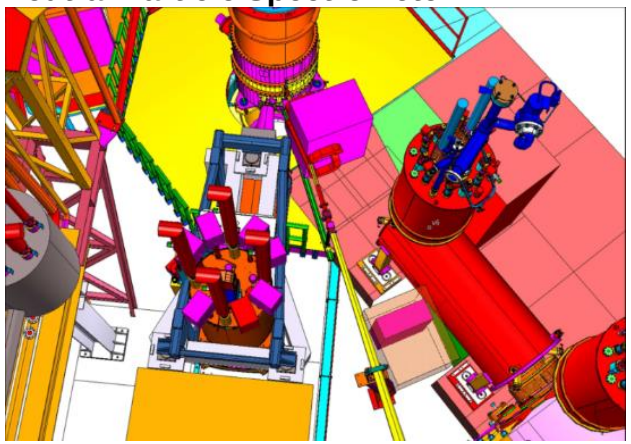
NPS Science and Project Status

The experimental Program in Hall C at 12 GeV JLab… and beyond

Neutral Particle Spectrometer

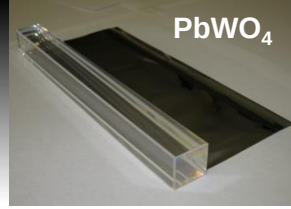


Tanja Horn

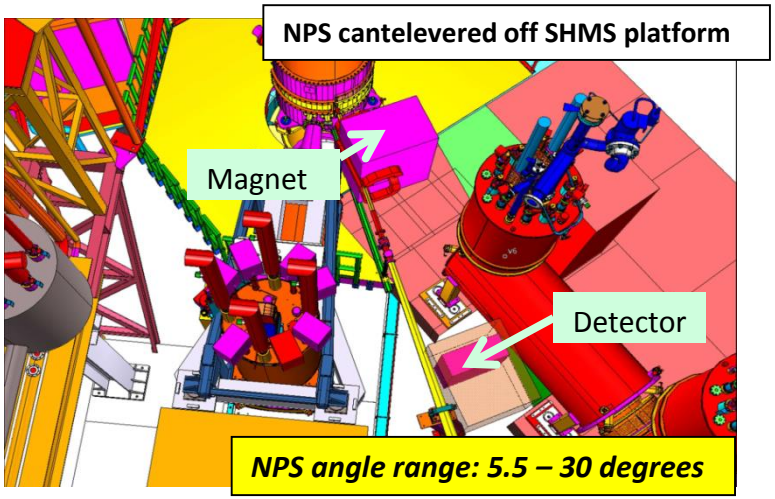
The Catholic University of America

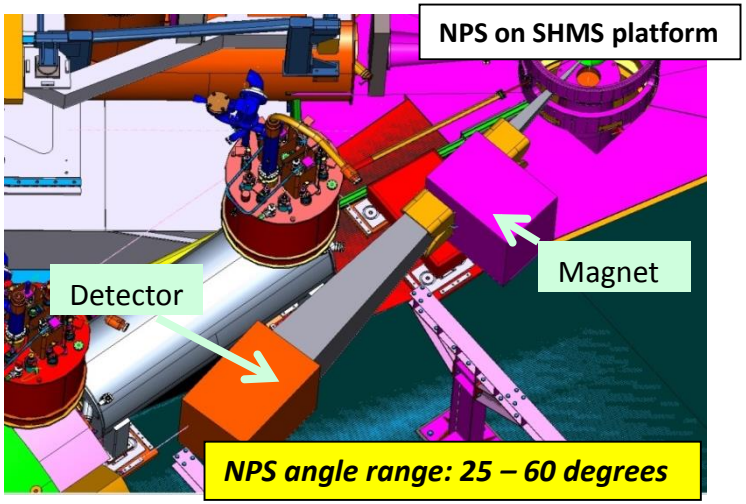
Jefferson Lab
Thomas Jefferson National Accelerator Facility

Neutral Particle Spectrometer (NPS)



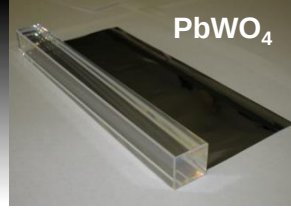
- The Neutral Particle Spectrometer (NPS) is envisioned as a facility in Hall C, utilizing the well-understood HMS and the SHMS infrastructure, to allow for precision (coincidence) cross section measurements of neutral particles (γ and π^0).





- Global design of a neutral-particle spectrometer between 5.5 and 60 degrees consists of a highly segmented, crystal-based electromagnetic calorimeter preceded by a sweeping magnet

NPS Collaboration



I. Albayrak, S. Ali, M. Amaryan, J. R.M. Annand, A. Asaturyan, V. Berdnikov, K-T. Brinkmann, M. Boer, A. Camsonne, M. Carmignotto, D. Day, V. Dormenev, D. Dutta, R. Ent, M. Guidal, D.J. Hamilton, T. Horn, C. Hyde, H. Mkrtchyan, G. Kalicy, D. Keller, C. Keppel, E. Kinney, A. Mkrtchyan, C. Munoz-Camacho, P. Nadel-Turonski, R. Novotny, R. Paremuzyan, I. Pegg, H. Rashad, J. Roche, O. Rondon, H. San, S. Sirca, I. Strakovsky, V. Tadevosyan, R. Trotta, A. Vargas, R. Wang, B. Wojtsekhowski, S. Wood, J. Zhang, C. Zorn

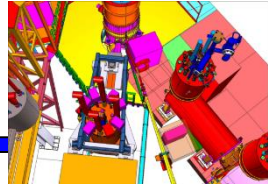
A.I. Alikhanyan National Science Laboratory/Armenia, Catholic Univ. of America, Vitreous State Laboratory, Institut de Physique Nucleaire d'Orsay/France, Univ. of Giessen/Germany, Univ. of New Hampshire, Univ. of Colorado, Mississippi State Univ., Jefferson Laboratory, Ohio University, Old Dominion Univ., Univ. of Glasgow/Scotland, Univ. Ljubljana/Slovenia, Akdeniz Univ./Turkey, Univ. of Virginia

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

Overview Scientific Program

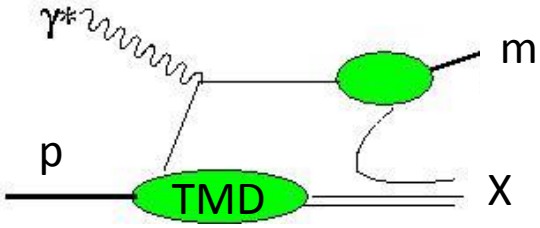
- 4 experiments fully approved by PAC to date
  - E12-13-007: Measurement of Semi-inclusive π^0 production as Validation of Factorization
  - E12-13-010 – Exclusive Deeply Virtual Compton and π^0 Cross Section Measurements in Hall C
  - E12-14-003 – Wide-angle Compton Scattering at 8 and 10 GeV Photon Energies
  - E12-14-005 – Wide Angle Exclusive Photoproduction of π^0 Mesons
- 1 conditionally approved experiment
  - C12-17-008 – Polarization Observables in Wide Angle Compton Scattering
- Ideas exist for future experiments and new scientific directions taking advantage of the compatibility of NPS with Hall infrastructure
  - Experiments with polarized targets
  - High-Intensity Photon Source
  - Exploring possibilities for correlation experiments
- 1 Letter of Intent
  - LOI12-15-007 – Timelike Compton Scattering with transverse target

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



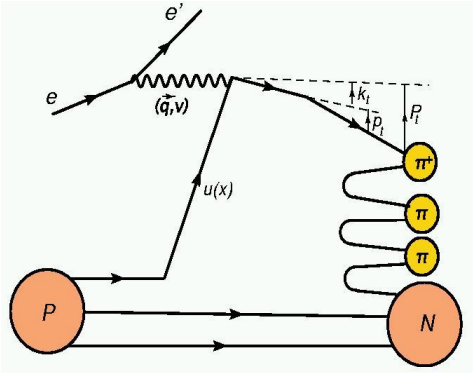
Linked to framework of *Transverse Momentum Dependent Parton Distributions*

- 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



$TMD^q(x,k_T)$

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!)

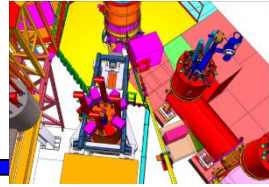
Requires new ~25 msr Neutral-Particle Spectrometer

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: $\sigma^{\pi^o}(x,z) = ½\,(\sigma^{\pi^+}(x,z) + \sigma^{\pi^-}(x,z))$
- 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 cross sections



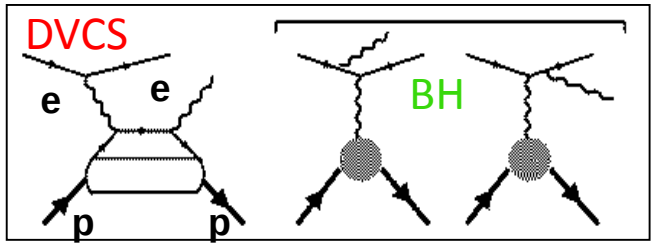
Simplest process: **e + p → e' + p + γ (DVCS)**

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

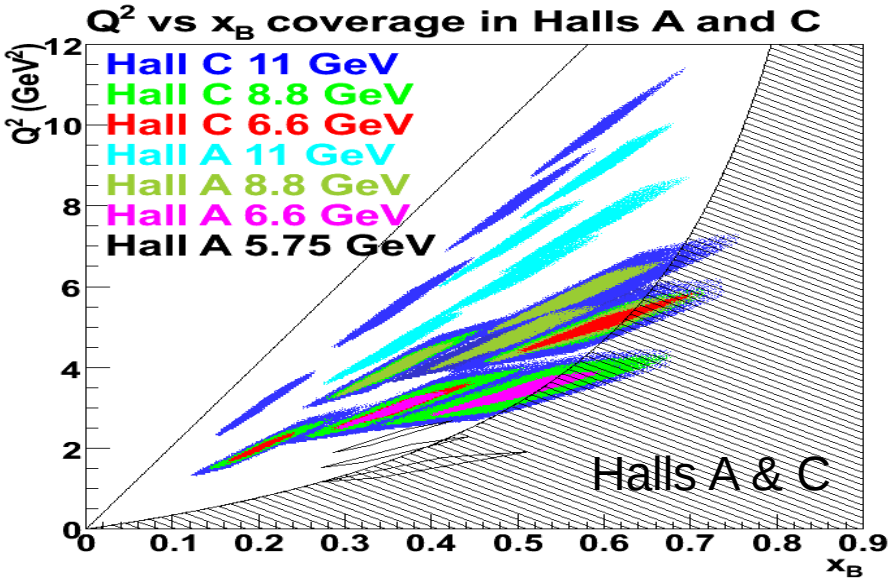
- Scaling of the Compton Form Factor
- Rosenbluth-like separation of DVCS:

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

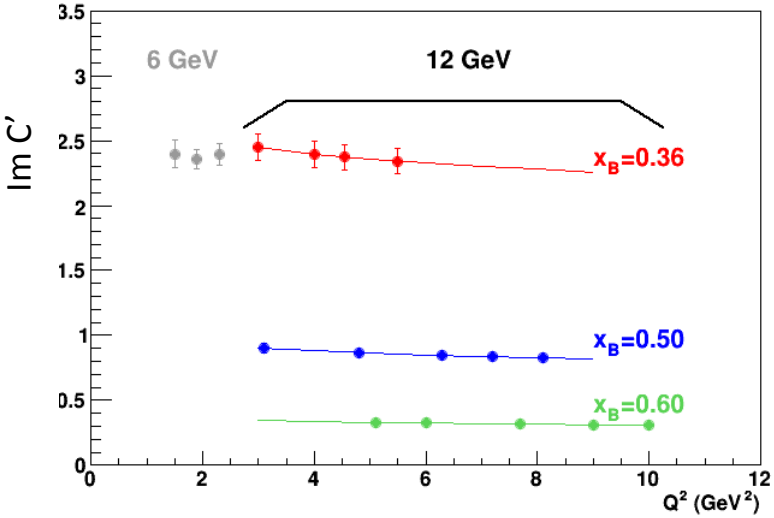
- L/T separation of π^0 production



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

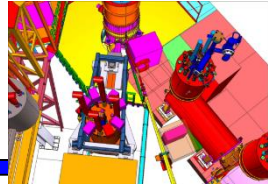


12 GeV projections: confirm formalism

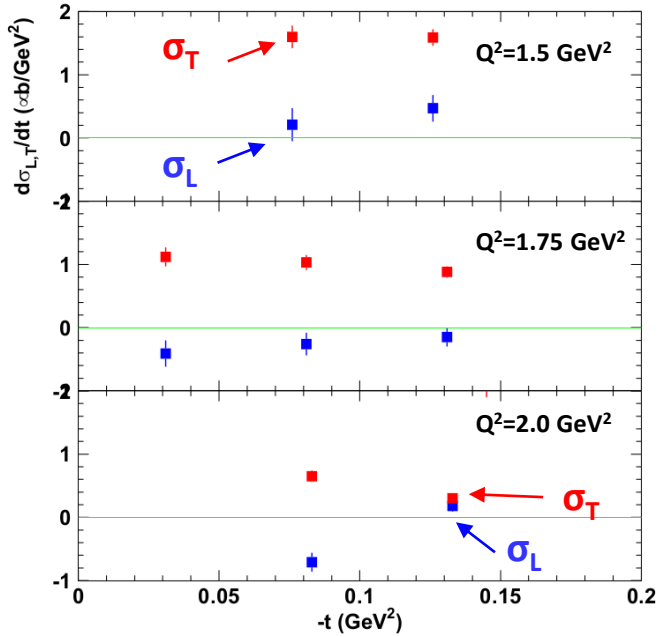


Extracting the real part of CFFs from DVCS requires measuring the cross section at multiple beam energies ($DVCS^2$–Interference separation)

E12-13-010: exclusive π^0 cross section

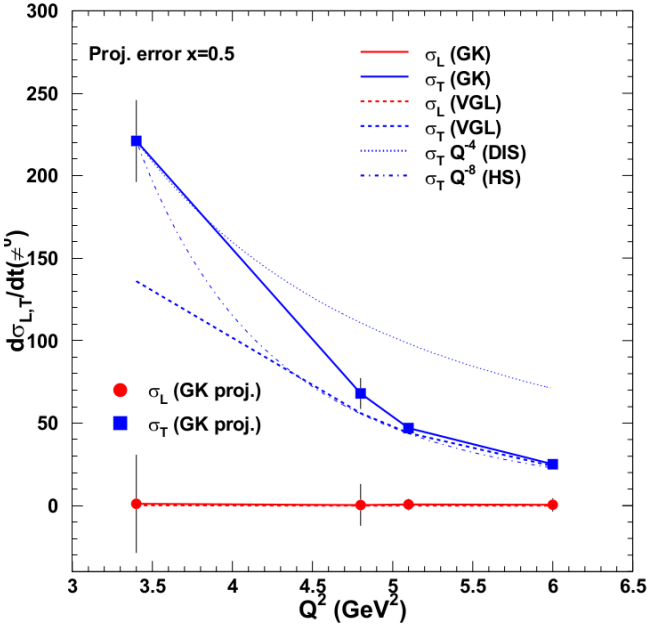


- Relative L/T contribution to π^0 cross section important in probing transversity
  - If σ_T large: access to transversity GPDs
- Results from Hall A at 6 GeV Jlab suggest that the longitudinal cross section in π^0 production is non-zero up to Q^2=2 GeV^2
- Need to understand Q^2/t dependence for final conclusion on dominance of σ_T



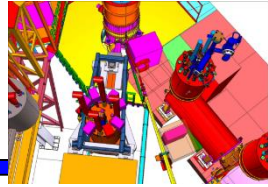
*M. Defurne et al, PRL **117** (**2016**) no.26, 262001*

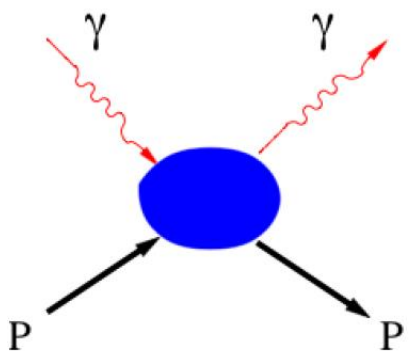
E12-13-010 projections



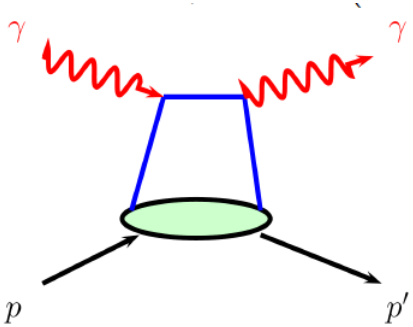
E12-13-010 will provide essential data on σ_T and σ_L at higher Q^2 for reliable interpretation of 12 GeV GPD data

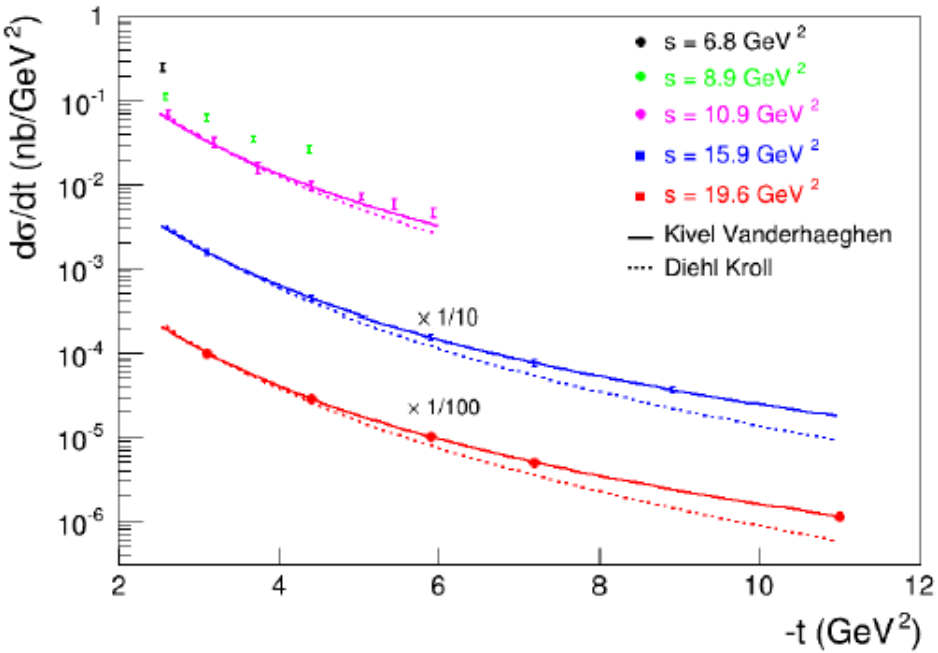
E12-14-003: Wide Angle Compton Scattering





- 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





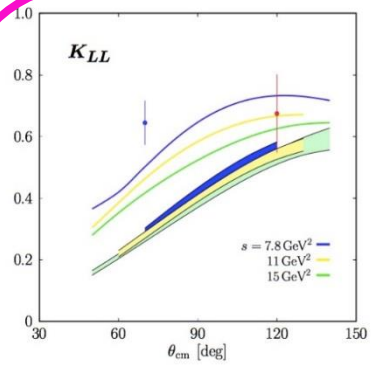
- Perhaps (6-GeV data) factorization valid for *s, -t, -u > 2.5 GeV²*
- 12-GeV data for *–u > 2.5* and *–t* up to *~ 10, s* up to *~ 20* GeV²

New Opportunities with NPS and a Compact Photon Source (CPS)

The Catholic University of America

6-7 February 2017 High-Intensity Photon Sources Workshop (CUA)

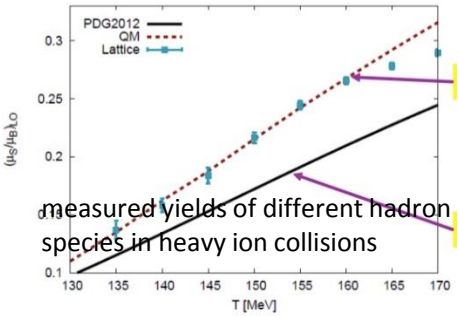
https://www.jlab.org/conferences/HIPS2017/



Polarization observables Wide Angle Compton Scattering
(K_{LL}, A_{LL}, K_{LS}, A_{LS},..)

Hadron Spectroscopy with secondary K_L beam

- Cross sections and polarization of Λ, Σ, Ξ, Ω hyperons
- Strange meson spectroscopy
- Connections to heavy ion physics
- Possibly link to doubly charged baryons?

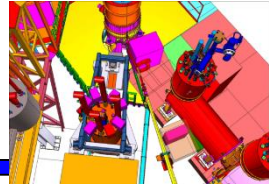


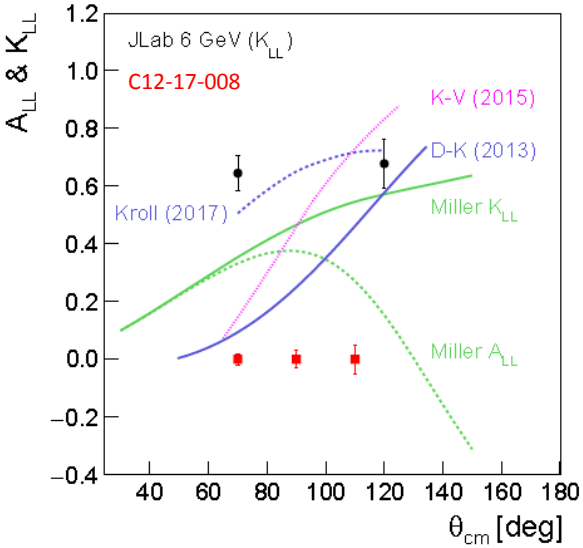
measured yields of different hadron species in heavy ion collisions

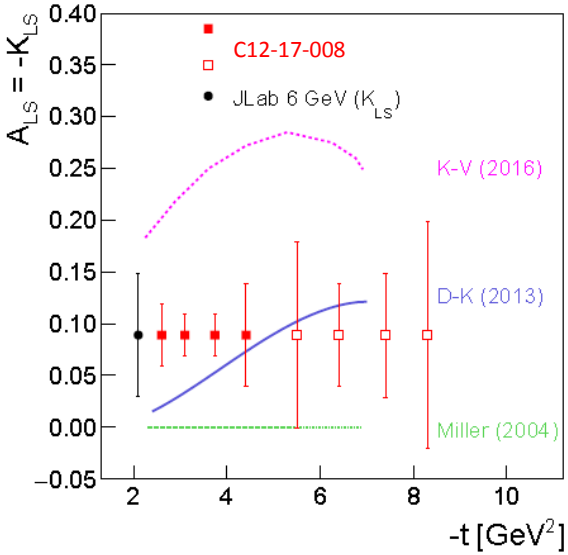
Additional Science Topics under study

- ❑ WACS exclusive photoproduction
- ❑ Timelike Compton Scattering
- ❑ Short Range Correlations
- ❑ Photoproduction of Few Body Systems
- ❑ *Also: Missing mesons, Phi production,…*

C12-17-008: Polarization Observables in Wide-Angle Compton Scattering



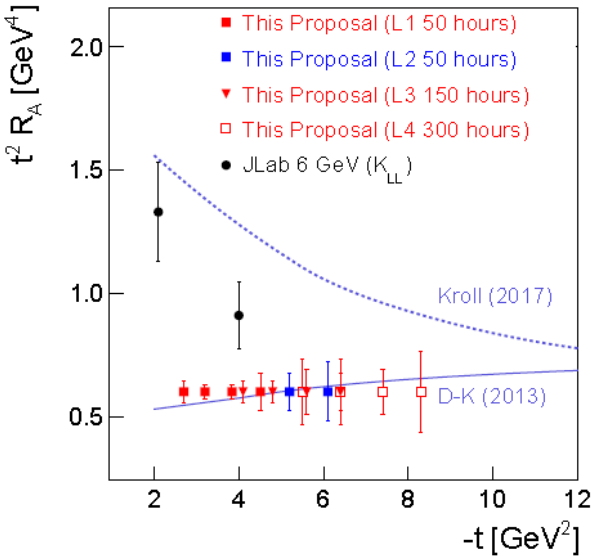




Kin	E_{Beam} [GeV]	E_{in} [GeV]	θ_γ [°]	E_γ [GeV]	D_{NPS} [m]	θ_p [°]	p_p [GeV/c]	D_{BB} [m]	θ^{cm} [°]
L1	8.8	6.0	21.5	4.16	3.0	35.5	2.62	1.5	70.0
S1	8.8	6.0	21.5	4.16	3.0	35.5	2.62	1.5	70.0
L2	11.0	9.5	17.4	6.49	3.0	30.5	3.82	1.5	70.0
L3	8.8	6.0	30.2	3.22	3.0	26.5	3.63	2.5	90.0
L4	8.8	6.0	42.3	2.25	1.0	19.4	4.55	3.5	110.0
S4	8.8	6.0	42.3	2.25	1.0	19.4	4.55	3.5	110.0

→ **See talk by D. Day**

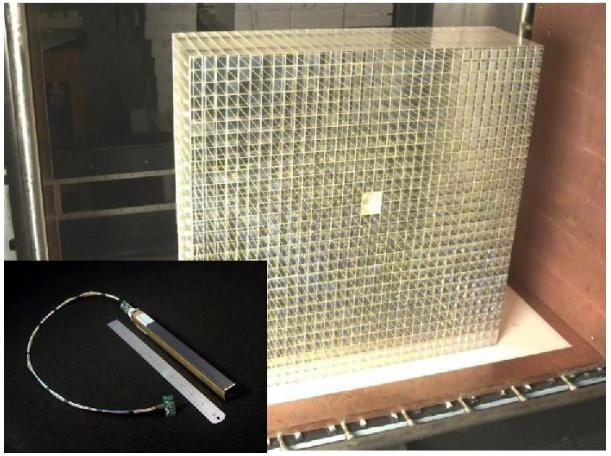
- Explicit, model-independent test of factorization by measuring the s-dependence of the polarization observables at fixed centre of mass angle
- Measurement of A_{LL} at large angles allowed for tests of relevant degrees of freedom in hard exclusive reactions
- Also extract the Axial and Pauli form factors - constrain GPDs $\tilde{H}$ and E at high –t



NPS General Design Concept

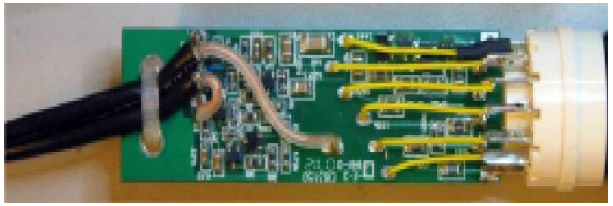
NSF MRI PHY-1530874

- 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

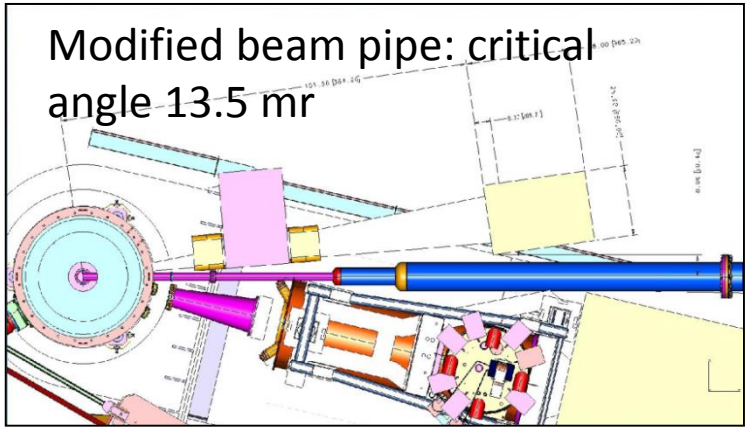
- Essentially deadtime-less digitizing electronics to independently sample the entire pulse form for each crystal – JLab-developed Flash ADCs



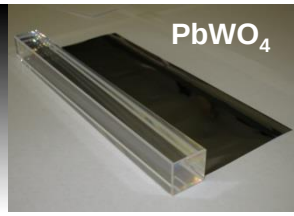
- A new 0.3Tm sweeping magnet allowing for small-angle and large angle operation at 0.6 TM. The magnet is compatible with existing JLab power supplies.

- 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) – new

- A beam pipe with as large critical angle as possible to reduce beamline-associated backgrounds – further study showed only a small section needs modification (JLab/Hall C)



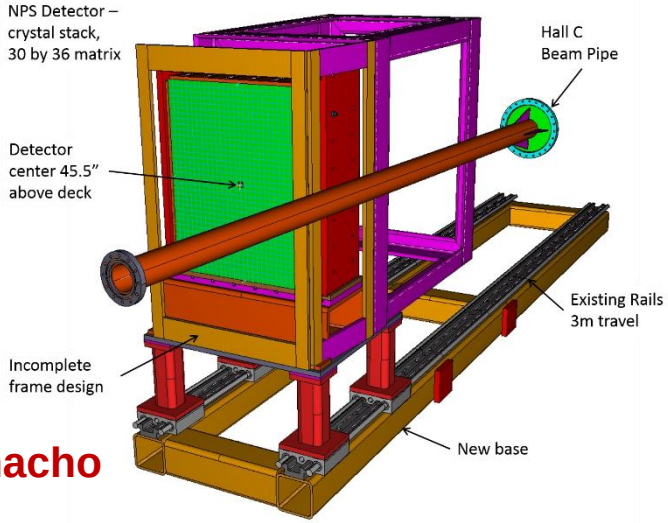
NPS Project Status



Four fully approved experiments, supported by NSF MRI PHY-1530874 (CUA, OU, ODU), international (IPN-Orsay, Glasgow, Yerevan), and JLab

- Magnet: corrector and main coil construction complete, corrector coil is in test lab, yoke steel cutting nearly final, setting up space in test lab for assembly

→ **See talk by C. Hyde**

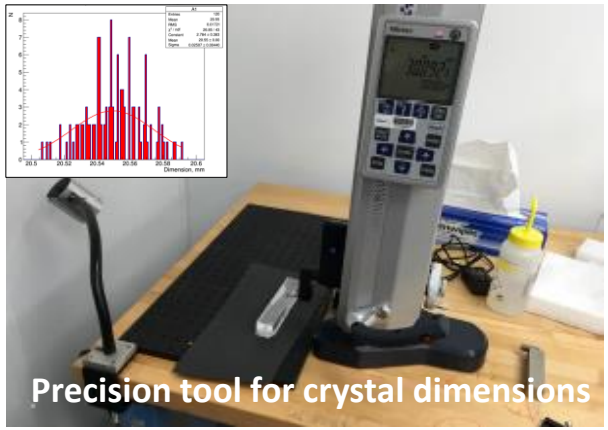


- PMT and HV bases: design drawings final, prototyping, procurements started

→ **See talk by F. Barbosa**

- Frame and integrated systems: concepts and initial design complete, detailed drawings to be presented this week

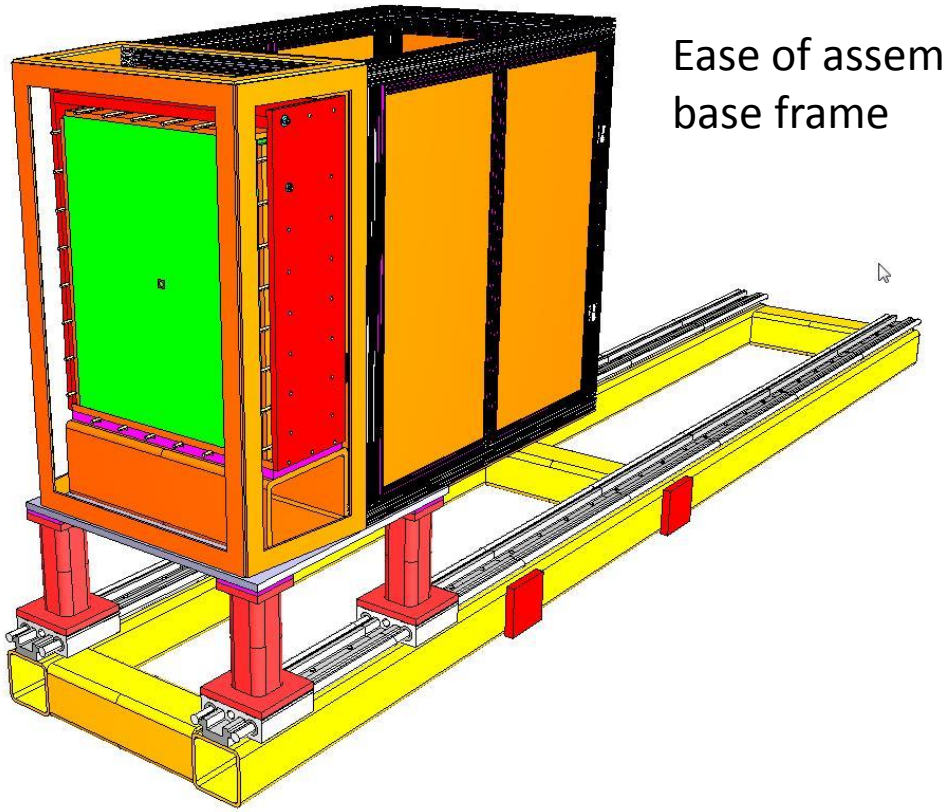
→ **See talk by C. Munoz-Camacho**



- Crystals: 460 crystals procured from SICCAS, full crystal testing facilities at CUA and IPN-Orsay, chemical analysis and crystal growth in collaboration with the VSL, synergy with EIC crystal calorimeter R&D, cleanroom ready

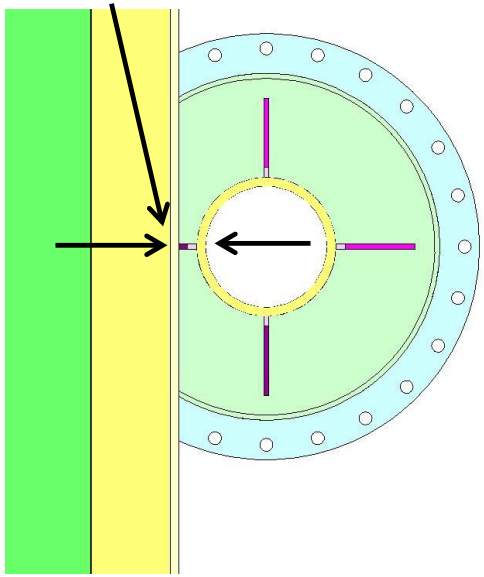
→ **See talk by V. Berdnikov**

Frame and integrated systems



Ease of assembly on base frame

1/5” clearance to beam pipe @ 6 deg.

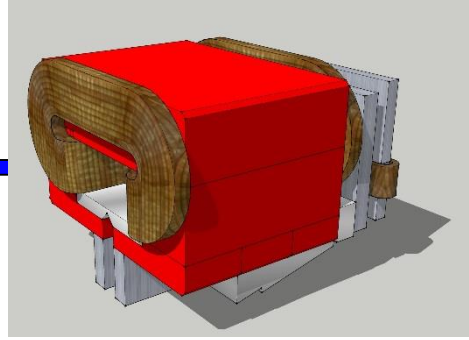


a) Adding in the cooling, cabling, etc. – ongoing now

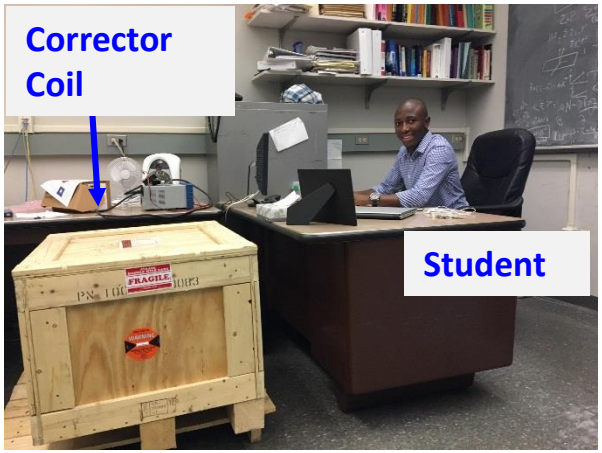
b) The cantelevered platform off SHMS – 2018 project

c) 3D overview drawing with NPS magnet, detector etc, with the spectrometers. – can in principle be done anytime, but for real fabrication drawings need to wait until detector is near completion

NPS Sweeper Magnet



Main Coil – on boat now

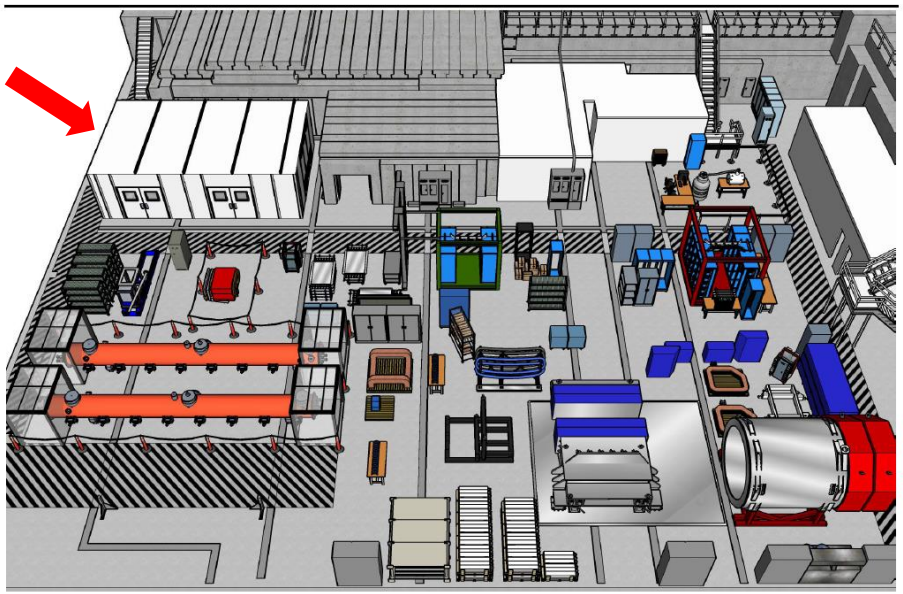


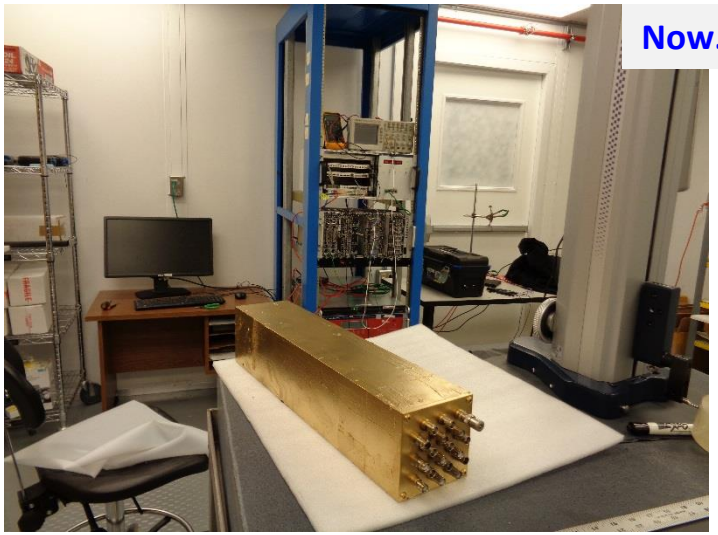
Yoke Steel - before

Yoke Steel – after
Expect at Jlab by 9 Feb.

- ❑ Expect all components at Jlab in next few weeks
- ❑ Next: Assembly and testing

Magnet Assembly Space and Crystal Clean Room - Ready





Crystal prototype and DAQ

Crystals and dimension measurements

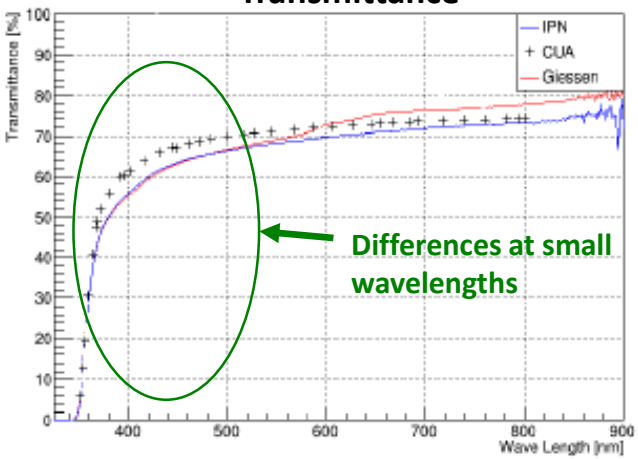
Infrastructure for crystal testing - *completed*

IPN-Orsay (France) – M. Josselin, C. Munoz-Camacho, H. San, R. Wang

➢ ***Cross check with subset of crystals previously tested at CUA, Giessen U. and Caltech***

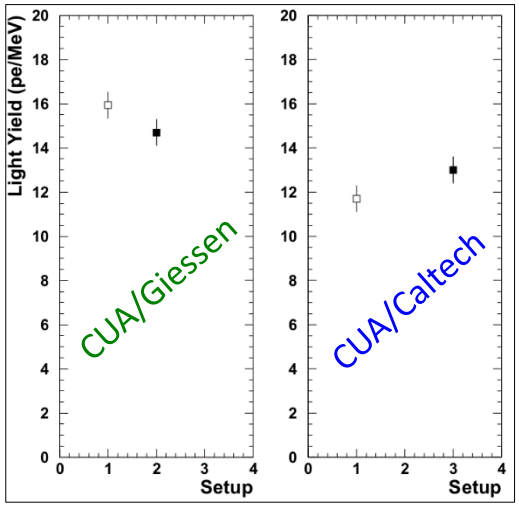
- Optical Transmittance (L/T)
  - PerkinElmer spectrophotometers (LambdaX50) and Varian Cary
  - Differences at small wavelengths may be due to misalignment – checks ongoing

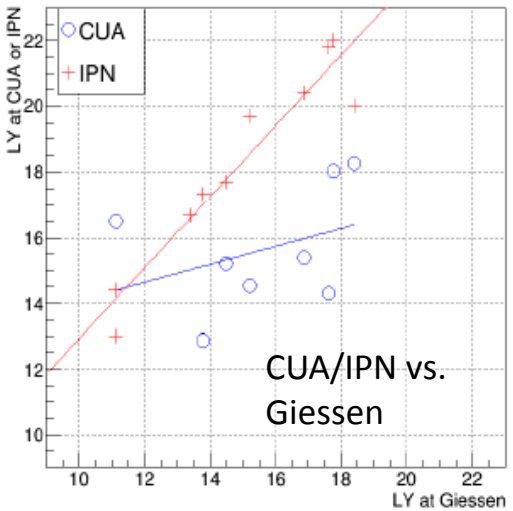
Transmittance



- Crystal light yield and timing
  - Measurements nominal at 18°C and with 100ns integration gate
  - PMT quantum efficiency may account for differences

Light Yield





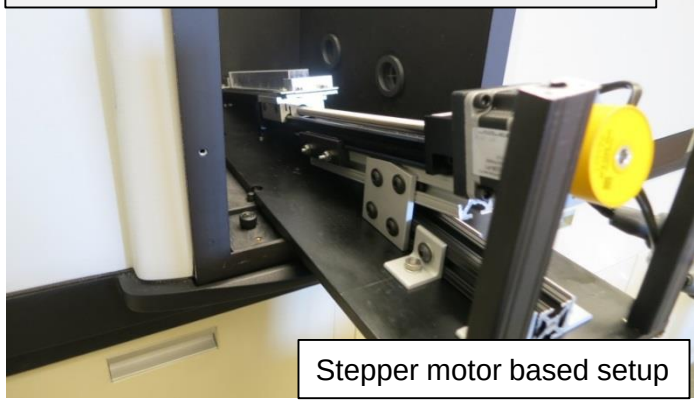
- Next: radiation hardness

Infrastructure for crystal testing - *completed*

The Catholic University of America

CUA (USA) – S. Ali, V. Berdnikov, T. Horn, I. Pegg, R. Trotta, A. Vargas, VSL

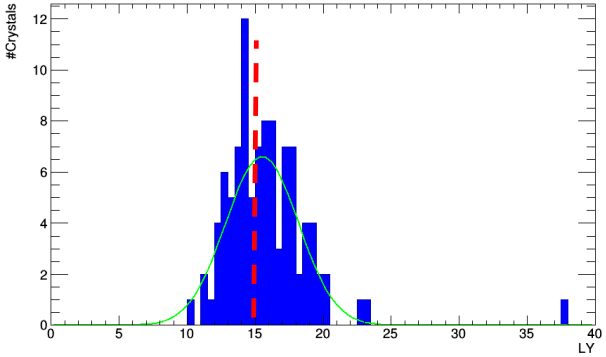
Spectrophotometer with integrating sphere (NSF MRI) in dedicated crystal lab



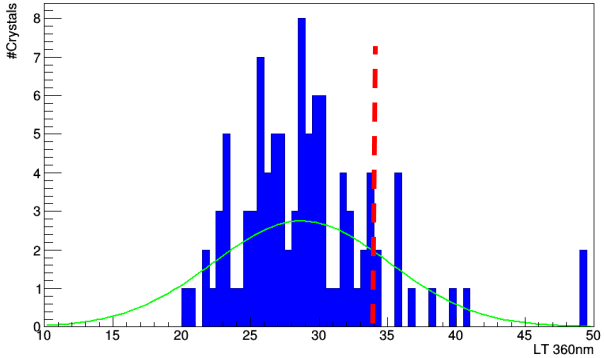
Stepper motor based setup

- Optical Transmittance (L/T)
  - 86% of SICCAS 2017 crystal subset passes at 420nm, only 10% at 360nm
  - 5% of crystals passing specification have mechanical flaws that impact uniformity of light collection
- Crystal light yield and timing
  - 55% (55/100) of SICCAS 2017 and ~50% (1/2) of Crytur crystals pass specs***, discussion with vendors about role of mechanical flaws, roughness and chemical composition in (controlled) increasing LY***

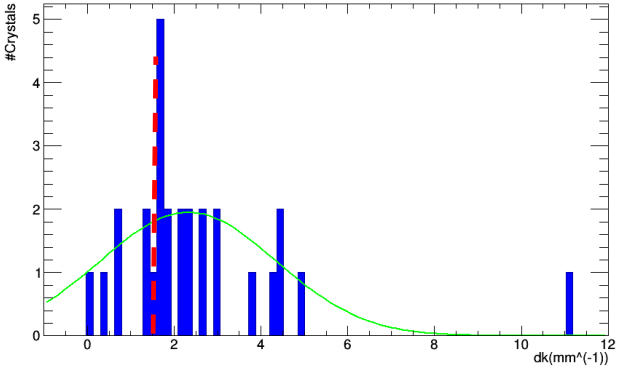
Light Yield



Transmittance 360nm

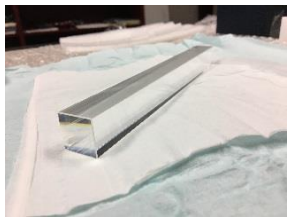


Absorption coefficient

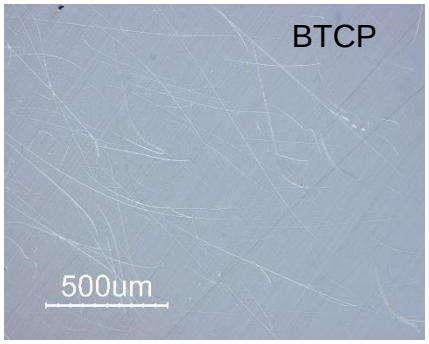


SICCAS 2017 crystals: Large variations in light yield, optical transmittance, and radiation resistance

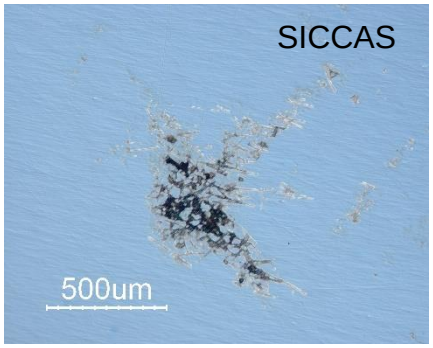
Crystal Quality: *Surface Analysis*



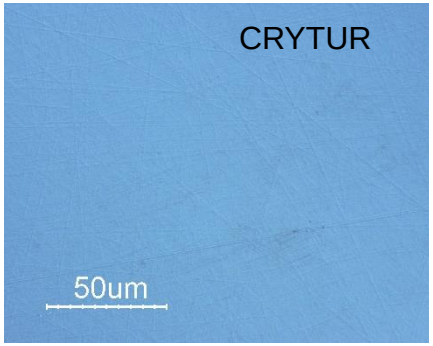
- Typical crystal surface quality



Out-of-business



Mass production may be available – 320 crystals delivered in 2017



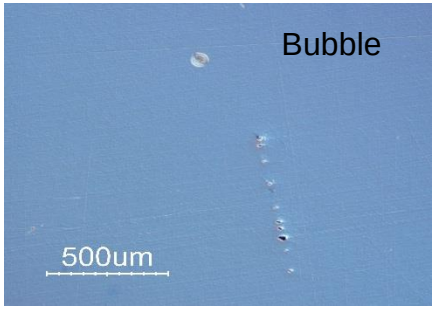
Mass production uncertain

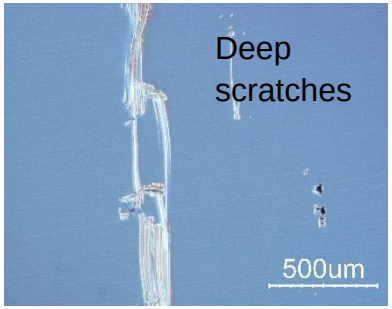
Measurements: scanning microscope in collaboration with VSL

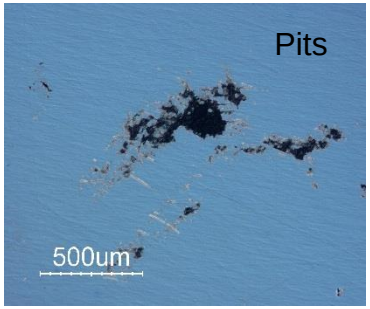
  - Scratches applied in a well-defined manner may benefit crystal properties – discussion with vendors ongoing

Anticipate 450 crystals from CRYTUR for testing

- Looking deeper into defects: SICCAS 2017 crystals







  - Defects result in high, but non-uniform light yield – discussion with vendors about mitigation ongoing

Summary and Outlook

- A Neutral Particle Spectrometer together with polarized targets enables precision cross section measurements with neutral particles

- 4 (1) experiments fully (conditionally) approved, more ideas being explored…

- Ongoing efforts of the NPS collaboration and Hall D to design and build a Compact Photon Source for additional science output in Hall A/C and Hall D