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What to expect from the DVCS NPS data in Hall C

J. Roche, on behalf of the NPS collaboration

- The NPS is a new stand-alone electromagnetic calorimeter that detects high-energy photons in high-radiation and high-rate environments.
- The NPS was successfully used for the first time from September 2023 to May 2024 to measure deep exclusive and inclusive reactions off protons and neutrons.

- These data aim to produce beam-polarized and unpolarized absolute cross sections with 5% statistical and 5% systematic precision, both for DVCS and π^0 production (talk by A. Singh Tuesday am).
- These measurements use the same methodology as previous Hall A DVCS measurements but extend the kinematic reach.

- Analysis is ongoing.

NSF-PHY#2209199

FOREVER OHIO

The NPS collaboration and sponsors

Detector built with funds from:
NSF MRI #1530874, CNRS France and JLab

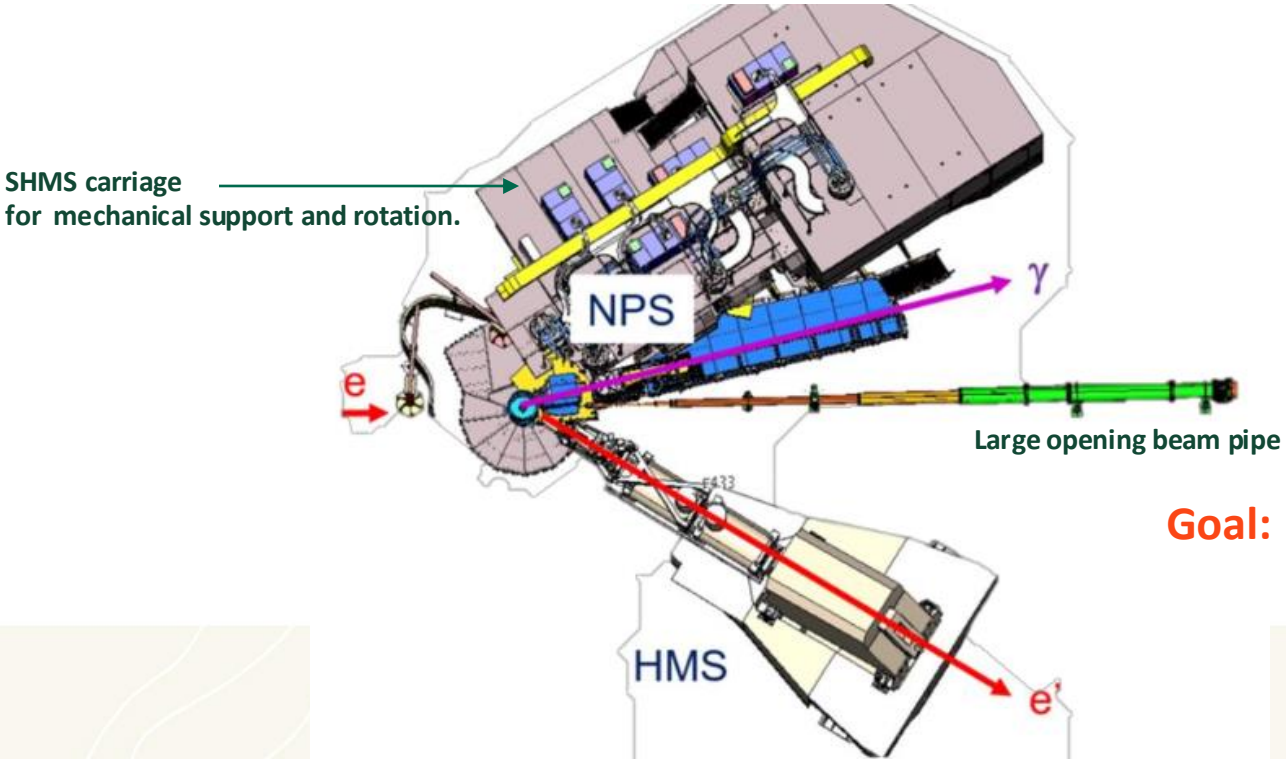
NSF cnrs Jefferson Lab

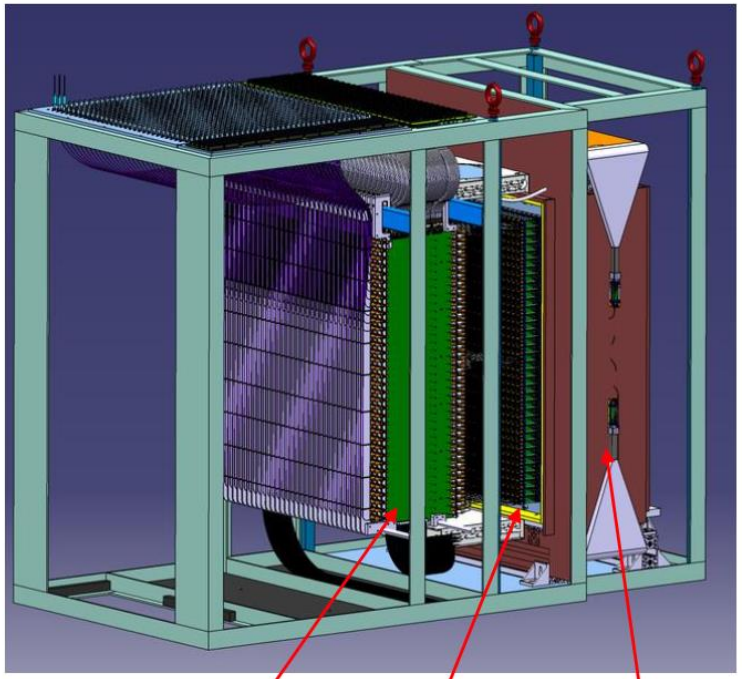
Talented graduate student working with us (by alphabetic order)

- Josh Crafts (CUA)
- Wassim Hamdi (Fac. de Monastir)
- Hao Huang (U. Paris-Saclay)
- Mitch Kerver (ODU)
- Mark Mathison (Ohio U.)
- Christine Ploen (ODU)
- Avnish Singh (CUA)
- Tae-Hee Song (Kyungpook Nal U.)
- Yaopeng Zhang (Tsinghua U.)

The Neutral Particle Spectrometer (NPS)

- A magnet to deflect low-energy charged particles
- A highly segmented EM calorimeter
  - 1080 PbW04 blocks in a 30X36 array.
  - LED system for curing and calibration.
  - Temperature-controlled frame
  - FADC with 4 ns sampling rate
- A VME Trigger Processor (VTP) based triggering system



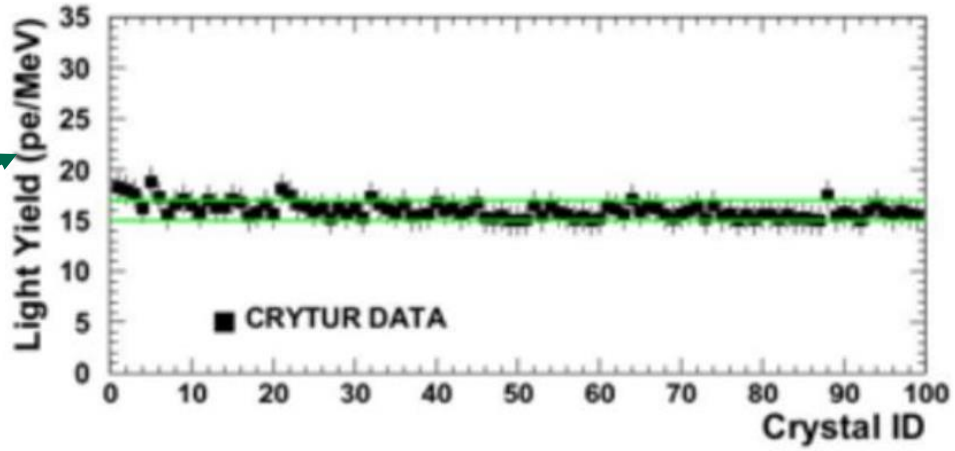


Goal: high resolution, high luminosity detection of neutral particles

High energy resolution: scintillating PbWO4 crystals

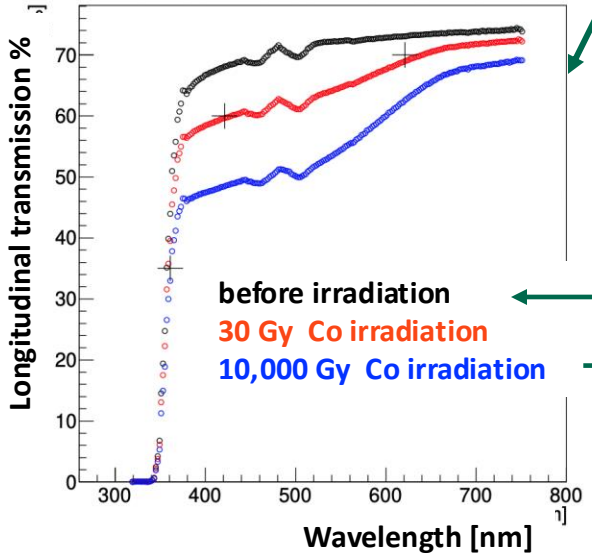
- High density material with no self-absorption
  Fast response time (5-16 ns) (limits pill up effect)

- Crystals manufactured by CRYTUR
  no optical defect => consistent light yield
  => radiation hard



Nucl. Inst. Meth. A, Volume 956, 11 March 2020, 163375

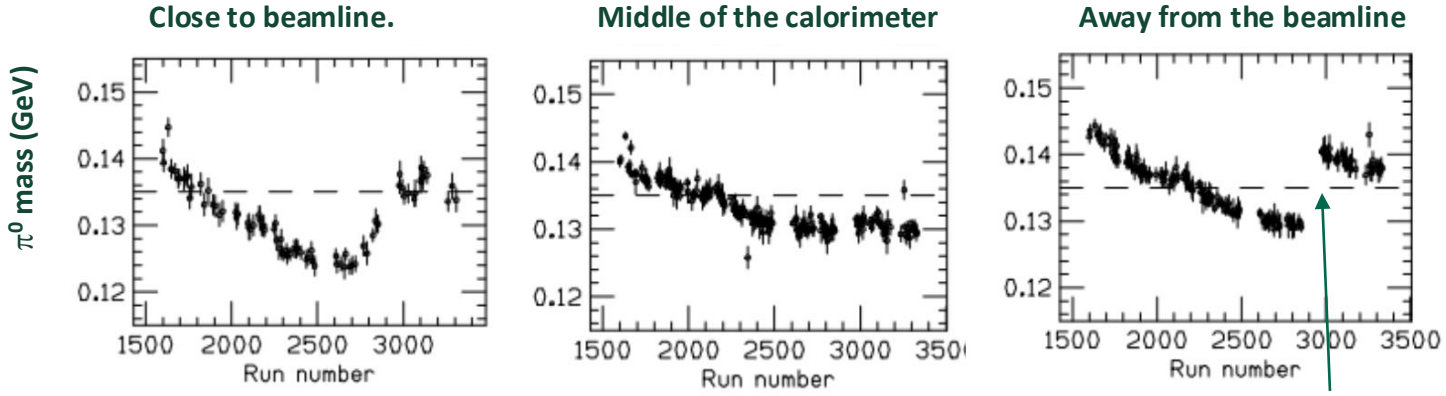
P-K Wang, Dissertation 04261759, U. Paris Saclay



Transmission can be restored by optical or thermal curing.

The radiation damage observed over the whole experiment did not require curing.

Estimated integrated dose on the most exposed blocks: 5kGy.

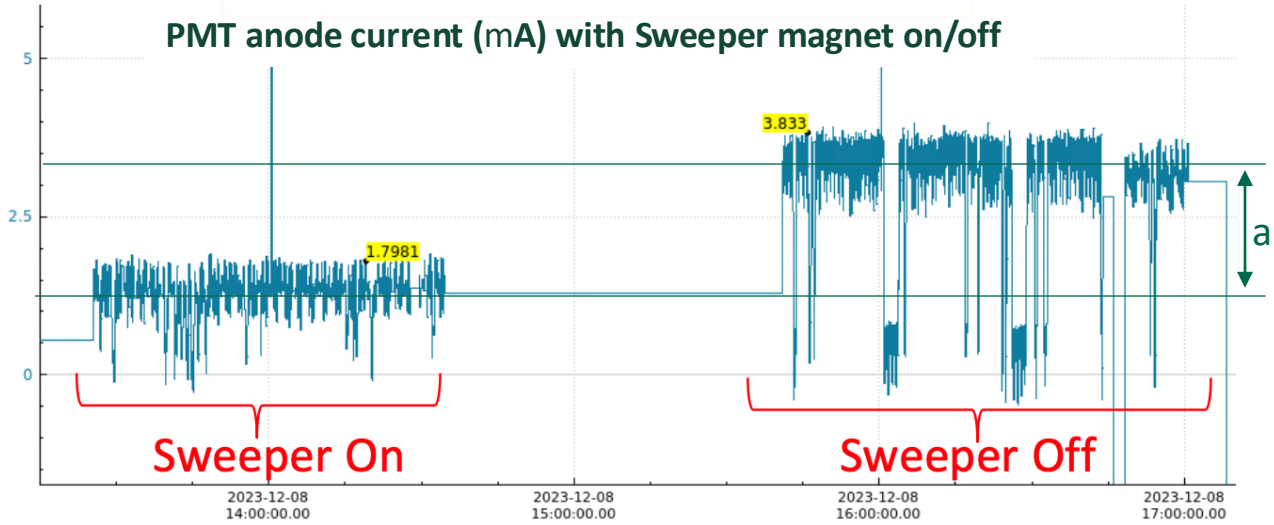


Study by P. Bosted

High luminosity: NPS sweeper magnet

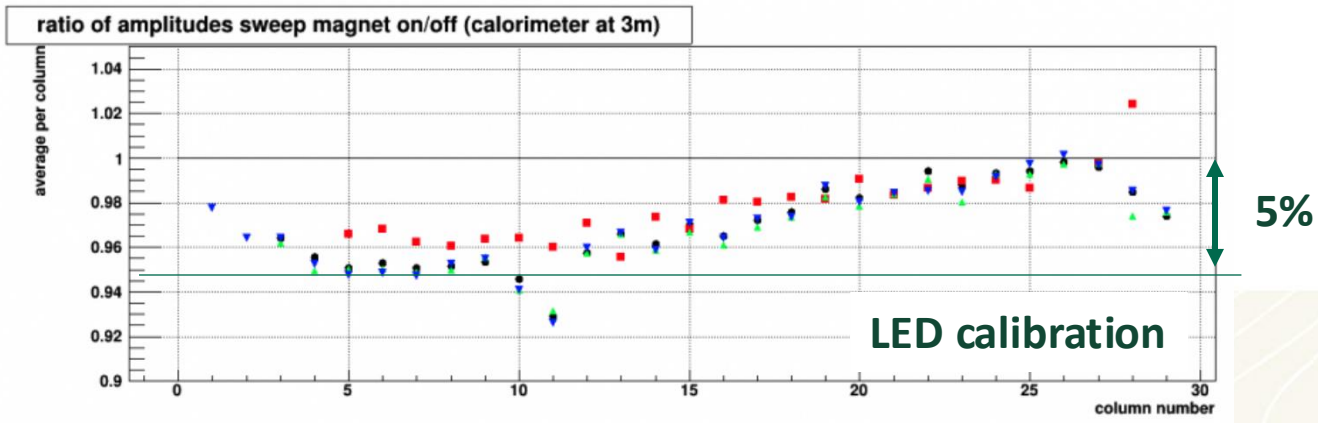
Reduces electromagnetic background for high-rate environment

PMTs anode current was sometimes the limiting factor in term of maximum luminosity.



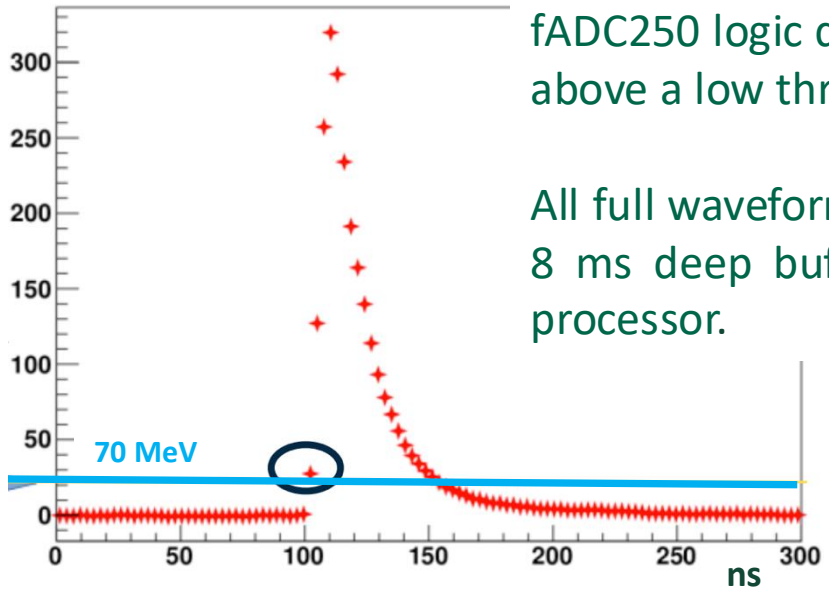
about × 3 for this setting

μ-metal shielding of the PMTs minimizes the effect of the fringe field on the PMTs



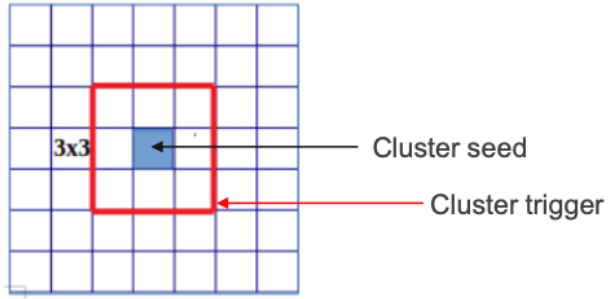
5%

High luminosity: semi-streaming DAQ



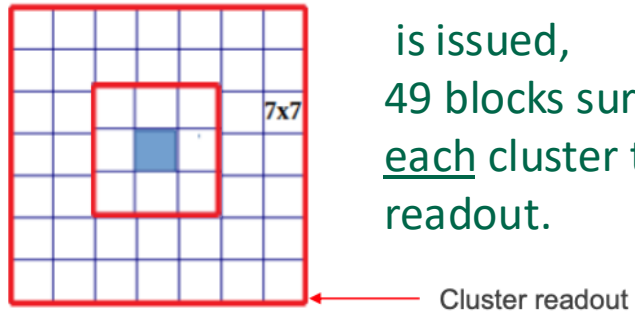
fADC250 logic detects any PMT signal above a low threshold.

All full waveforms are streamed to the 8 ms deep buffer of the VXS trigger processor.



A threshold of 1600 MeV is applied on the sum of the 9 blocks of a cluster with signals within 20 ns of each other.

We detect 5-10 GeV photons.

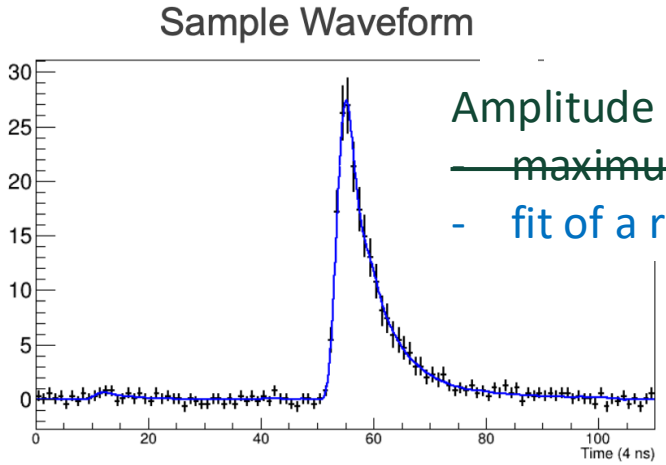


If an external trigger is issued,
49 blocks surrounding <u>each</u> cluster triggers are readout.

Achieved 240 MBy/s or about 2.5 kHz of data with 90% live time.
We usually recorded between 100-200 blocks.

DAQ bandwidth was sometimes a limitation to the luminosity.

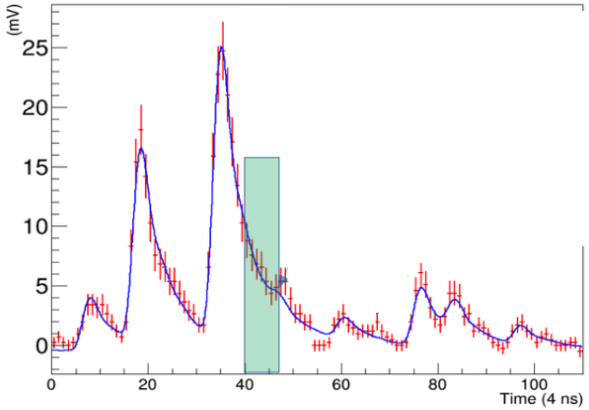
High energy resolution at high luminosity: waveform fitting



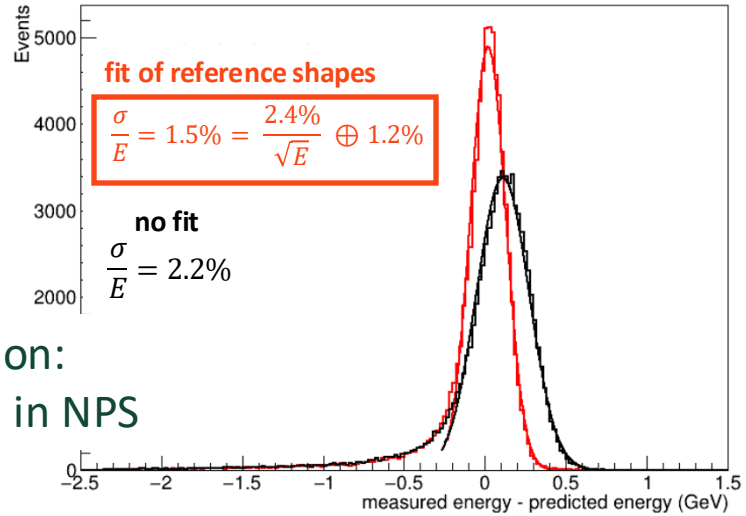
Amplitude detected by :

- ~~maximum voltage (no fit), or~~
- fit of a reference shape

very clean waveform: 1 pulse

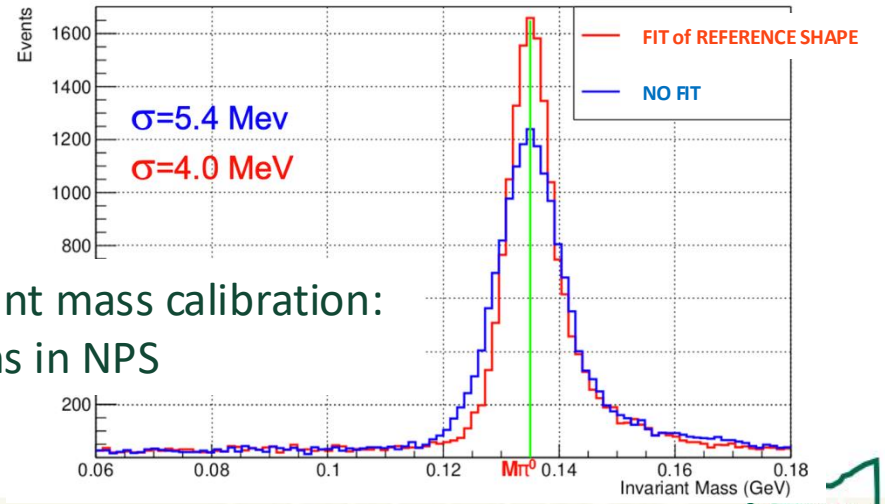


very busy waveform: 7 pulses



Elastic calibration:
7 GeV electron in NPS

Consistent with PRIMEX resolution at much lower luminosity
(M. Kubantsev et al., AIP Conf. Proc. 867:51-58, 2006)



Pion invariant mass calibration:
two photons in NPS

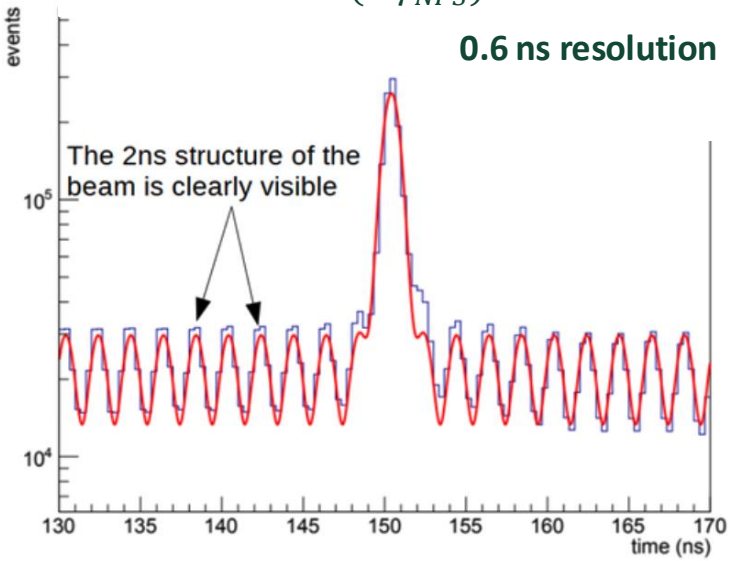
Study by M. Mazouz and W. Hamdi

High energy resolution at high luminosity: exclusivity results

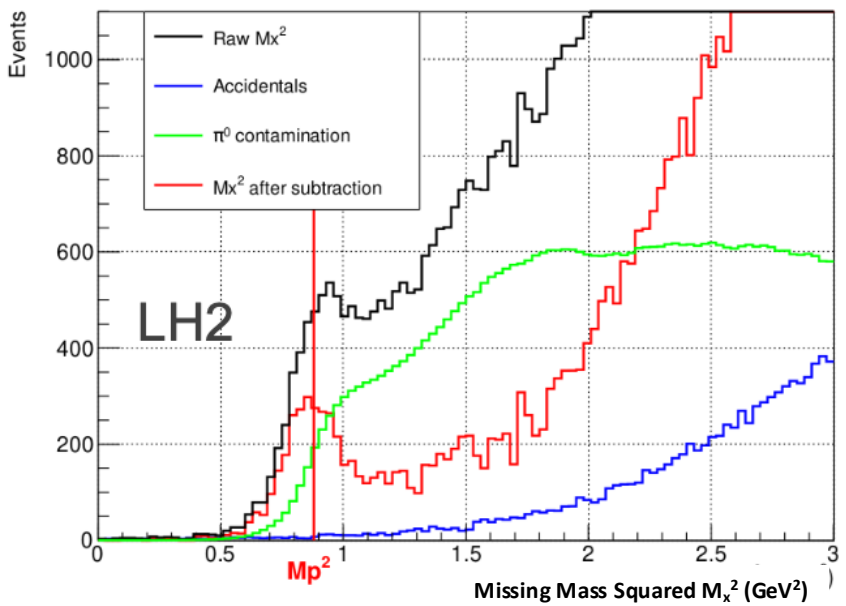
The NPS Science Program includes
10 JLab-approved experiments studying nucleon structure through exclusive and semi-inclusive reactions.

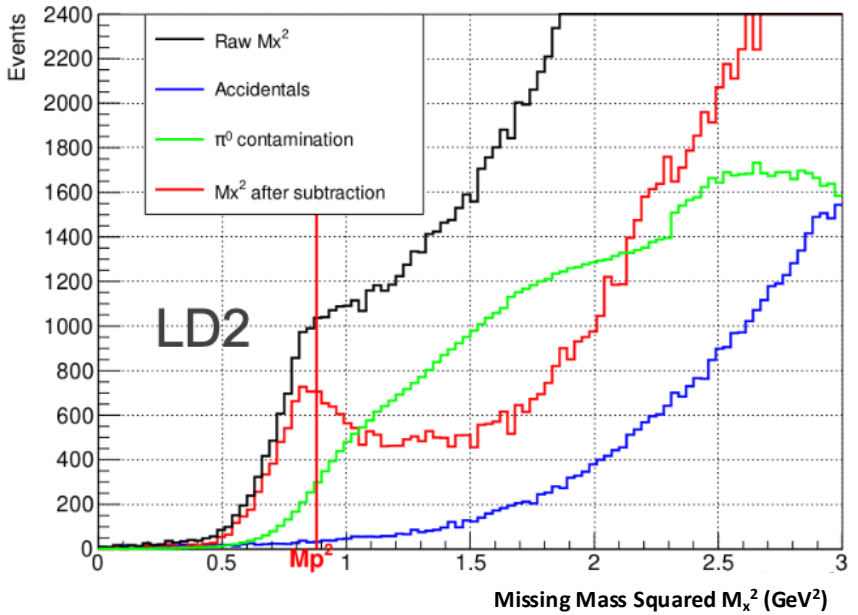
Fall 23-Spring 24 experiments:
DVCS
Exclusive pion production
Semi-inclusive pion production
LH2 and LD2 targets

coincidence time $(e'\gamma_{NPS})$



$H(e, e'\gamma_{NPS})X$





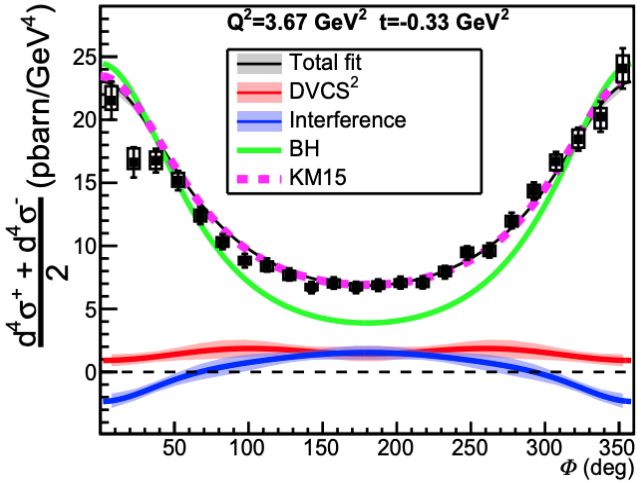
Study by W. Hamdi

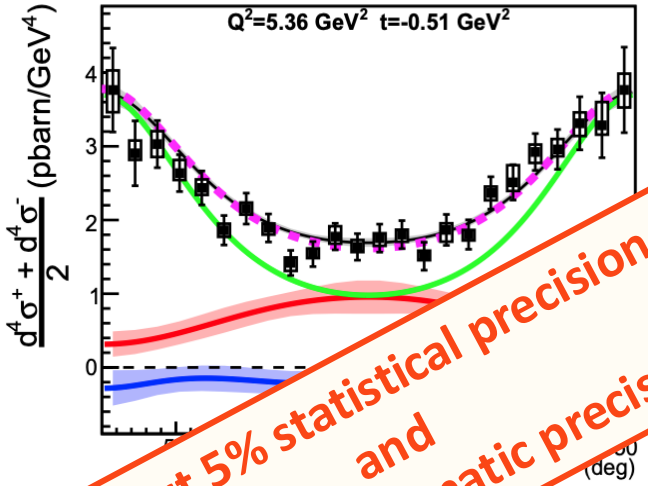
DVCS in Hall A: 12 GeV results.

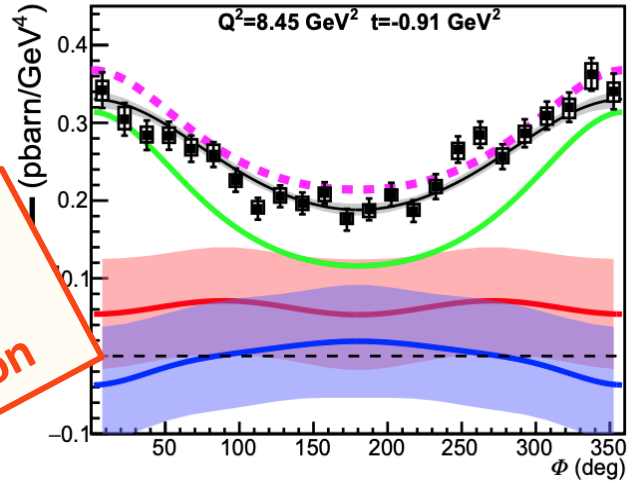
F. Georges et al., Phys.Rev.Lett. 128 (2022) 25, 252002

$$\frac{d^4\sigma(lp \to lp\gamma)}{dx_B dQ^2 d|t| d\phi} = d\sigma^{BH} + d\sigma^{DVCS}_{unpol} + P_l \; d\sigma^{DVCS}_{pol} + e_l \left(Re(I) + P_l Im(I)\right)$$

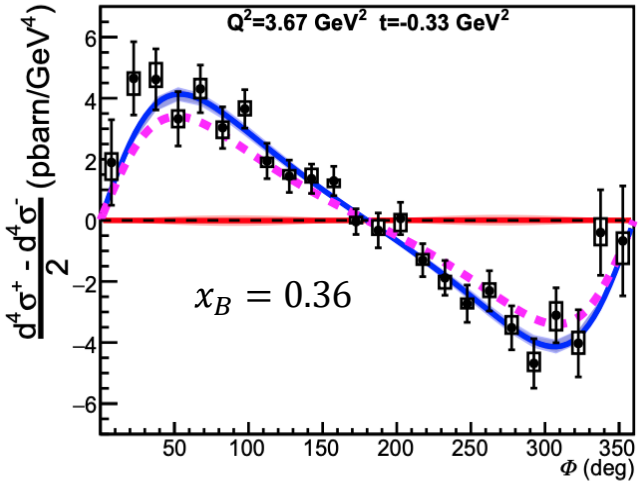
BH | DVCS² | Interference

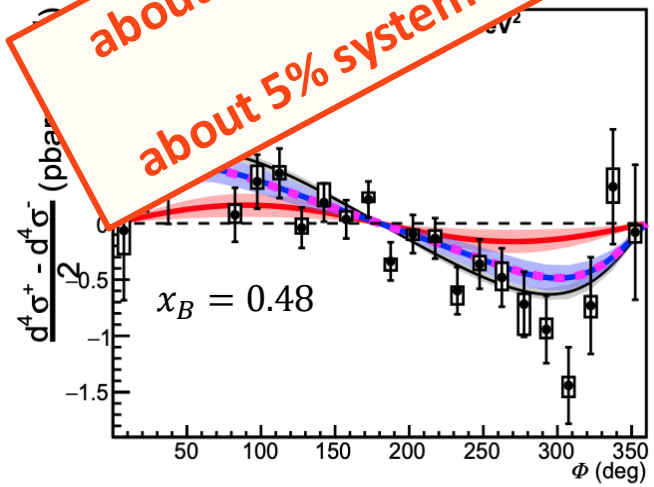


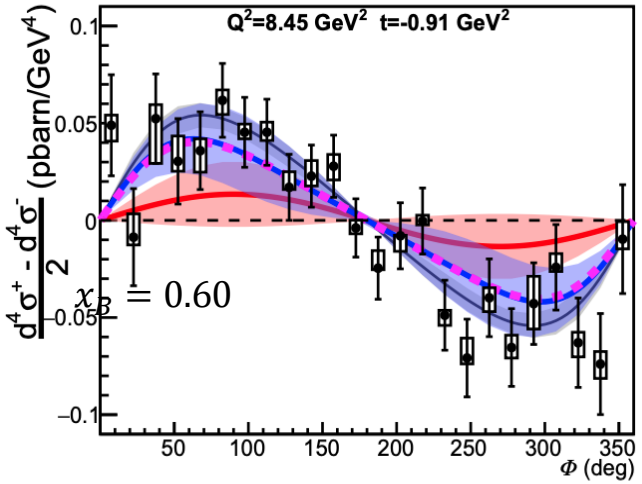


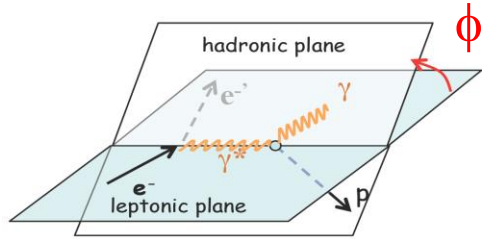


about 5% statistical precision
and
about 5% systematic precision









Braun-Manashov-Müller-Pirnay formalism, Phys. Rev. D 89, 074022 (2014).

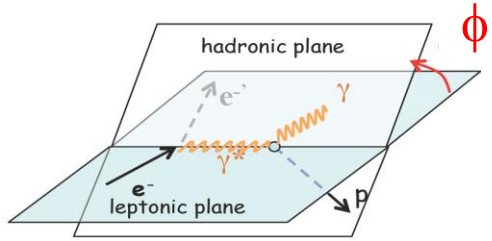
[KM15] K. Kumericki and D. Mueller,
EPJ Web Conf. 112 (2016) 01012

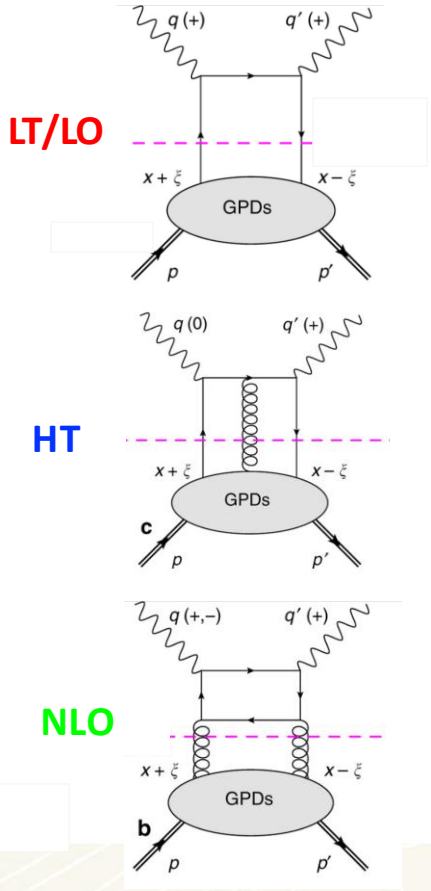
How to parametrize the DVCS cross-sections?

$$\frac{d^4\sigma(lp \to lp\gamma)}{dx_B dQ^2 d|t| d\phi} = d\sigma^{BH} + d\sigma^{DVCS}_{unpol} + P_l \; d\sigma^{DVCS}_{pol} + e_l \left(Re(I) + P_l Im(I)\right)$$

$$\begin{aligned}
d\sigma^{BH} &\propto c_0^{BH} + c_1^{BH}\cos\phi + c_2^{BH}\cos 2\phi \\
d\sigma^{DVCS}_{unpol} &\propto c_0^{DVCS} + c_1^{DVCS}\cos\phi + c_2^{DVCS}\cos 2\phi \\
d\sigma^{DVCS}_{pol} &\propto s_1^{DVCS}\sin\phi \\
Re\ I &\propto c_0^{I} + c_1^{I}\cos\phi + c_2^{I}\cos 2\phi + c_3^{I}\cos 3\phi \\
Im\ I &\propto s_1^{I}\sin\phi + s_2^{I}\sin 2\phi
\end{aligned}$$

$$s_1^I = F_1\mathcal{H} + \xi(F_1 + F_2)\tilde{\mathcal{H}} + kF_2\mathcal{E}$$





World-wide GPDs analysis include more or less terms: both in terms of harmonics (c_i's and s_i's) and in term of GPD/CFFs.

DVCS in Hall A program

1st Generation (2004)

Q^2 dependence of the red terms

- Hint of factorization over a small Q^2 range

2nd Generation (2010)

Beam energy dependence study at fixed x_B and Q^2

- Separate C_0^{DVCS} from C_0^I
- Separate HT and NLO from LT/LO coefficients but not from each others

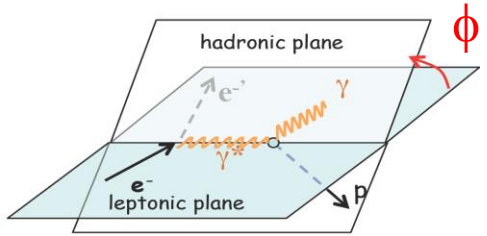
3rd Generation (2014-2016)

Multiple x_B and Q^2 measurements

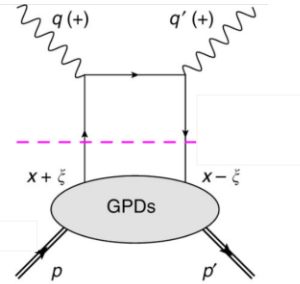
- Experimental extraction of the CFFs as a function of x_B
- Importance of considering all CFFs when extracting CFFs

$$
\begin{aligned}
d\sigma^{BH} &\propto c_0^{BH} + c_1^{BH}\cos\phi + c_2^{BH}\cos 2\phi \\
d\sigma_{unpol}^{DVCS} &\propto c_0^{DVCS} + c_1^{DVCS}\cos\phi + c_2^{DVCS}\cos 2\phi \\
d\sigma_{pol}^{DVCS} &\propto s_1^{DVCS}\sin\phi \\
\mathrm{Re}\, I &\propto c_0^I + c_1^I\cos\phi + c_2^I\cos 2\phi + c_3^I\cos 3\phi \\
\mathrm{Im}\, I &\propto s_1^I\sin\phi + s_2^I\sin 2\phi
\end{aligned}
$$

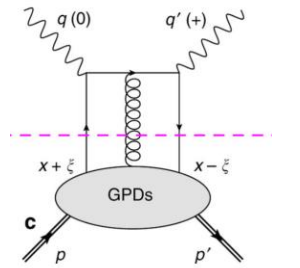
$$s_1^I = F_1\mathcal{H} + \xi(F_1+F_2)\tilde{\mathcal{H}} + kF_2\mathcal{E}$$



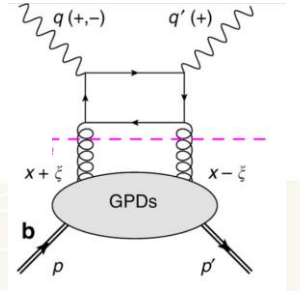
LT/LO



HT

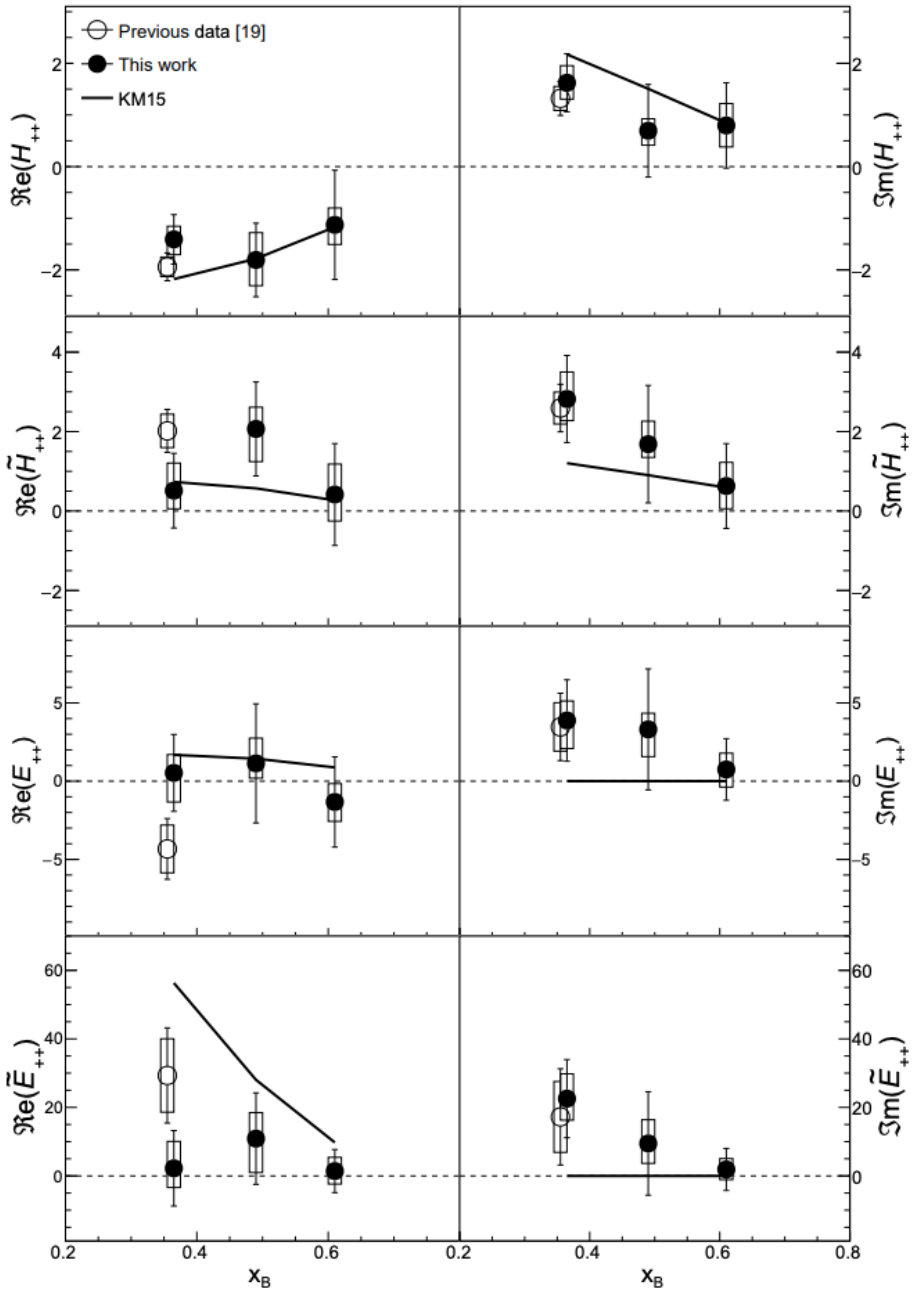


NLO



Results from Hall A:
off LH2 and LD2 (neutron)
on DVCS and DVMP- π^0

DVCS in Hall A: 12 GeV results



The average t values are **−0.281 GeV²** for [19] and **−0.345**, **−0.702**, **−1.050 GeV²** at xB=**0.36**, 0.48, 0.60, respectively for this work..

- [This work] F. Georges, Phys.Rev.Lett. 128 (2022) 25, 252002
  - Error bars: statistical
  - Error boxes: systematic
- [19] M. Defurne et al., Phys. Rev. C92, 055202 (2015)
- [KM15] K. Kumericki and D. Mueller, EPJ Web Conf. 112 (2016) 01012

The precise measurement of cross-sections at the same x_B-Q^2 bin but multiple beam energies is essential for this extraction.

Also demonstrated in
- M. Defurne et al., Nat. Commun. 8, 1408 (2017).
- B. Kriesten et al., Phys. Rev. D 101, 054021 (2020).
- M. Čuić et al., Phys. Rev. Lett. 125, 232005 (2020).

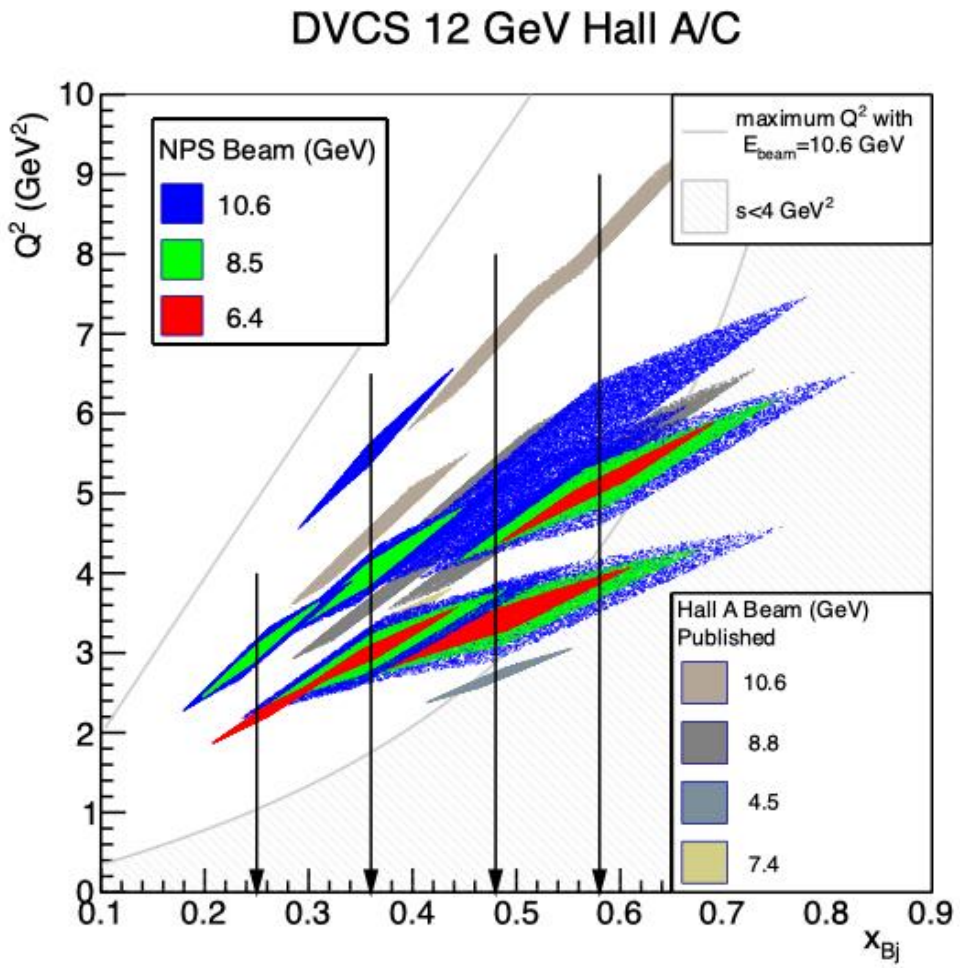
$CFF_{\lambda\lambda'}$ λ : polarization state of virtual photon (0,+,-)
λ□: polarization state of outgoing real photon (+,-)

Fit has 24 CFF

$$(\tilde{H}, H, \tilde{E}, E) \otimes (\Re e, \Im m) \otimes (++, 0+, +-)$$

but only the results from the LO ones (++) are shown.
Fits performed at constant x_B and t over Q^2 and ϕ bins.
No Q^2 evolution of the CFFs.

NPS data set: analysis on going



$\Delta(t\text{-}t_{min})$ range:
- depends on the electron kinematics and the NPS-target distance
- from 0.08 (x_B=0.25) to 0.7(x_B=0.58) GeV^2

Analysis status

Completed:
- beam line charge, energy, and polarization
- HMS detectors
- HMS optics (momentum above 5.5 GeV)

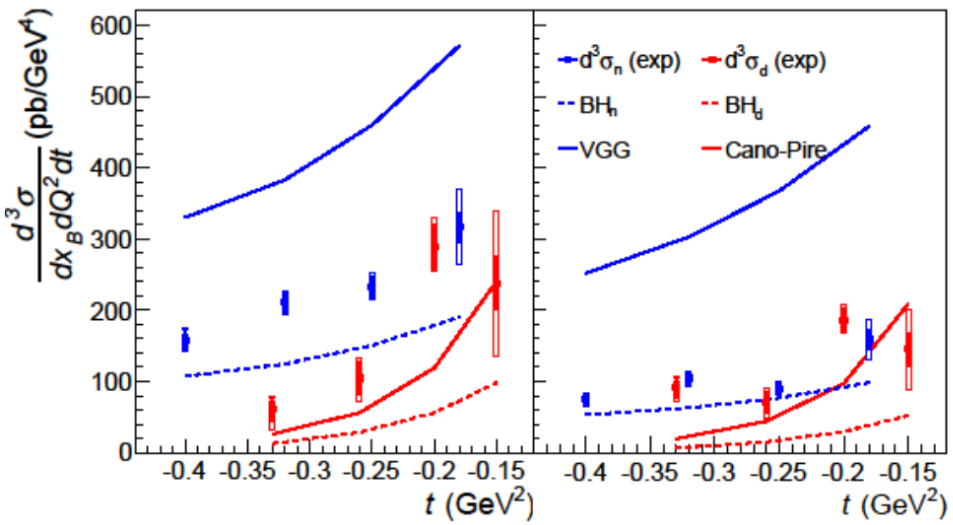
In progress:
- NPS Wave form fitting (multi threading)
- NPS energy calibration
- Match of NPS simulation with data
- Benchmarking against DIS cross sections (LH2 target issue)

DVCS@Hall A neutron data

Combined neutron and proton targets data allow for flavor separation of the GPDs.

Neutron data are uniquely sensitive to the elusive GPD E (no connection to PDFs).

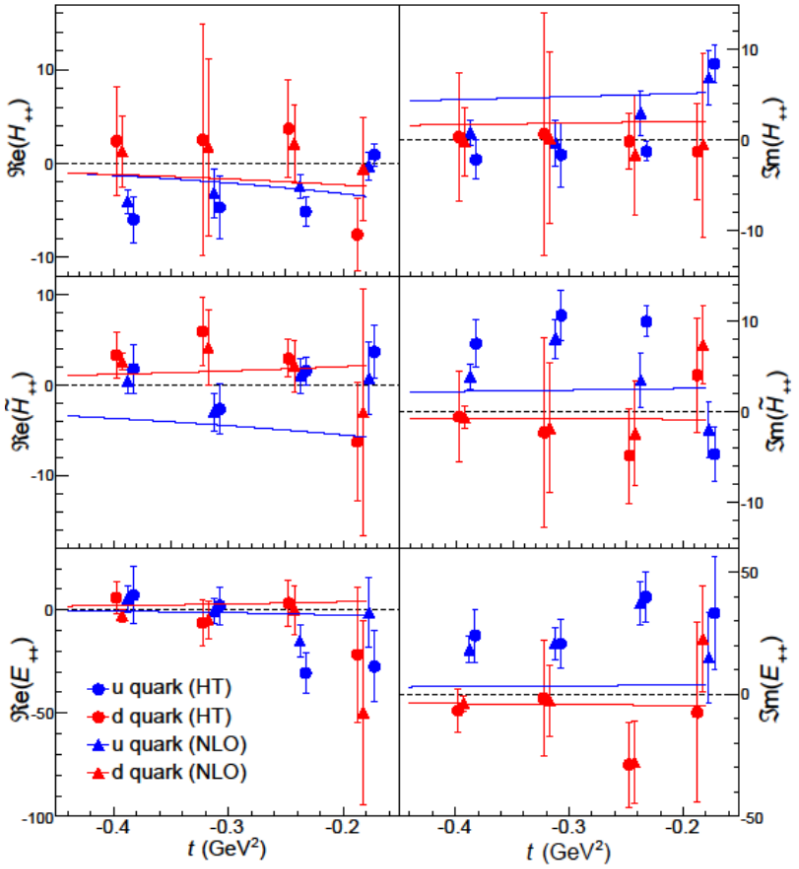
Cross section measurements from E08-205



Q^2=1.9 GeV^2, x_B=0.36

Benali et al, Nature Phys. 16, 191 (2020)

Flavor separation of Compton Form Factors



Extracting DVCS neutron data

Below the two pions threshold
Assume impulse approximation

$$D(e,e'\pi^0)X = d(e,e'\pi^0)d + n(e,e'\pi^0)n + p(e,e'\pi^0)p.$$

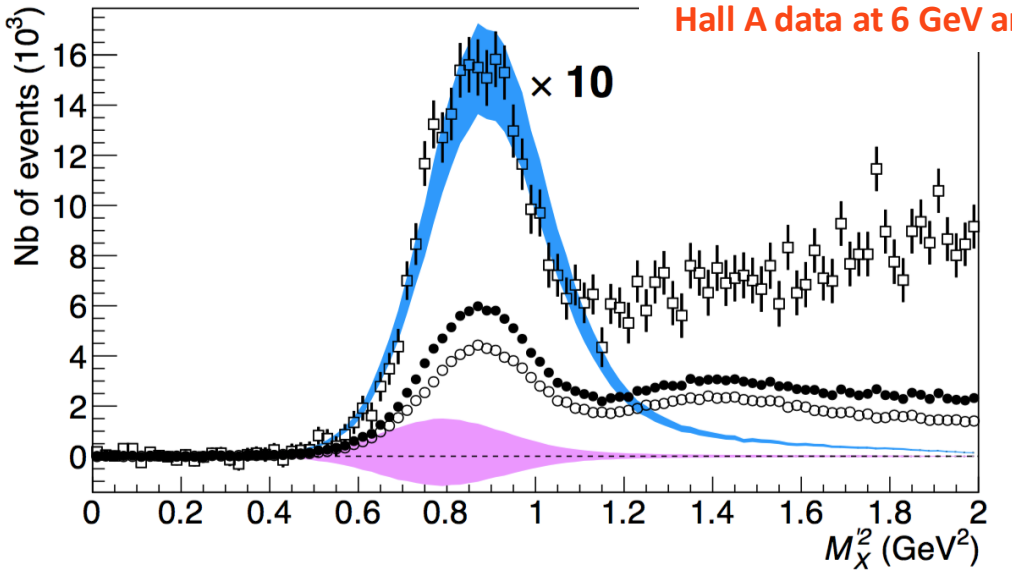
- ● LD2
- ○ LH2
- □ LD2-LH2

- $d(e,e'\pi^0)d$
- $n(e,e'\pi^0)n$

separated by

$$\Delta M_X^2 = t(1 - M/M_d) \approx t/2$$

Figure from M. Mazouz PRL 118 (2017) 22, 222002
Hall A data at 6 GeV and with a PbF2 calorimeter



Computed for $n(e,e'\pi^0)X$

Using the PbW04 calorimeter with NPS kinematics

12 GeV → higher x_B → higher t_{min}

NPS has higher energy resolution → smaller $\sigma_{M_x^2}$

nominally 2 to 12 times better separation of nDVCS and dDVCS at 12 GeV with NPS at high x_B

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The NPS detects high-energy photons in high-radiation and high-rate environments.

PbWO4 will be used at the EIC as part of the EEEMCal calorimeter.

The NPS was successfully used for the first time from September 2023 to May 2024.

All channels performed well at very high luminosity on LH2 and LD2 ($\sim 8 \times 10^{37} cm^2/s$).

The expected energy resolution was achieved (1.3% at 7 GeV).

Our analysis of the DVCS and exclusive and inclusive π^0 NPS data is ongoing.

Thank you for your attention!