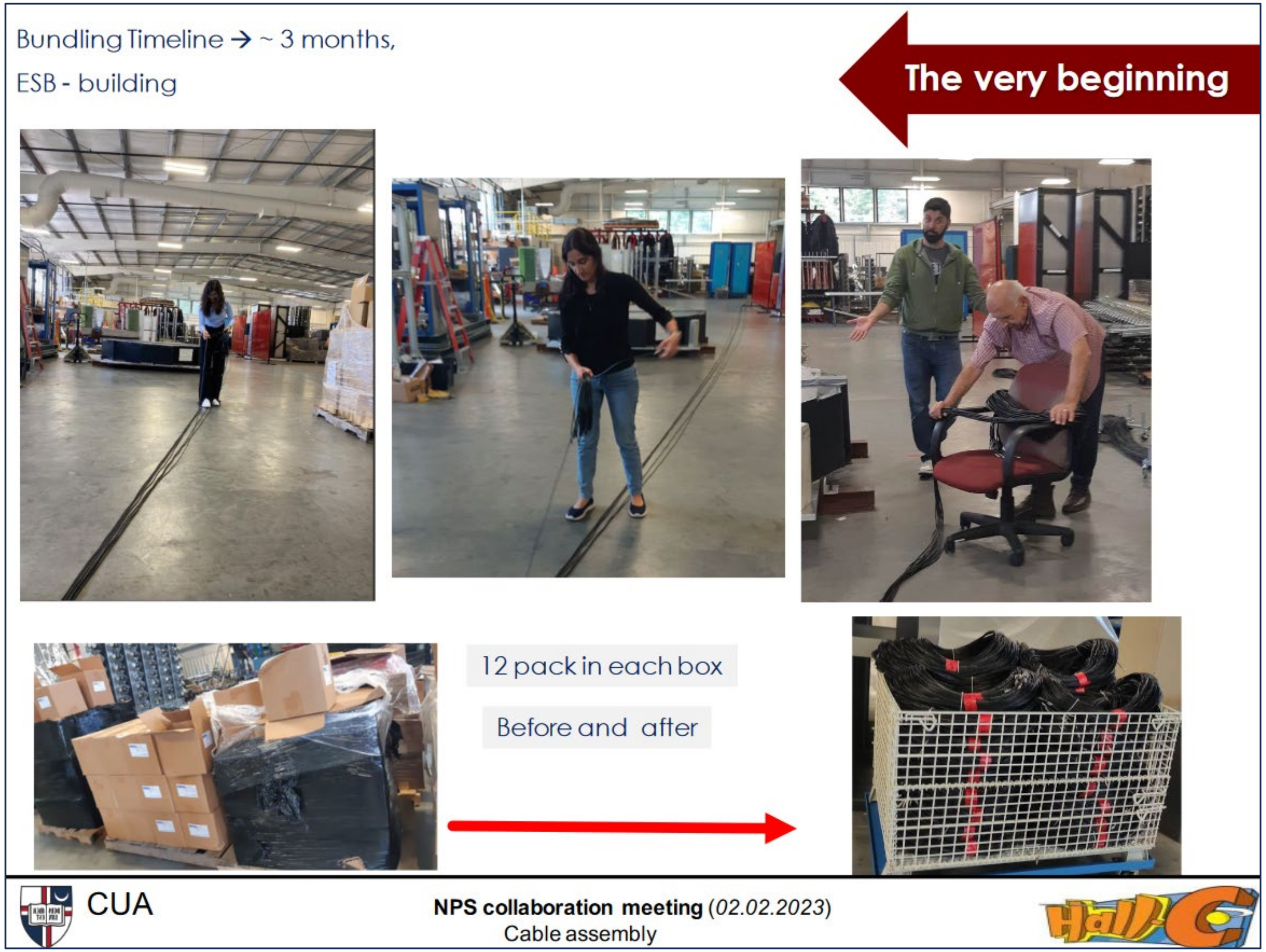
A. ALIKHANYAN National Laboratory

THE CATHOLIC UNIVERSITY OF AMERICA

UIC UNIVERSITY OF ILLINOIS CHICAGO

Jefferson Lab

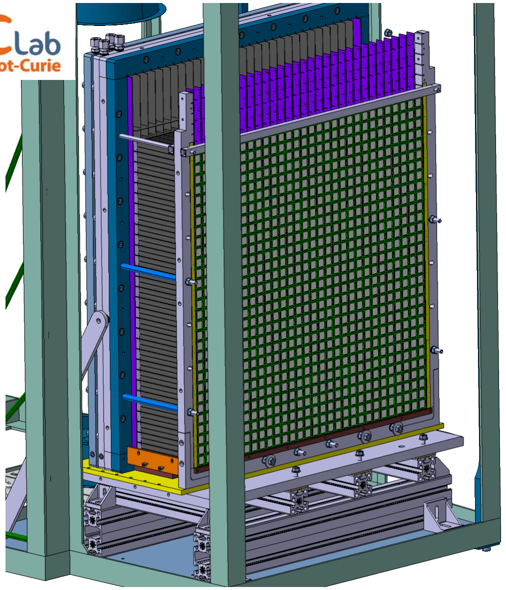
Cable bundling

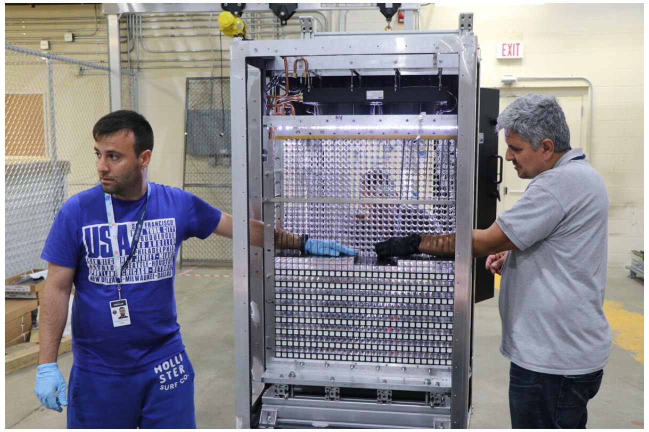


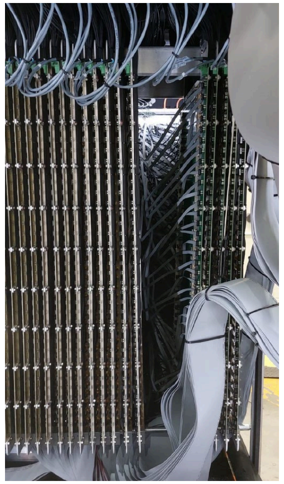
More day-to-day updates: [NPS Logbook]

NPS Assembly in EEL108 - complete

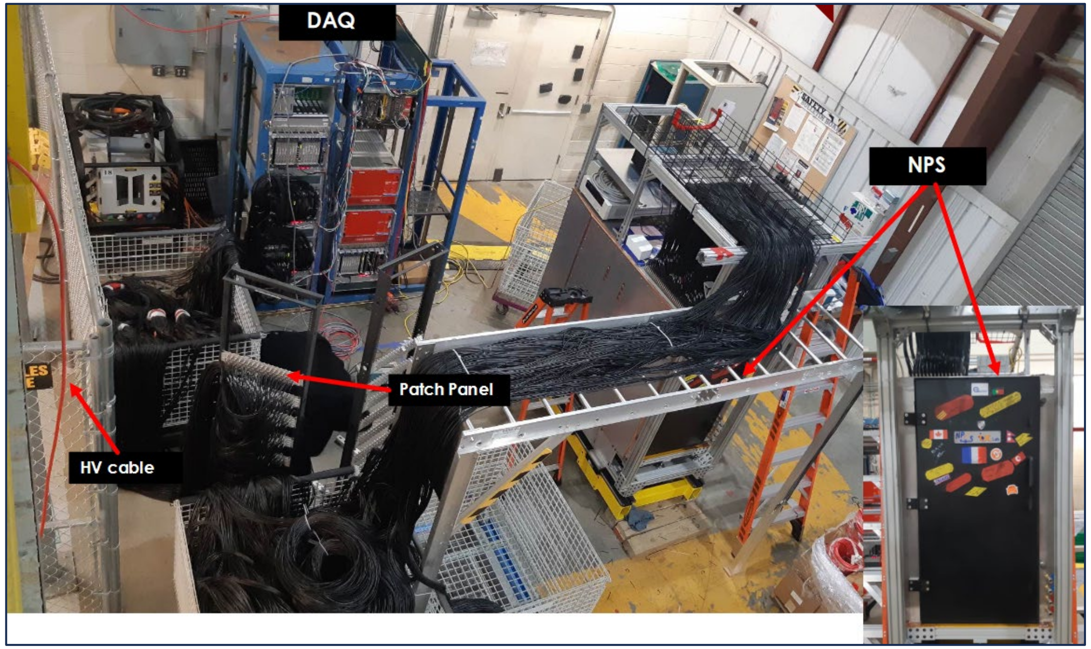
Complex procedure (77+ steps): assemble frame, insert crystals, and PMT+boards, cooling, cable+tests, etc.

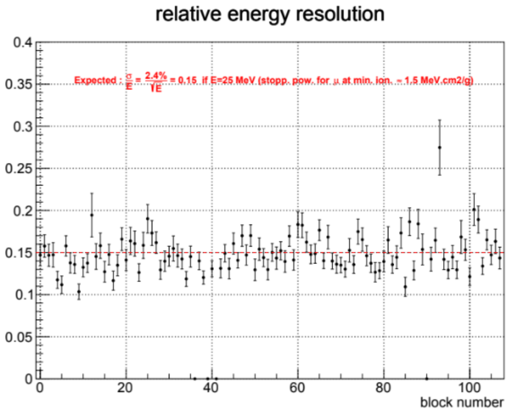


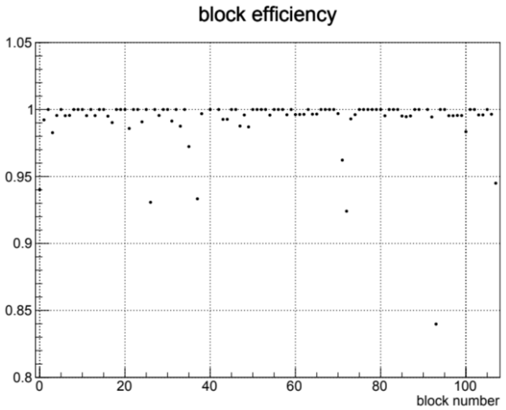




DAQ test setup and cabling for cosmics testing
Tests coordinated by Simona Malace (Hall C)



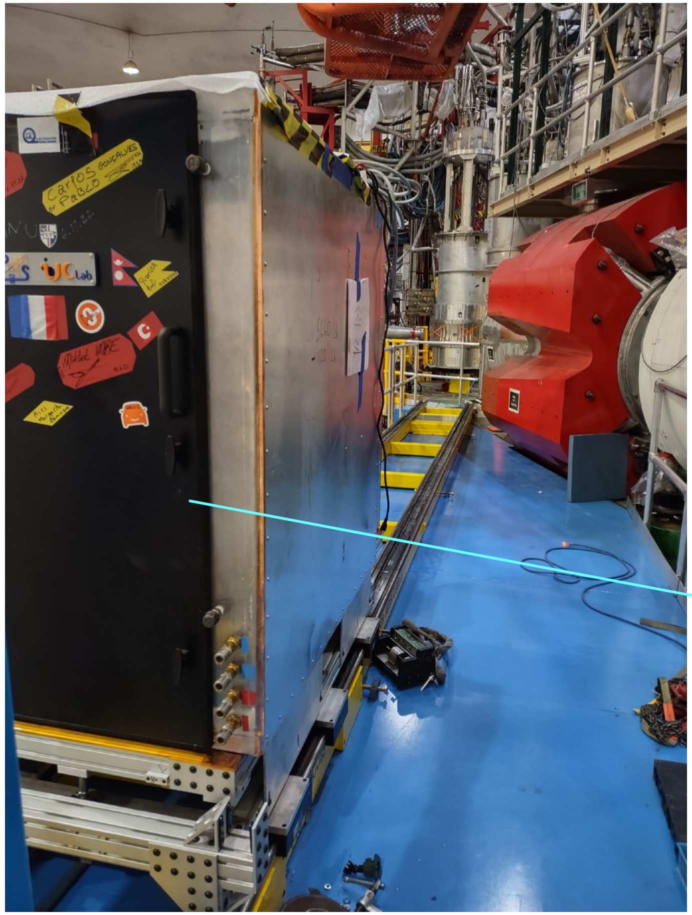


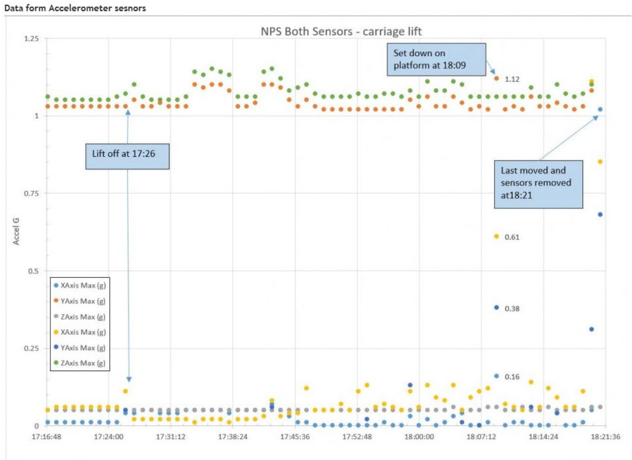


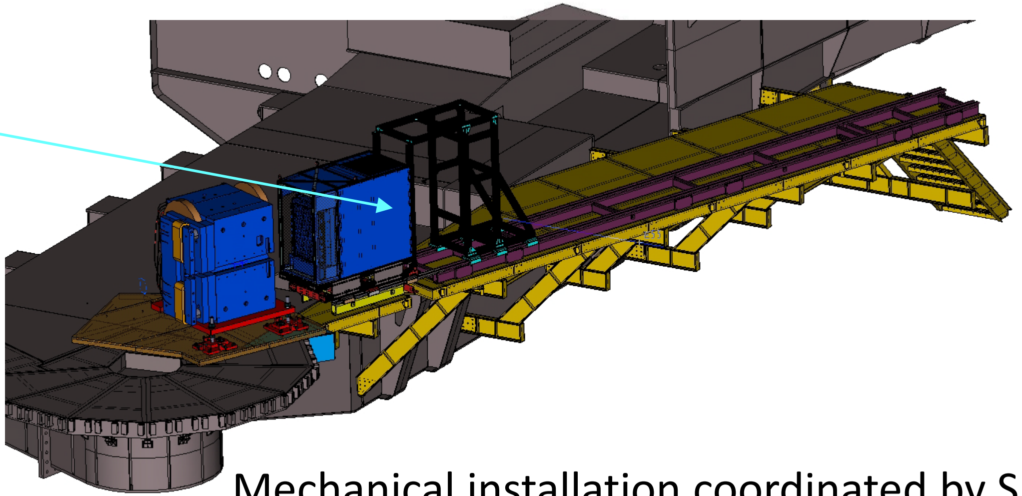
More day-to-day updates: [NPS Logbook]

NPS Status – installation on the SHMS platform

Move the NPS in one piece from EEL108 to Hall C and from floor onto the platform
Many preparation steps completed prior to this – see detailed schedule in NPS Logbook



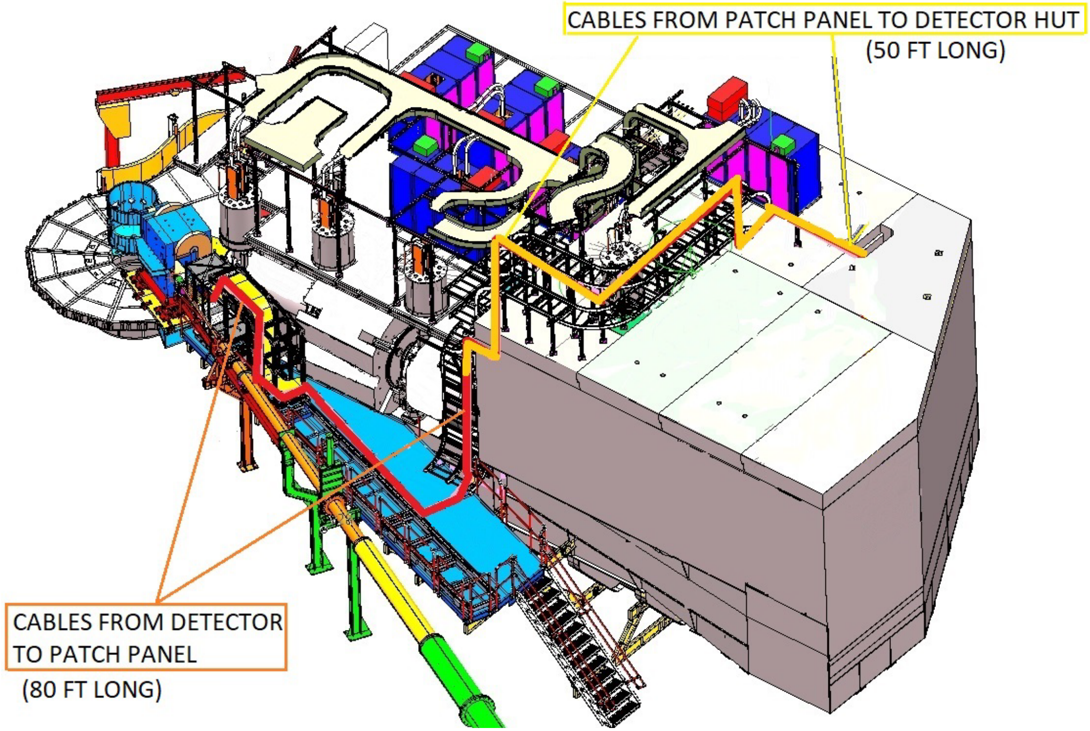


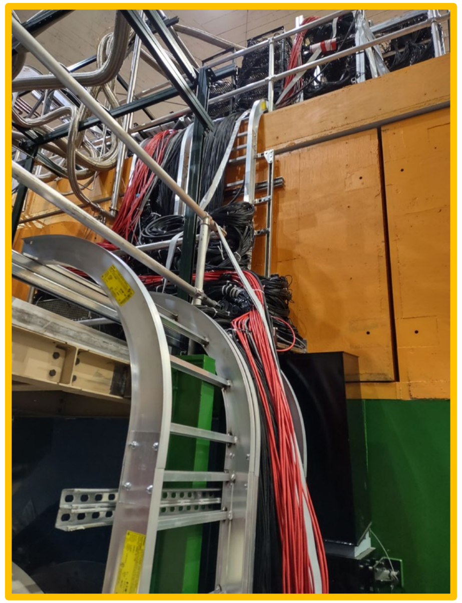


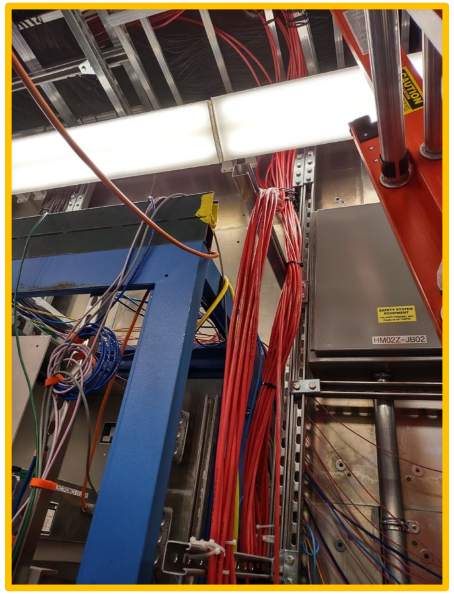
Mechanical installation coordinated by S. Lassiter, W. Kellner, and the Hall C tech team

More day-to-day updates: NPS Logbook

NPS Status – Cabling in Hall C

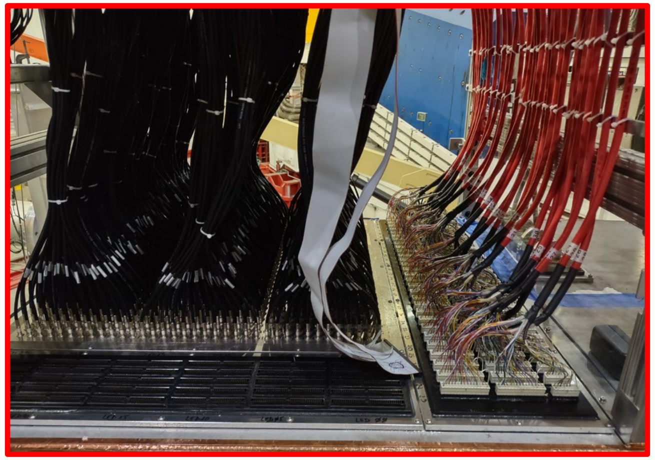






Cables (signal, HV, LV, LED) from patch panel to detector hut

Cables from detector top to patch panel

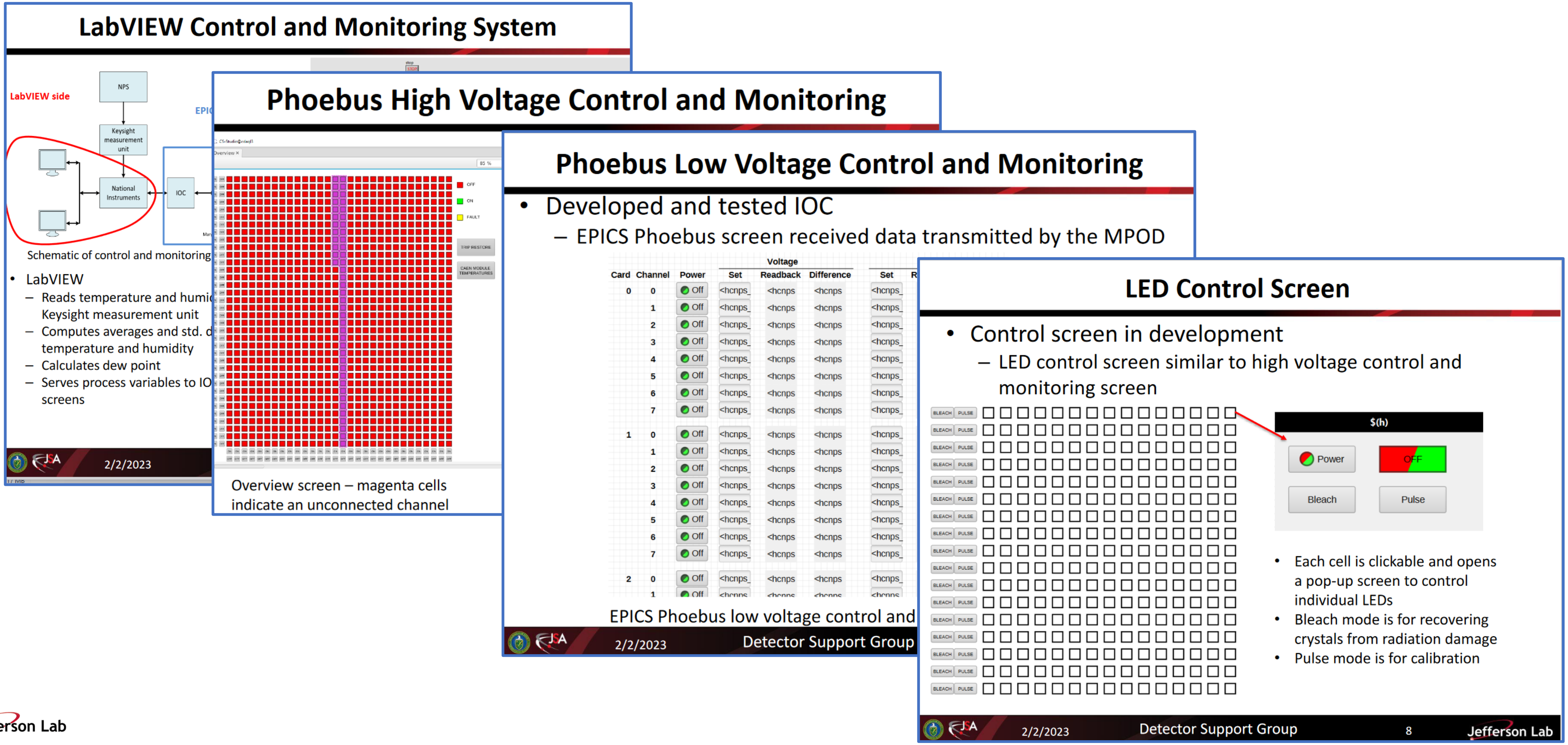


Cabling and testing coordinated by Simona Malace (Hall C)

OLD DOMINION UNIVERSITY · OHIO UNIVERSITY · A. ALIKHANYAN National Laboratory · MISSISSIPPI STATE UNIVERSITY · THE CATHOLIC UNIVERSITY OF AMERICA

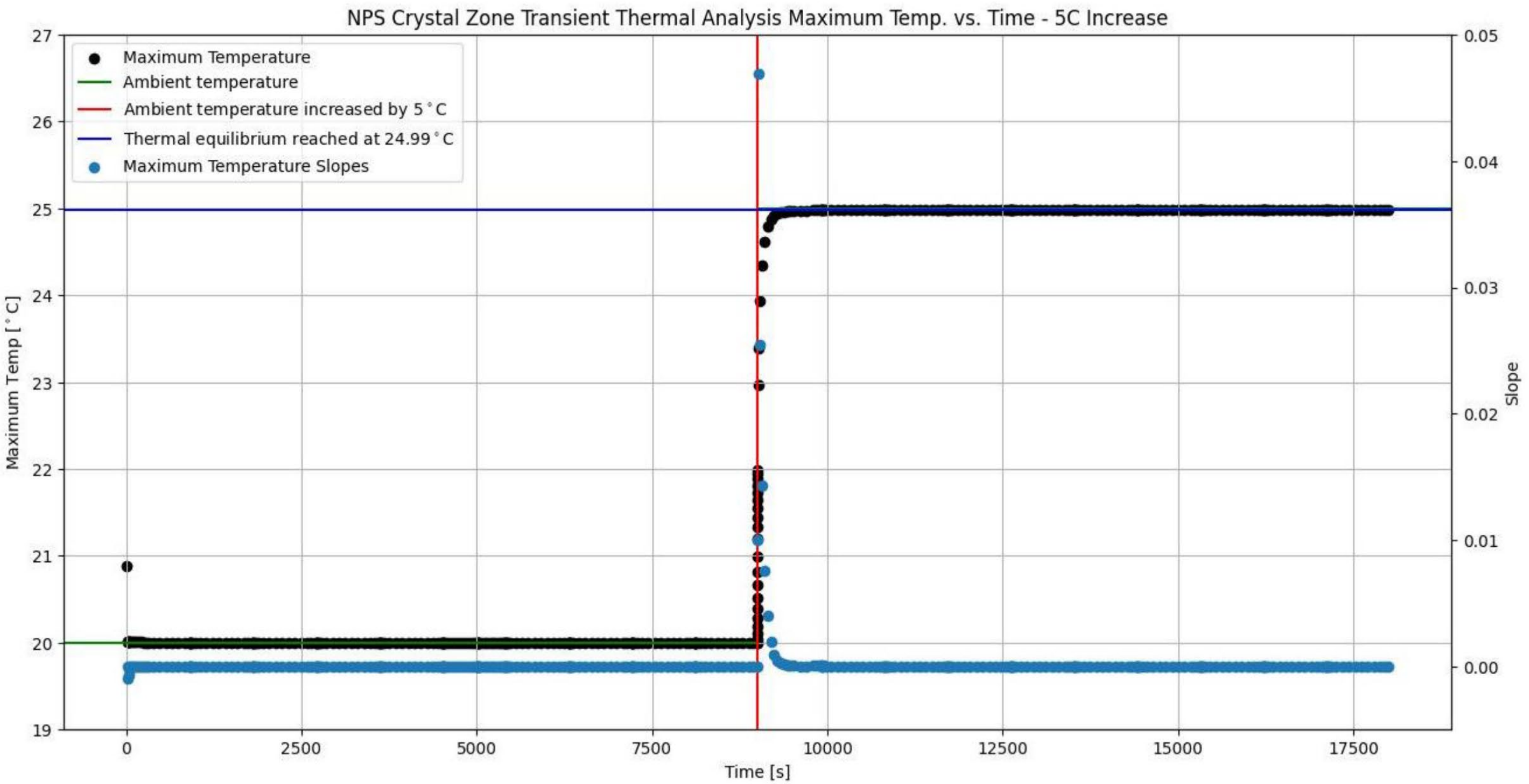
More day-to-day updates: NPS Logbook

NPS Status – Controls (HV, LV, LED, temperature)

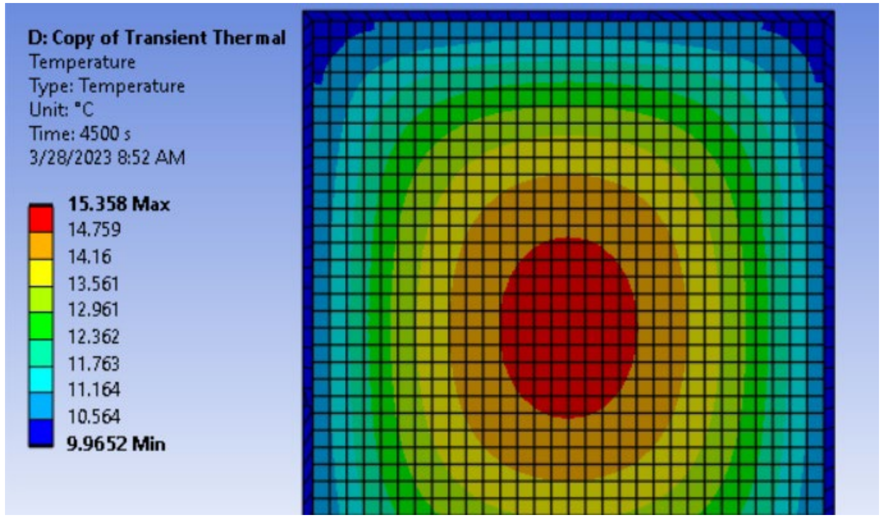


NPS Status – Thermal Analysis Crystals

Detector Support Group: interesting study of crystal thermal behaviors



Copper shell temp: 10°C (constant)
Q = 0.3 W per crystal
Ambient temp: 20°C



- ❑ Temperature stabilization has a long time constant: takes ~1 hour to reach equilibrium → not sensitive to short term variations
- ❑ Stabilization temperature of the crystals is dictated by the ambient temperature → transient and steady state simulations agree

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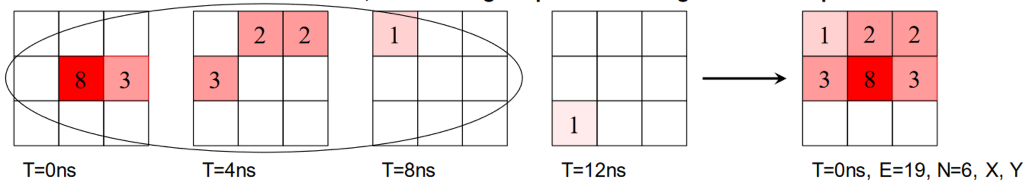
More day-to-day updates: NPS Logbook

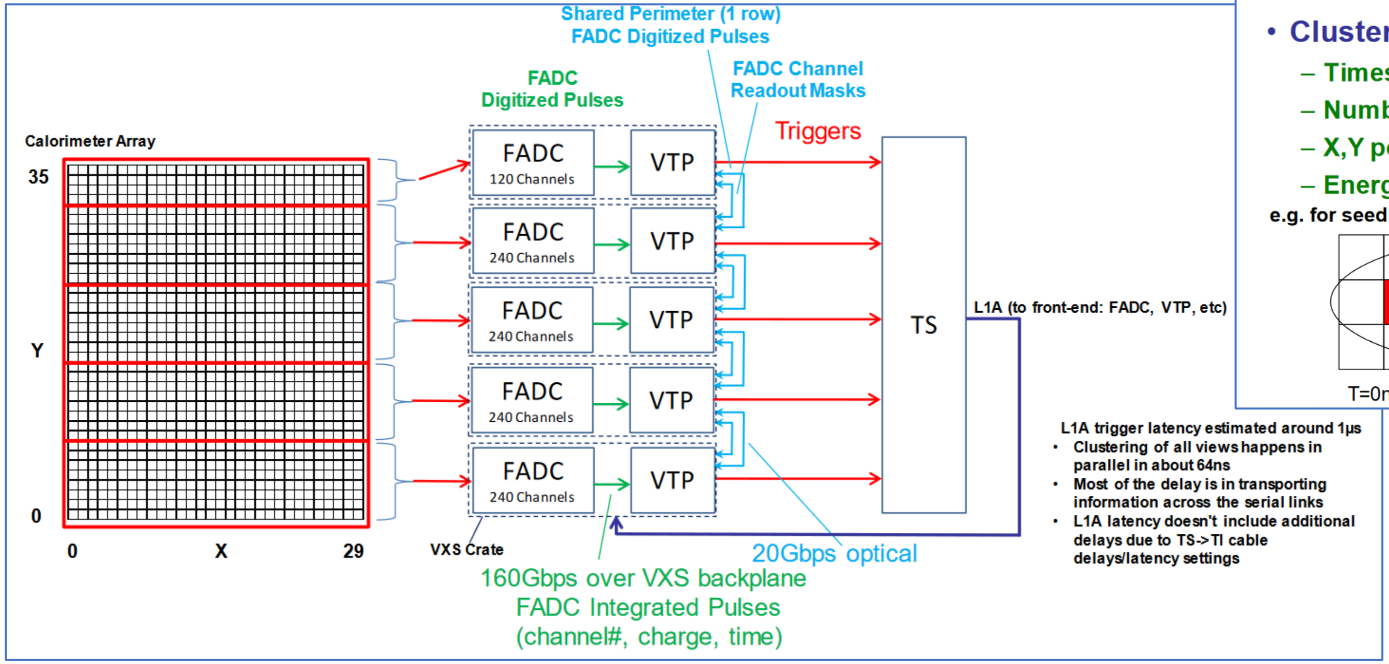
NPS Status – VTP Trigger

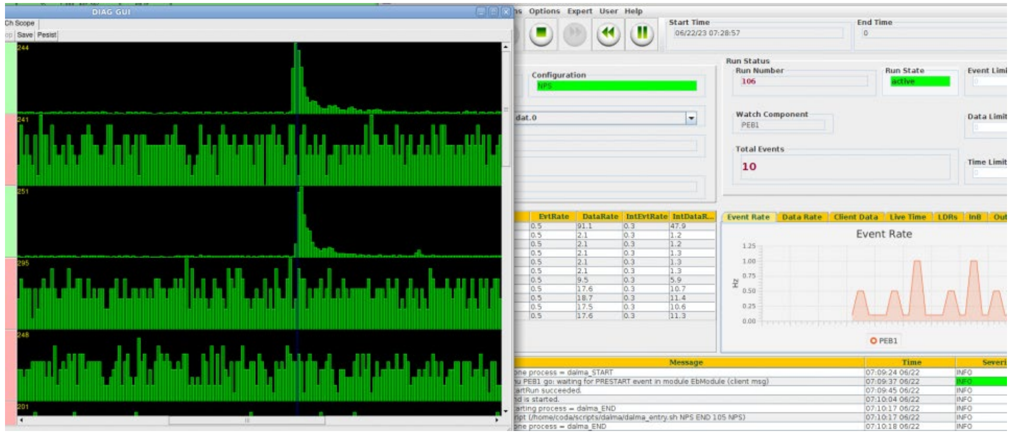
Cluster finding is done by (using 3x3 tower views, all views evaluated in parallel):

- **Seed hit (center) must be >= seed threshold**
- **Seed hit must also be a local maximum in both space and time**
- **Cluster is reported with:**
  - **Timestamp of seed hit (large amplitude hit => lowest jitter)**
  - **Number of hits in cluster**
  - **X,Y position of seed hit**
  - **Energy in MeV units**

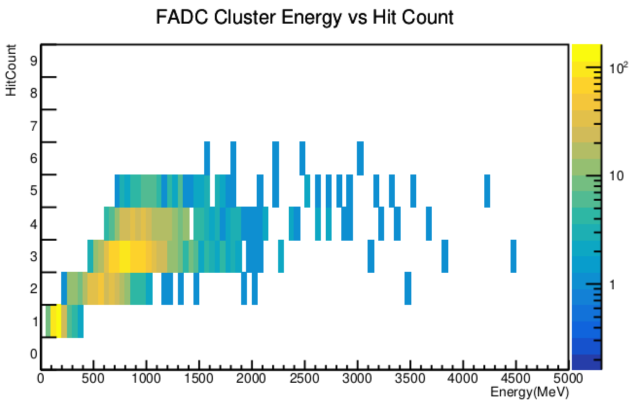
e.g. for seed threshold of 2 and hit Δt=+/-8ns, the following hit pattern evolving in time will report 1 cluster:

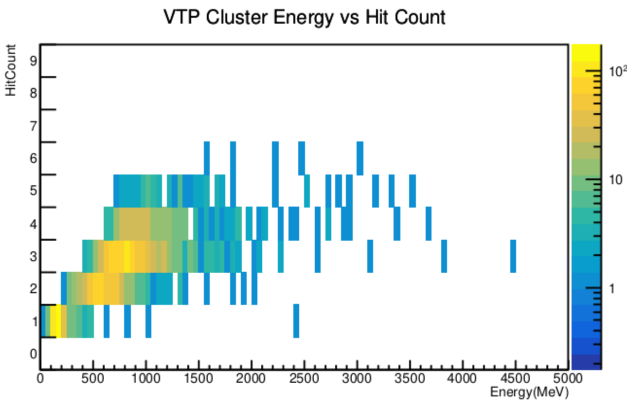






Initial data looks good – more tests ongoing





Fast Electronics Group + Hall C

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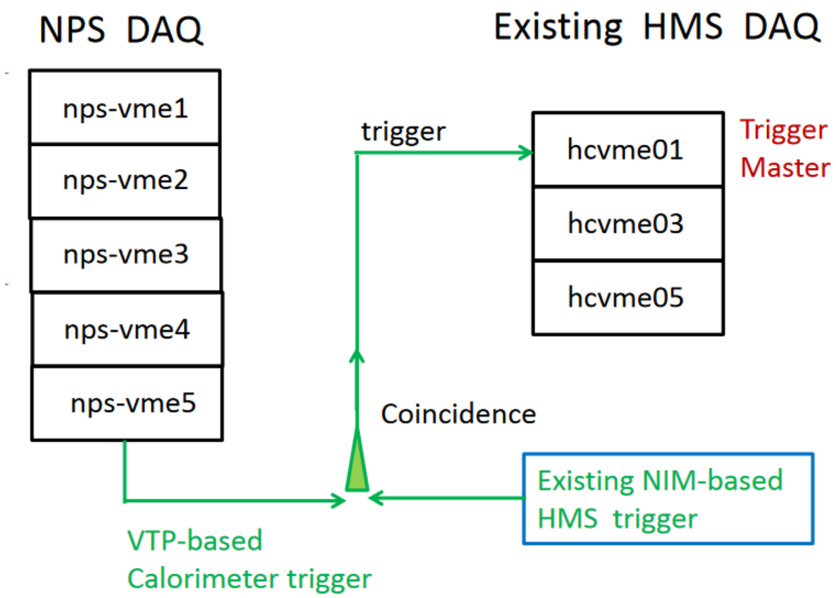
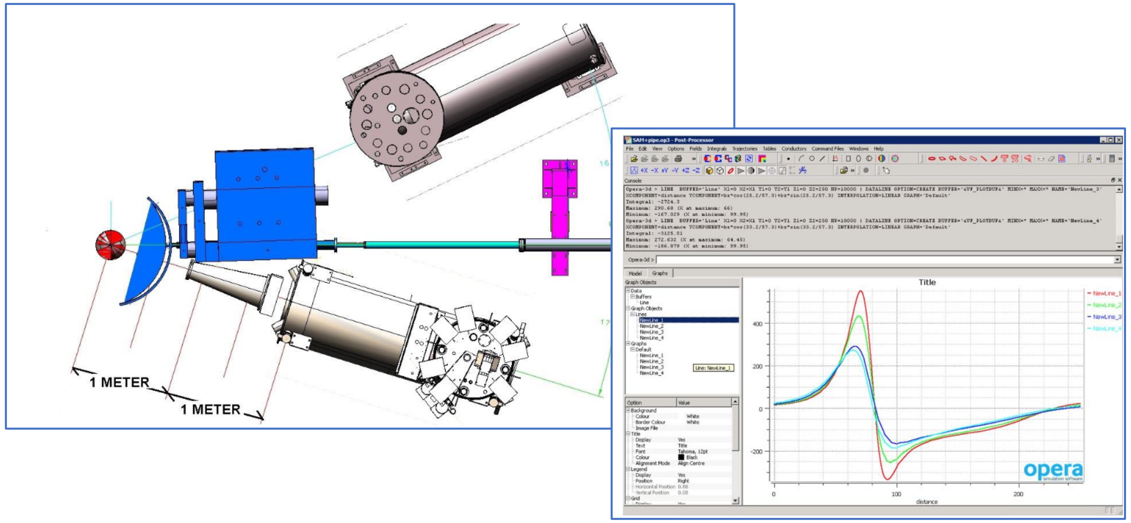
More day-to-day updates: NPS Logbook

NPS Status – Further Ongoing Activities

- ❑ Upgrade HMS DAQ and checkout
- ❑ DAQ System and Software Preparations and Testing
    - Coincidence trigger setup
    - Synchronization system
    - DAQ tests
    - Analysis scripts
    - EPICS alarms and archiving
- ❑ Preparations for HMS optics tests with spectrometers at small angles – minimum separation 23.5 degrees
    - Possible effects of NPS fringe fields at HMS
- ❑ Background radiation studies for additional shielding
- ❑ Run plan development
- ❑ ….

More detail in:
NPS Wiki DAQ section
NPS Logbook HMS DAQ





Many opportunities for groups (and students) to get involved even if not on one of the Run Group 1 experiments

More day-to-day updates: NPS Logbook

Summary

- NPS is a new facility in Hall C allowing for high-precision studies of cross sections and polarization observable involving neutral final states
- The currently approved NPS science program consists of 10 approved experiments aiming at
  - Systematically study the reaction mechanism and factorization
  - Map out nucleon structure in new kinematic regimes
- Some exciting new physics ideas are under development combining NPS with positron beam and/or other equipment in Hall C (possibly 22 GeV JLab)
- NPS run group 1 is scheduled to start as soon as September 2023 – NPS installation and preparations for the run are ongoing
- Shift schedule is open - many opportunities for students and/or interested groups.

NPS - activities