Measurement of DVCS on protons with the Neutral Particle Spectrometer in Hall C at Jefferson Lab

DIS2026

- Introduction
- Experimental setup in Hall C
- DVCS cross section extraction
- Preliminary proton DVCS cross section
- Summary & outlook

Hao Huang

on behalf of the NPS collaboration

DIS2026 conference

2026.05.05

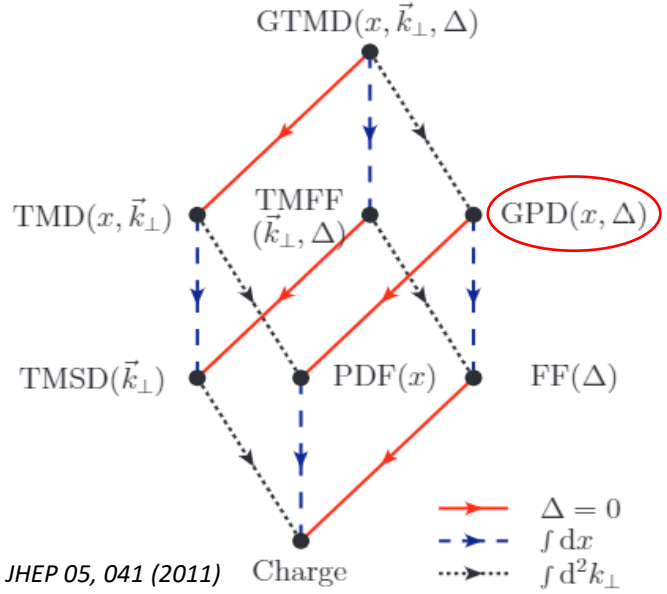
NPS Jefferson Lab Exploring the Nature of Matter

IJCLab Irène Joliot-Curie Laboratoire de Physique des 2 Infinis

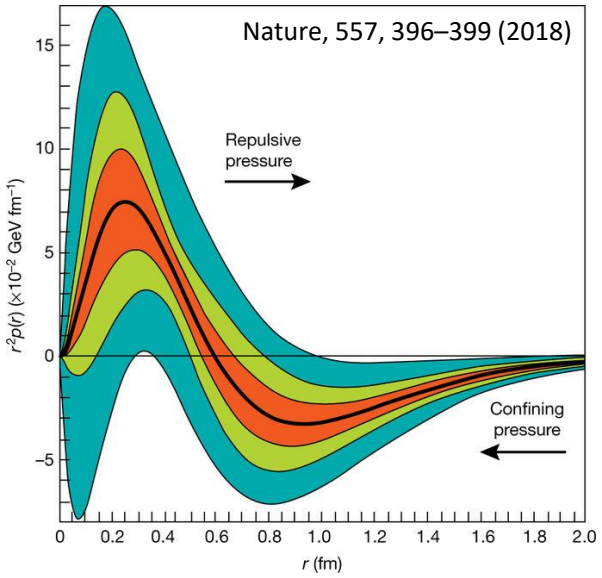
cnrs IN2P3 Institut national de physique nucléaire et de physique des particules

Generalized Parton Distributions (GPDs)

- FFs and PDFs lack spatial–momentum correlation information
- GPDs, introduced in 1990s, offer insights into the 3D structure of the nucleon



JHEP 05, 041 (2011)

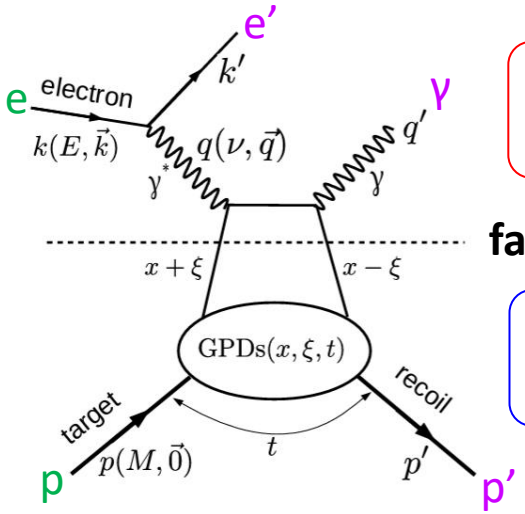


- ✓ Correlation between spatial and momentum distributions
- ✓ Access to radial pressure distribution
- ✓ Quark and gluon total angular momentum contribute to nucleon spin (Ji's sum rule)

- GPDs are accessible via exclusive processes
  - Deeply Virtual Compton Scattering (DVCS)
  - Double DVCS (DDVCS)
  - Deeply Virtual Meson Production (DVMP)

Deeply Virtual Compton Scattering (DVCS)

- DVCS ($ep \rightarrow e'p'\gamma$) is the simplest probe to investigate GPDs
- Experimentally, GPDs are accessed by DVCS via Compton form factors (CFFs)

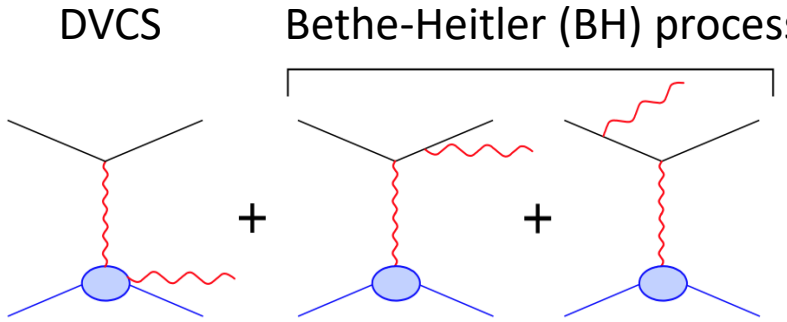


Hard process
- perturbatively calculable

factorization

Soft process
- parametrized by GPDs

$ep \rightarrow e'p'\gamma$ =



(cannot be separated experimentally)

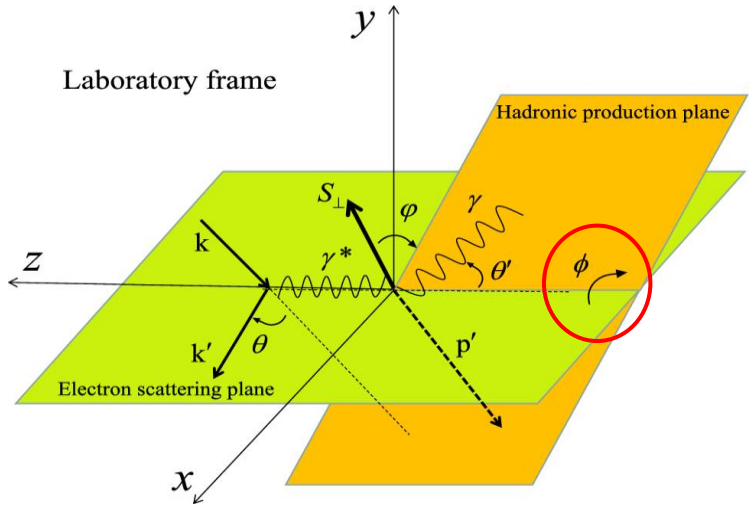
- $\frac{d^4\sigma}{dQ^2 dx_B j dt d\phi}(ep \rightarrow e'p'\gamma) \propto \underbrace{|T_{BH}|^2}_{\text{pure QED process}} + \underbrace{|T_{DVCS}|^2}_{\text{bi-linear combination of CFFs}} + \underbrace{I(BH \cdot DVCS)}_{\text{linear combination of CFFs and FFs}}$

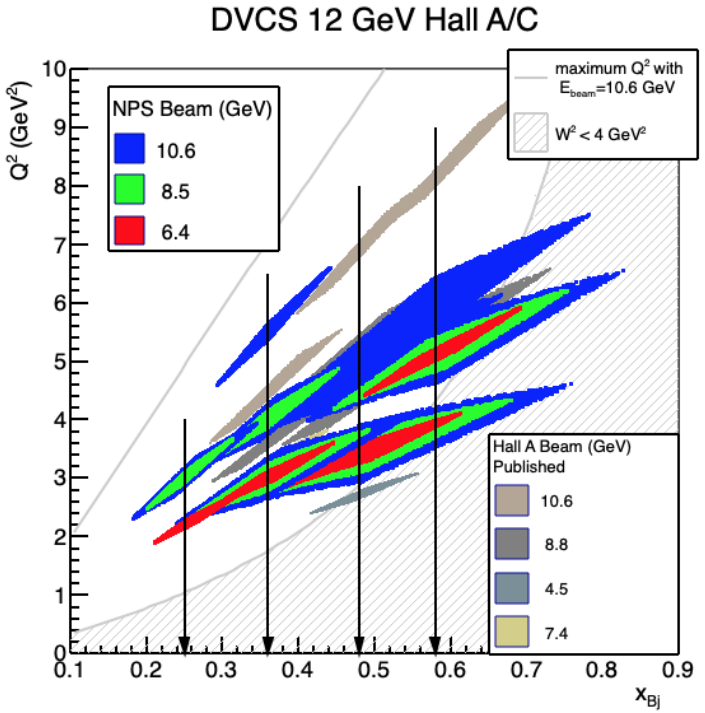
T_{BH}: Amplitude of Bethe-Heitler process
T_{DVCS}: DVCS amplitude
I: interference term

Disentangle DVCS and interference term by kinematical dependence

- At leading twist:
  - $\frac{d^4\sigma^{\rightarrow} - d^4\sigma^{\leftarrow}}{2} \propto \Im[I(BH \cdot DVCS)]$
  - $\frac{d^4\sigma^{\rightarrow} + d^4\sigma^{\leftarrow}}{2} \propto \underbrace{|\mathrm{T}_{BH}|^2}_{\text{known to 1\%}} + \underbrace{|T_{DVCS}|^2}_{\propto E_{beam}^2,\ \phi\text{ dependence}} + \underbrace{\Re[I(BH \cdot DVCS)]}_{\propto E_{beam}^3,\ \phi\text{ dependence}}$

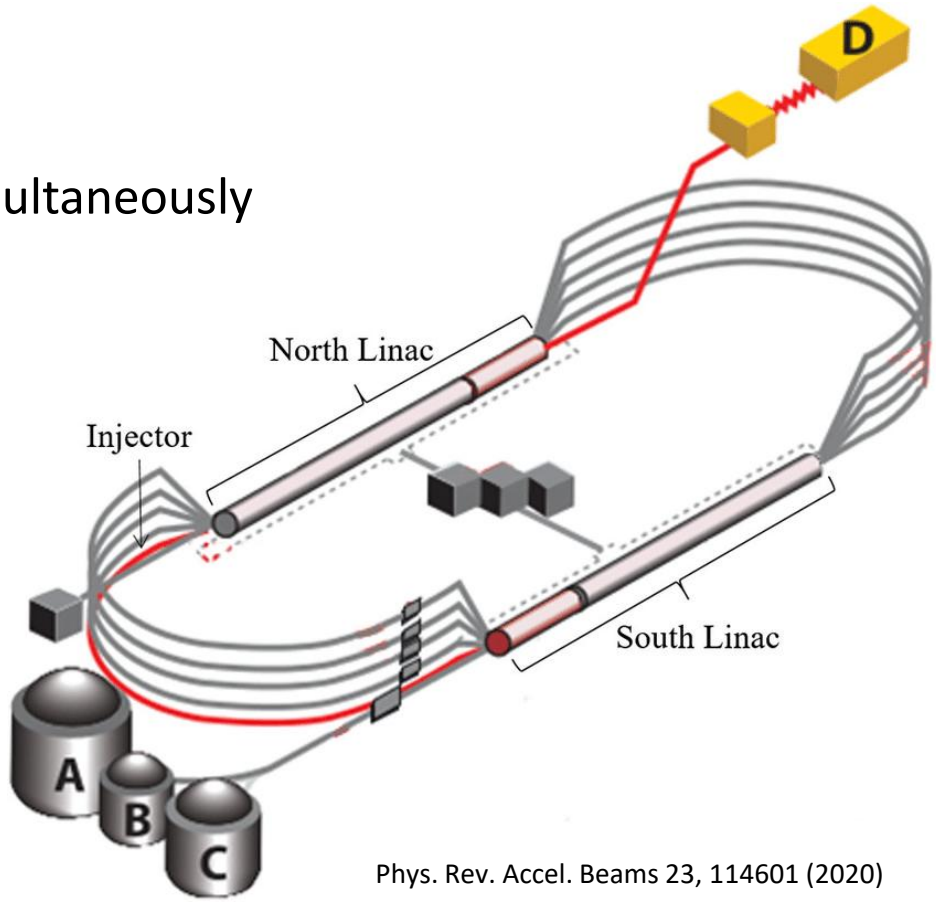
Beam helicity dependence
($\sigma^{\rightarrow}$ & $\sigma^{\leftarrow}$: positive & negative helicity)





Thomas Jefferson National Accelerator Facility (Jefferson Lab or JLab)

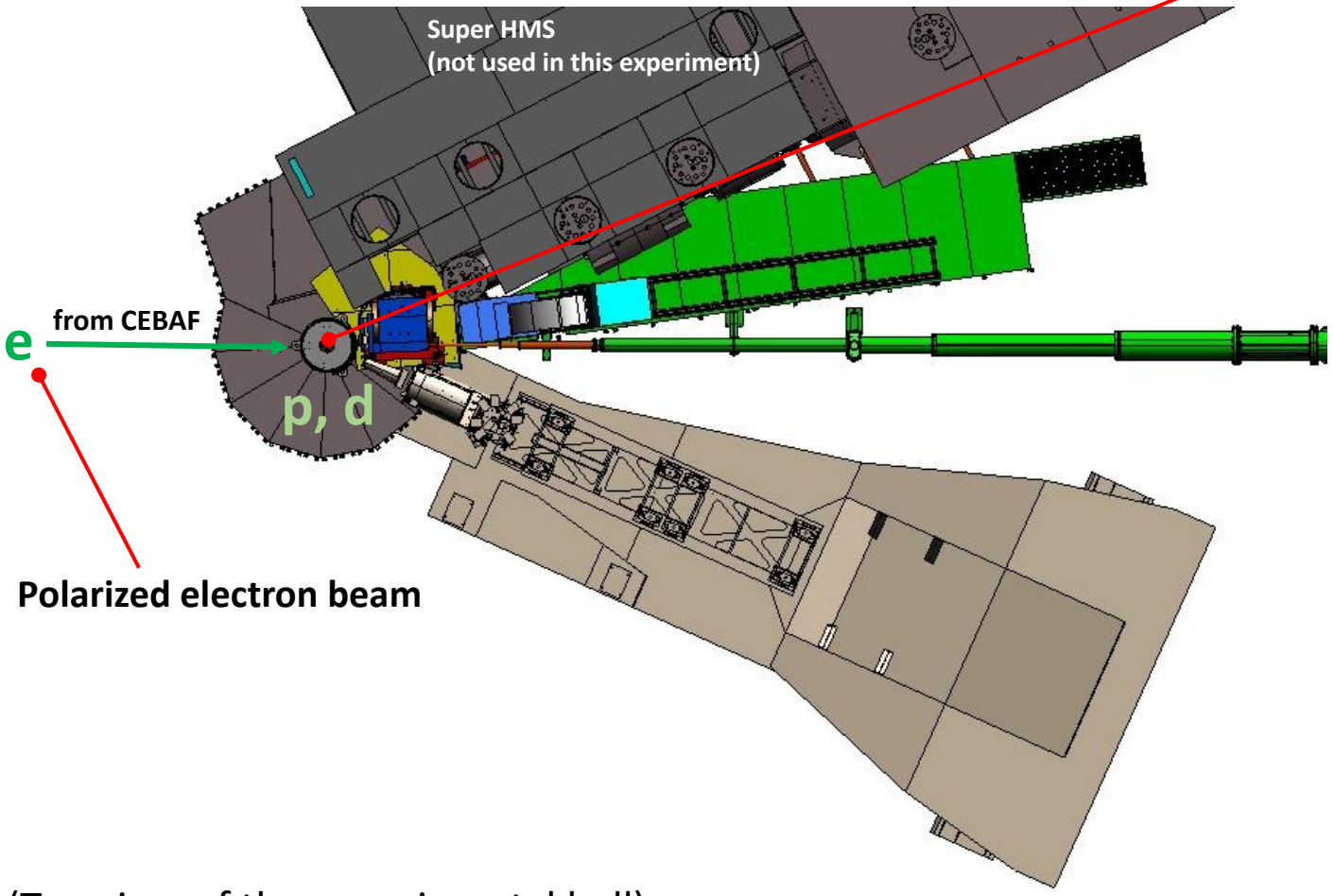
- Newport News, Virginia, USA
- Continuous Electron Beam Accelerator Facility (CEBAF)
  - Polarized electrons, up to 12 GeV
  - Delivers continuous beam to different Halls (A, B, C ,and D) simultaneously
  - Rich opportunities for nuclear physics



Phys. Rev. Accel. Beams 23, 114601 (2020)

DVCS experimental setup in Hall C

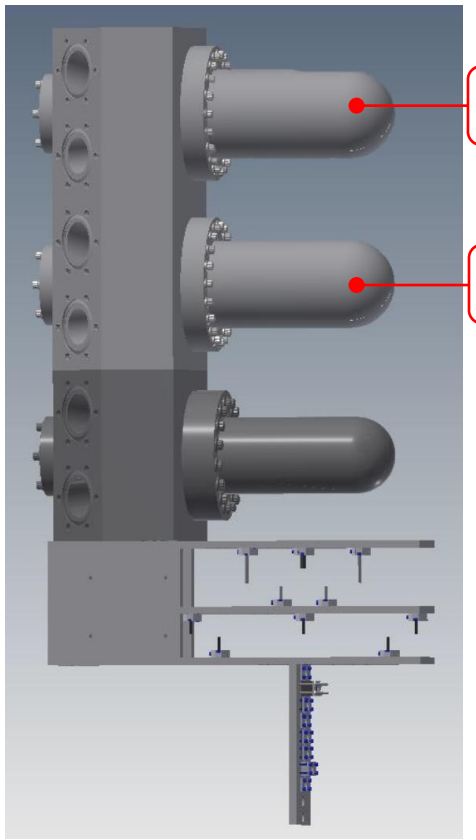
Run period: Sep. 2023 – May 2024



(Top view of the experimental hall)

Target chamber

- Unpolarized targets in 10 cm AL cell

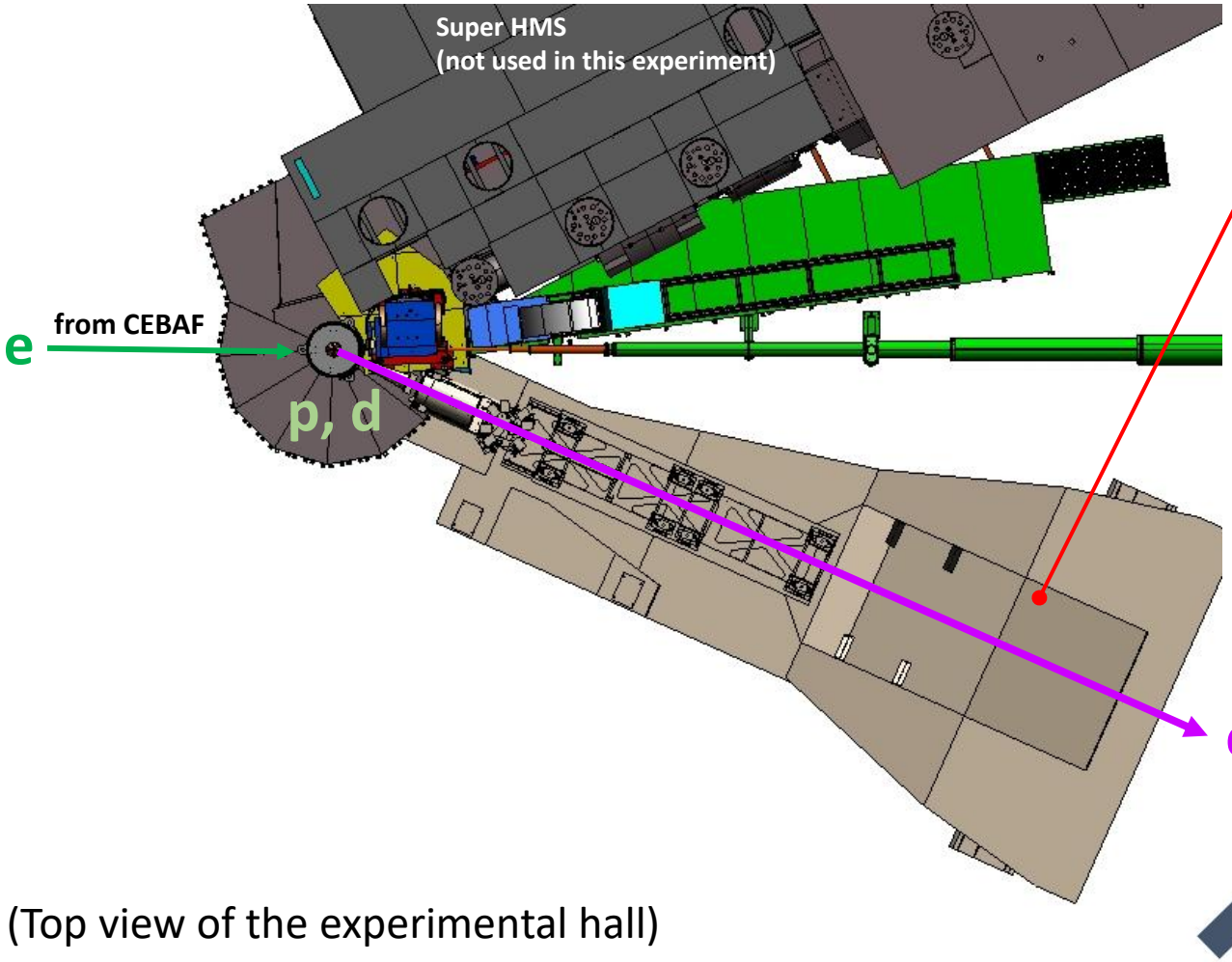


⬆CAD views of the cryogenic and solid target ladders

Jefferson Lab Hall C Standard Equipment Manual

DVCS experimental setup in Hall C

Run period: Sep. 2023 – May 2024



(Top view of the experimental hall)

High Momentum Spectrometer (HMS)

- Tracking of scattered electrons
- Trigger on events
- Particle identification

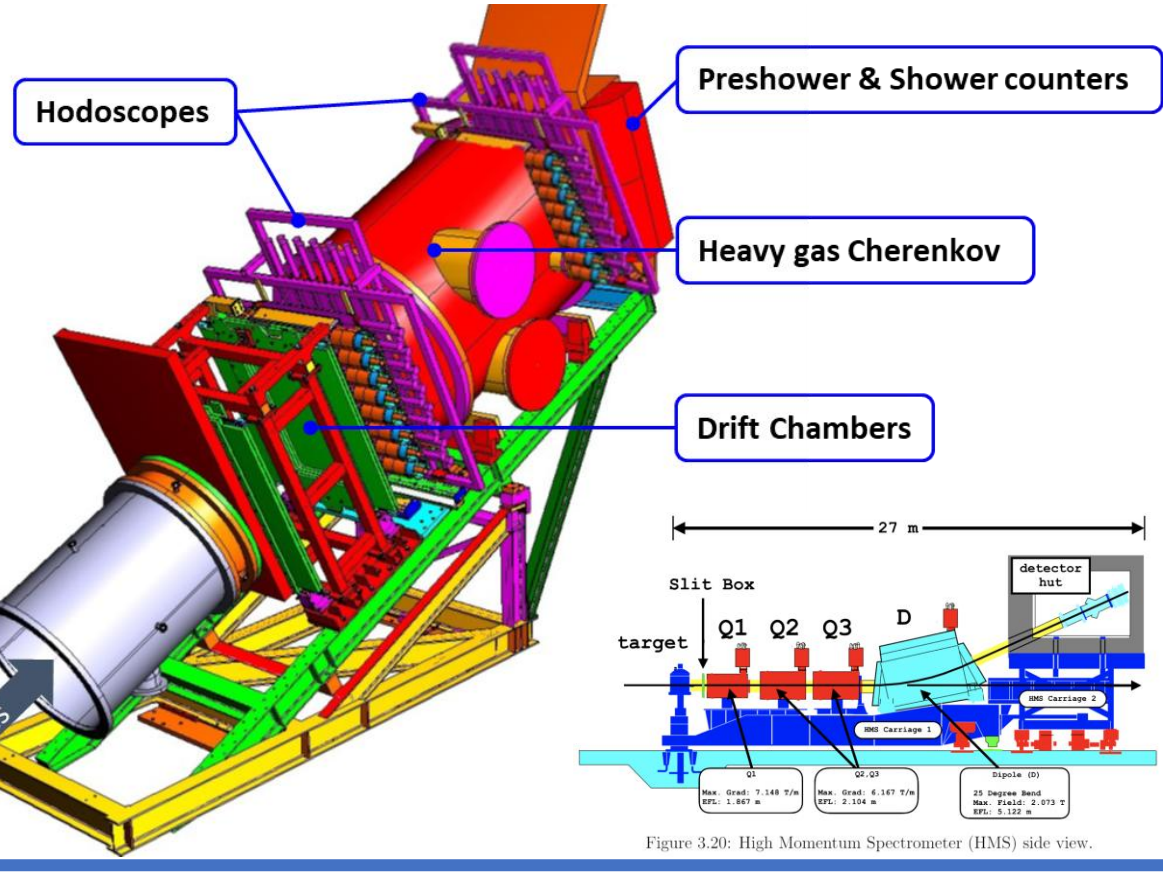
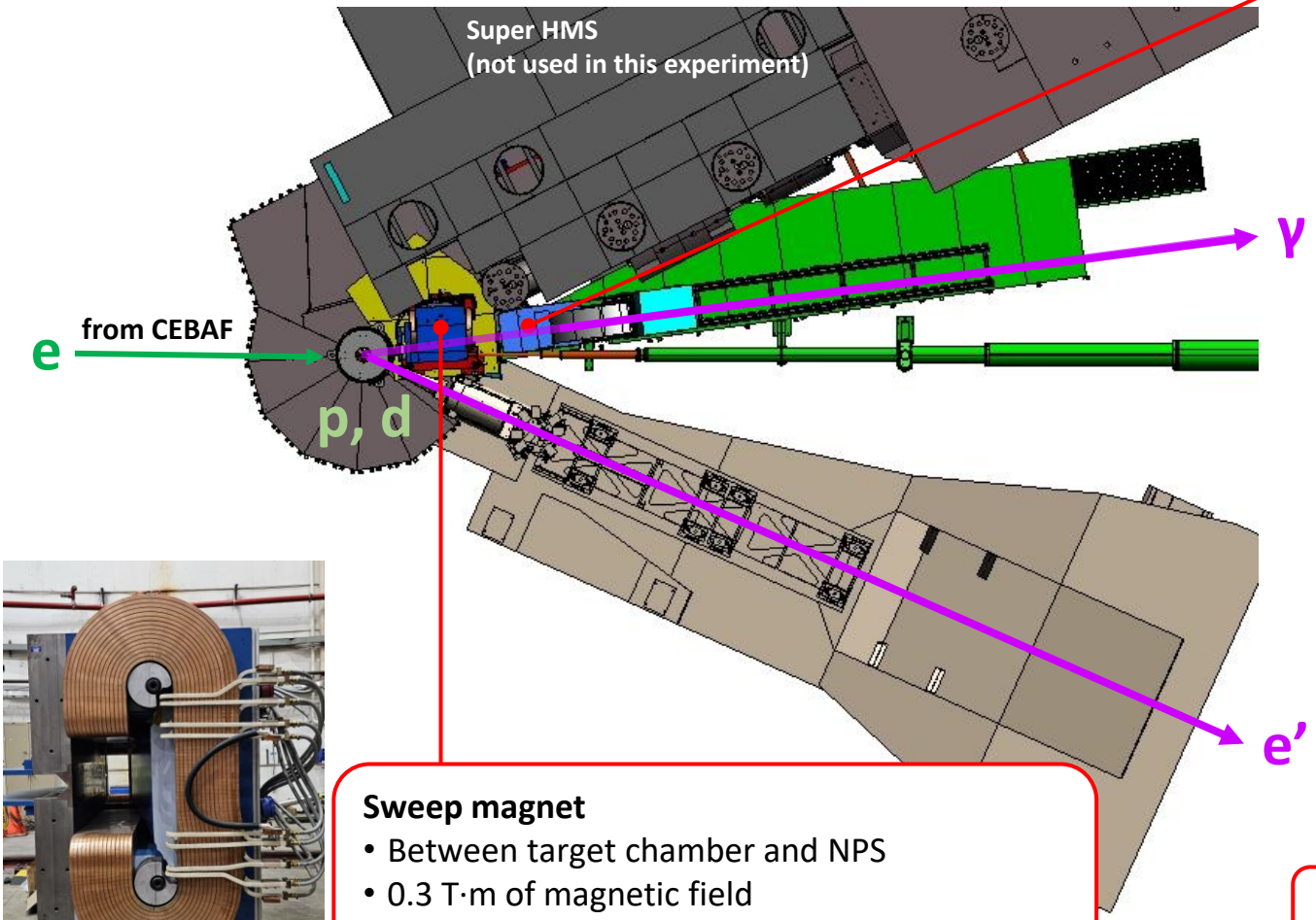


Figure 3.20: High Momentum Spectrometer (HMS) side view.

DVCS experimental setup in Hall C

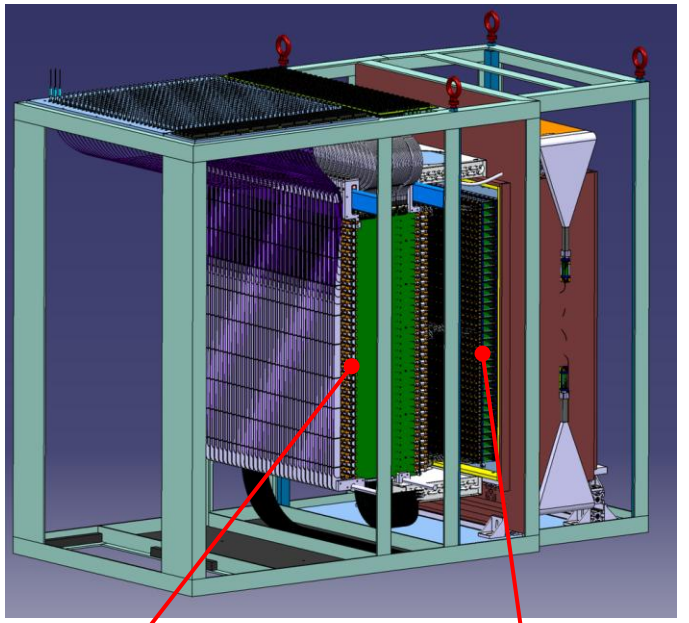
Run period: Sep. 2023 – May 2024



Sweep magnet
- Between target chamber and NPS
- 0.3 T·m of magnetic field
- Reduce the low energy background electrons

Neutral Particle Spectrometer (NPS)

- Detect emitted photon with high resolution
- Array of 1080 $PbWO_4$ crystals
- Newly installed on a platform attached to Super HMS



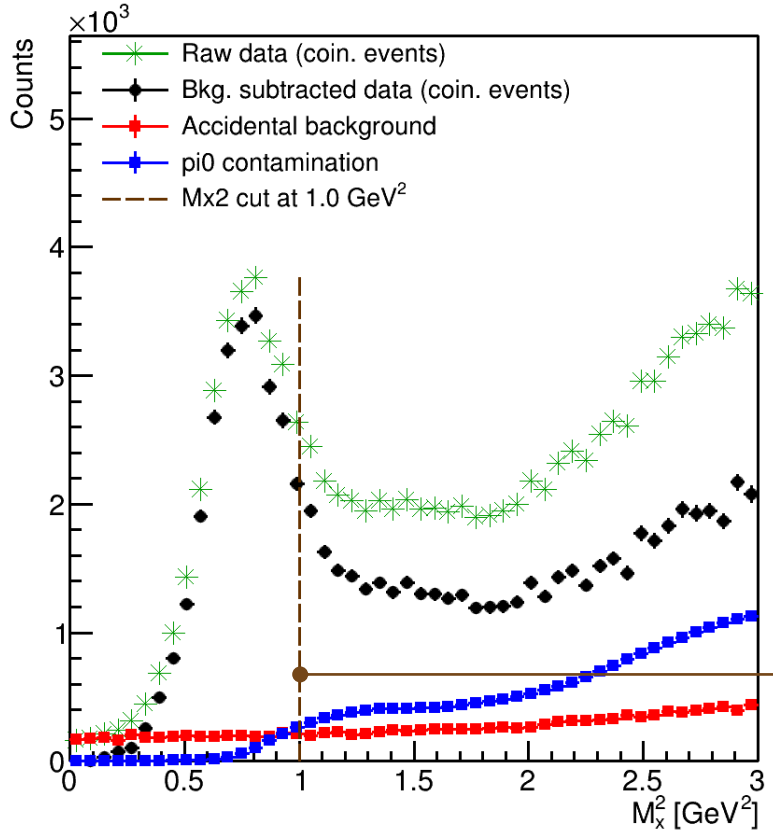
Distribution boards for signal and high voltages

Photomultipliers (**PMTs**) and **HV divider base**

Front view of **30×36 NPS crystal array**

DVCS signal extraction: missing-mass technique

- Missing mass square $M_x^2 = (k_e + P_p - k'_e - q_\gamma)^2$ of recoil proton (undetected)



Raw M_x^2

- Photon timing in [-3, 3] (ns) compared to the timing of electron

Background subtraction

1. Accidental background: γ and e' from different events
2. π^0 contamination: photons from $\pi^0 \rightarrow \gamma\gamma$ asymmetric decay
3. SIDIS background
   - Lowest M_x^2: $ep \rightarrow e'\gamma p'\pi^0 \sim 1.15\ GeV^2$
   - Remove by a cut on M_x^2
   - Correction using simulation data

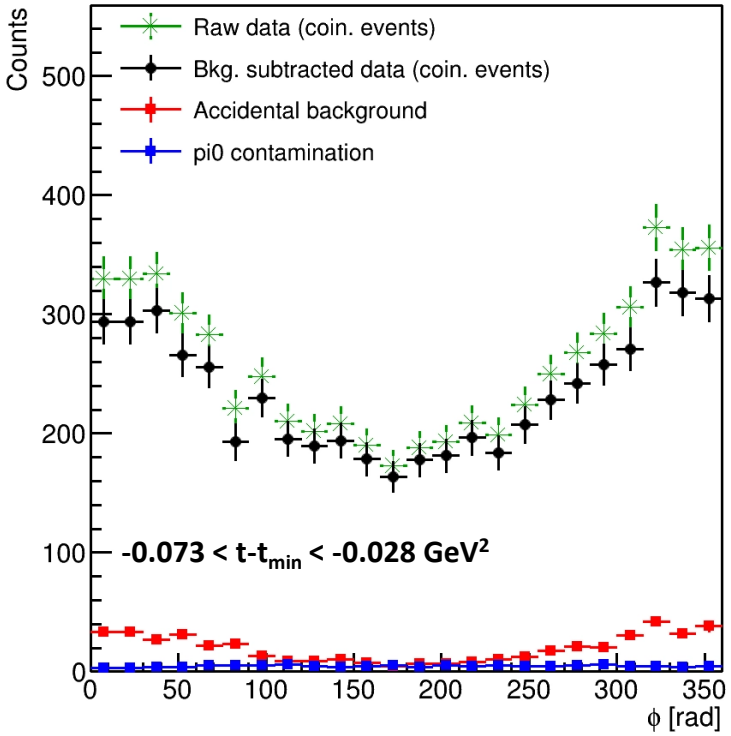
- E_γ resolution in NPS plays a key role for better signal–background separation
- σ_e/E_e = 1.2% to 1.3% between 4.5 GeV and 7.3 GeV after refined analysis and calibration

(Nucl. Instrum. Methods A 1086 (2026), 171323)

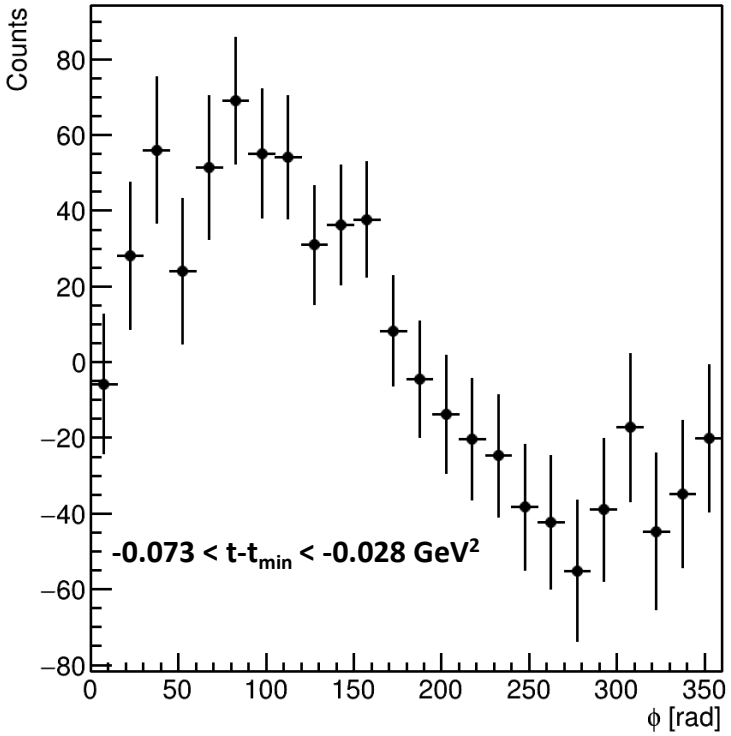
ϕ distributions of DVCS events

- Kinematics: $\langle Q^2 \rangle$ = 4 GeV^2, $\langle x_{Bj} \rangle$ = 0.36, E_{beam} = 10.54 GeV
- 5 bins of t-t_{min} between 0 and -0.35 GeV^2 (M_x^2 cut: 0 to 1 GeV^2)
- Background subtracted & detector efficiency corrected (tracking, electron PID)

Helicity **independent** distribution



Helicity **dependent** distribution



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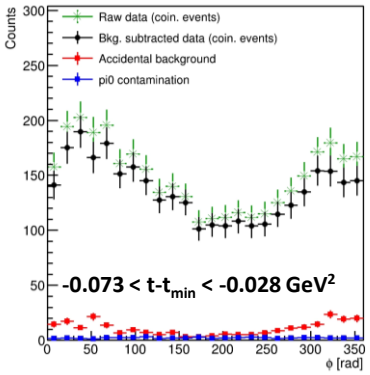
Positive helicity



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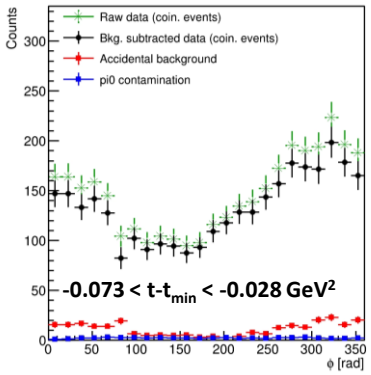
Negative helicity



Unfolding procedure (account for bin migration and resolution effects)

- The cross section is the summation of CFF combinations multiplied by kinematics pre-factors

$$\frac{d^4\sigma^{\rightarrow} \pm d^4\sigma^{\leftarrow}}{2} = \sum_{n=1}^{N} \Gamma^n(x) F^n(CFFs)$$

- $F^n(\mathrm{CFFs})$: the nth CFF combination
- $\Gamma^n(\mathrm{x})$: the corresponding pre-factor
- x: kinematic point (Q^2, x_{Bj}, t, ϕ)

- In a vertex bin v, the number of events N_v can be calculated:

$$N_v = \mathcal{L}_{int} \int_{x_v \in bin(v)} \left[\sum_{n=1}^{N} \Gamma^n(x_v) F_v^n \right] dx_v$$

- N_v cannot be measured directly, but in the generated level of the simulation

- In a reconstructed bin r, the number of events N_r is

$$N_r = \sum_{v=1}^{V} N_v K(x_r|x_v)$$

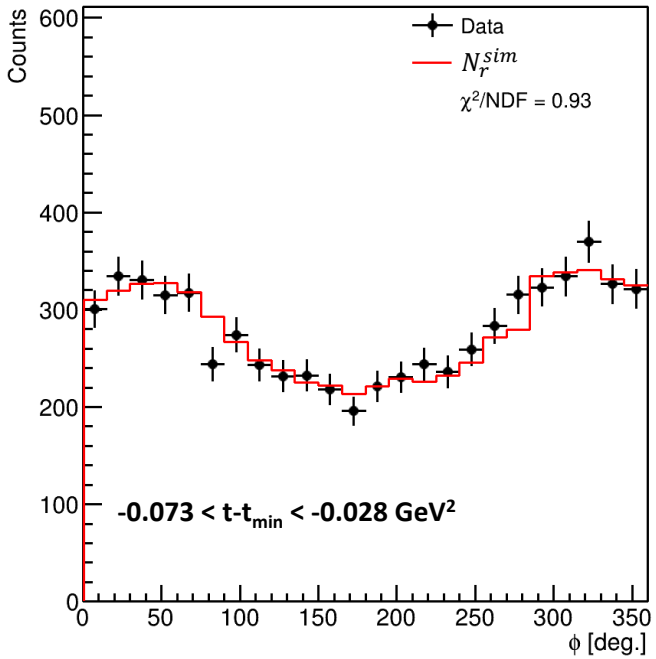
- $K(x_r|x_v)$: migration matrix, taking care of bin migration and detector acceptance
- N_r can be measured experimentally, and also in the reconstructed level of the simulation

- Minimizing $\chi^2(\langle F^n \rangle_v) = \sum_{i=1}^{R} \frac{(N_r^{exp} - N_r^{sim})^2}{(\sigma_r^{exp})^2}$ to extract $\langle F^n \rangle_v$

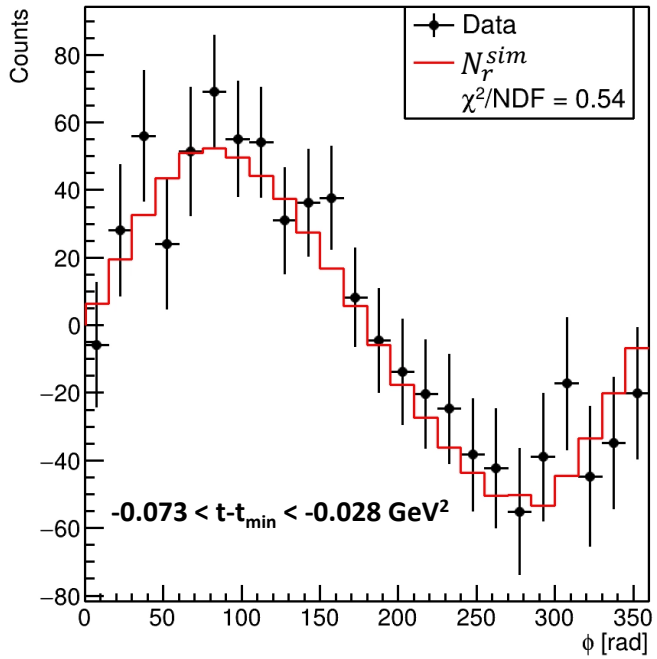
- N_r^{sim}: number of simulated events
- N_r^{exp}: experimental data
- σ_r^{exp}: experimental uncertainty (statistics)

Extraction of experimental cross section

Fitted result (helicity **independent**)



Fitted result (helicity **dependent**)



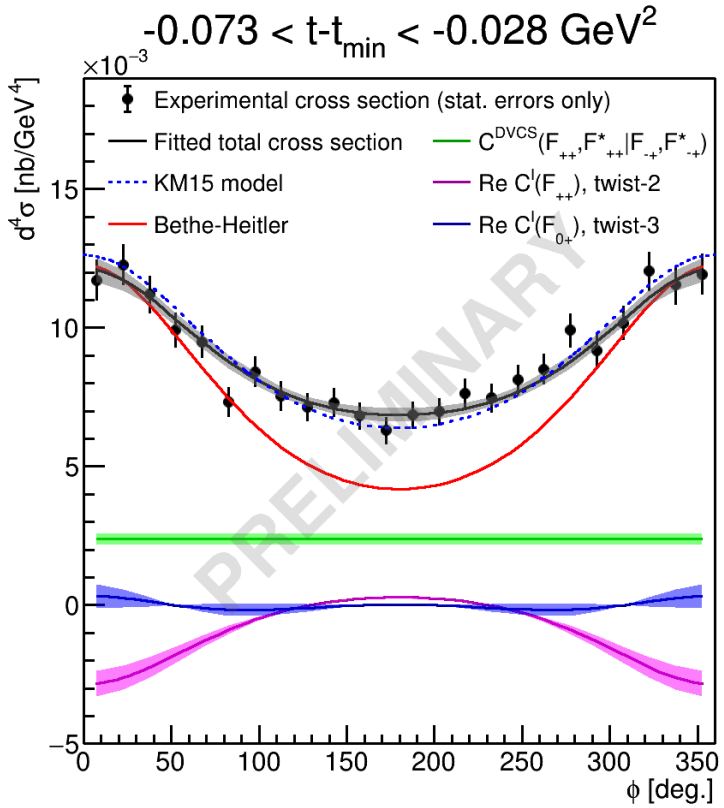
- For each bin r, the experimental cross section can then be extracted by

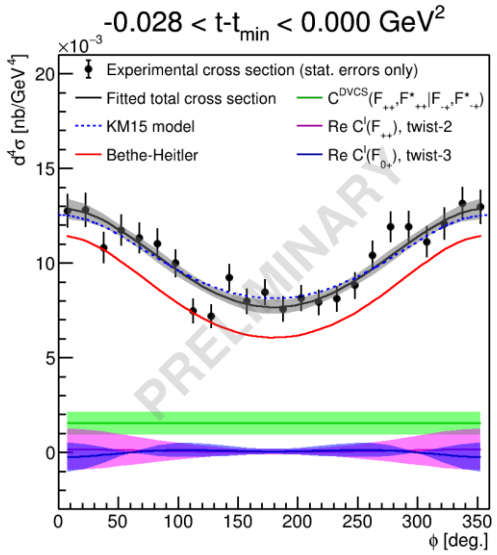
$$\frac{d^4\sigma_r^{exp}}{dQ^2 dx_{Bj} dt d\phi} = \frac{N_r^{exp}}{N_r^{sim}} \underbrace{\frac{d^4\sigma_r^{fit}}{dQ^2 dx_{Bj} dt d\phi}}$$

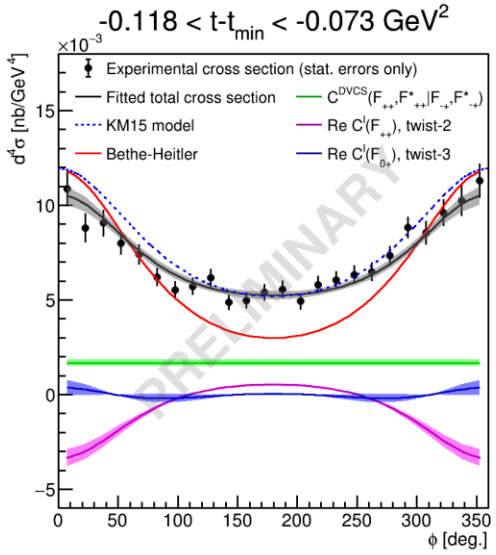
total fitted cross section, calculated using fitted $\langle F^n \rangle_v$

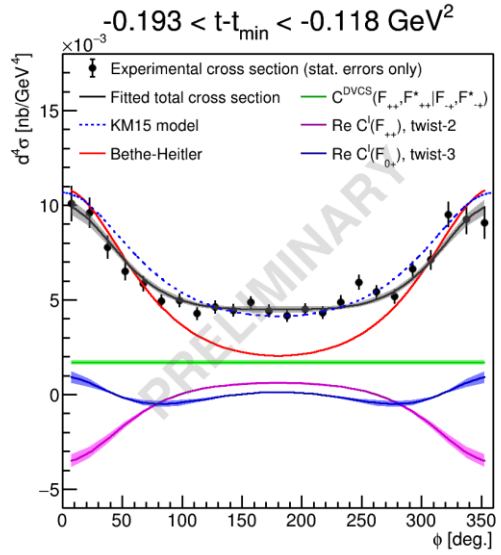
Preliminary cross section (helicity independent)

- Only the statistical errors included
- Systematic uncertainties are under evaluation
- Good agreement with the KM15 model:
  parametrization of CFFs fitted to previous DVCS data









Preliminary cross section (helicity dependent)

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- Systematic uncertainties are under evaluation
- Good agreement with the KM15 model:
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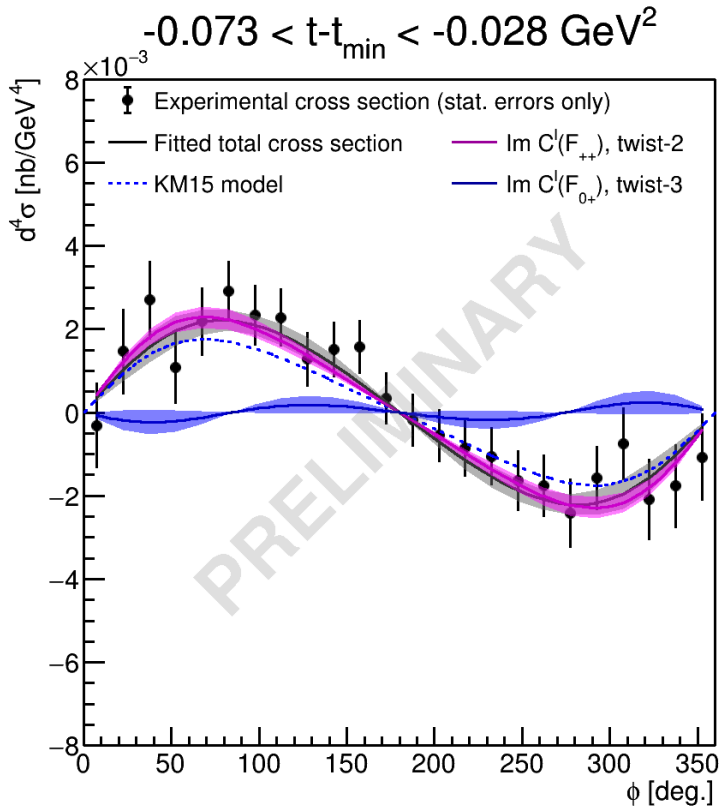
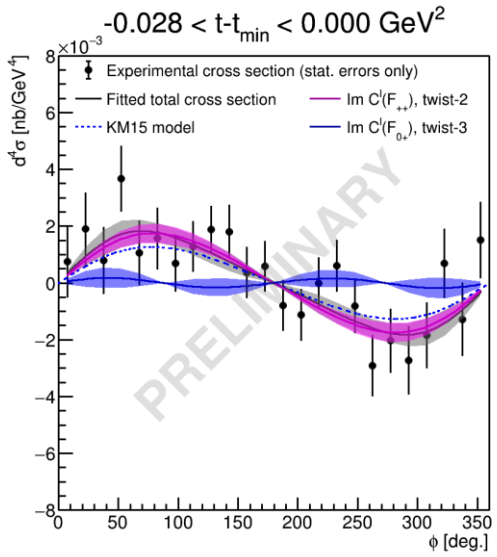
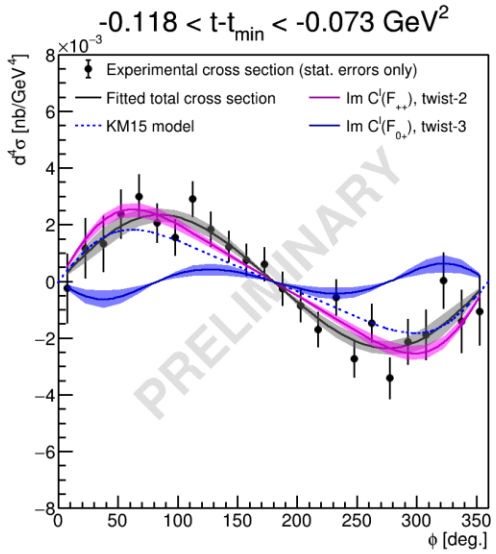
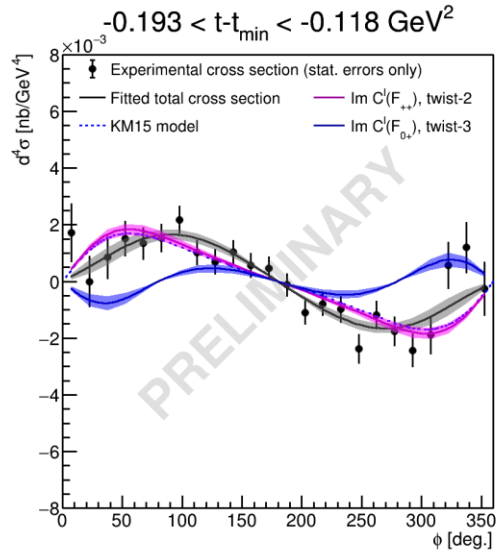


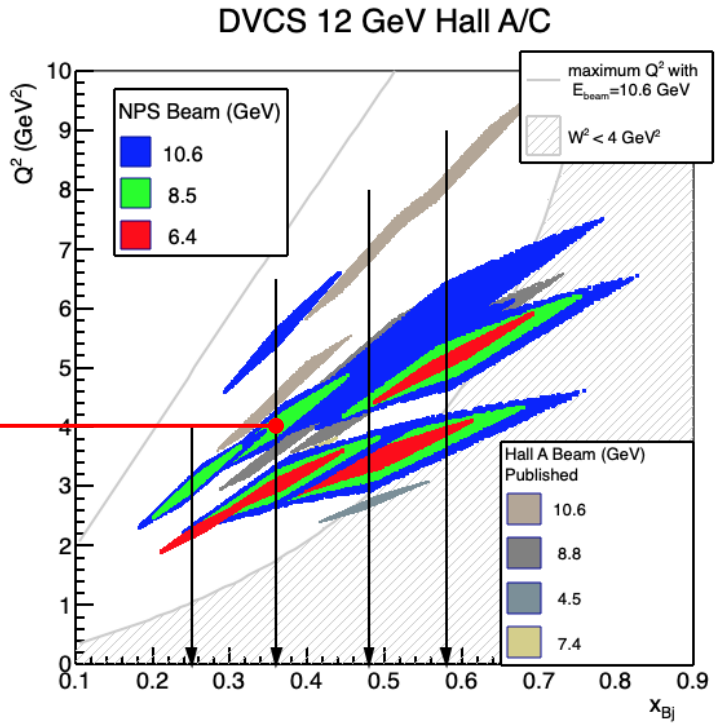






Summary and outlook

- The DVCS experiment in Hall C at JLab
  - The simplest approach for accessing GPDs through CFFs
  - Several beam energies for most of the kinematic settings for DVCS-interference separation
- Preliminary DVCS cross section on proton
  - Extracted the cross sections for one kinematics setting
  - Compatible with the KM15 model
- Future work
  - Optimize event selections and detector acceptance cuts
  - Study for systematic uncertainties (e.g., M_x^2 cut, selection of CFFs for the cross section extraction)
  - Analysis for more kinematic settings
- Outlook
  - An extension of Hall A kinematics regions: further separation of DVCS and interference terms
  - Results from LD2 datasets for DVCS off neutron



Backups

Optimizing E_γ resolution: energy calibration

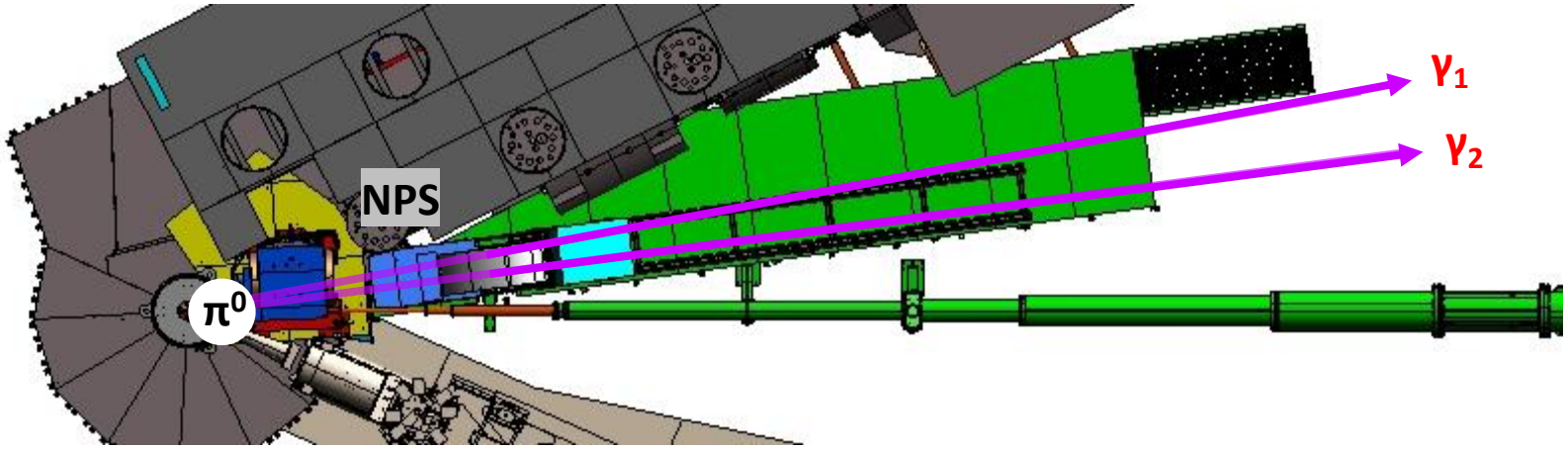
- Measured energy of a particle in the NPS: $E^{NPS}_{cluster} = \sum_j C_j A_j$
  - j: channels in the cluster
  - A: amplitude measured in the channel [mV]
  - C: calibration coefficient, convert amplitude to energy [GeV/mV]
- Calibration by optimizing the width of $\pi^0 \to \gamma\gamma$ peak

$$F = \sum_{i=1}^{N_{events}} (m_i^2 - m_0^2)^2 + 2\lambda \sum_{i=1}^{N_{events}} (m_i^2 - m_0^2)$$

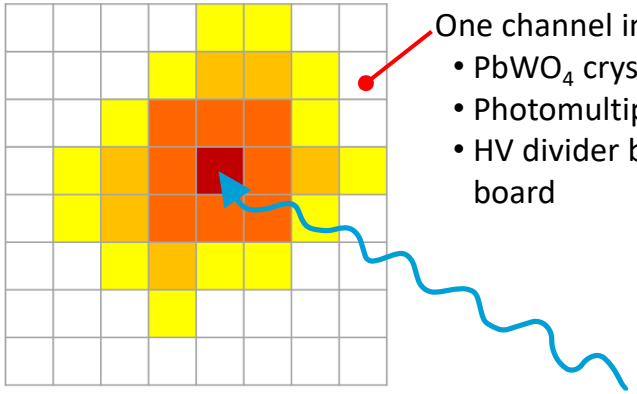
resolution term — constraint $\langle m_i^2 \rangle = m_0^2$

$m_0 = M_\pi = 0.1349766$ GeV
m_i: reconstructed $M_{\gamma\gamma}$
λ: Lagrange multiplier

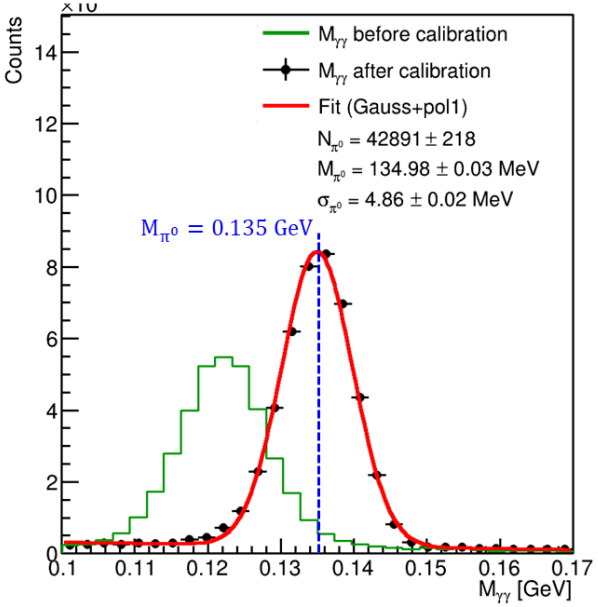
(Nuclear Instruments and Methods in Physics Research A 566 (2006) 366–374)



Cluster forms in the NPS when a particle is detected

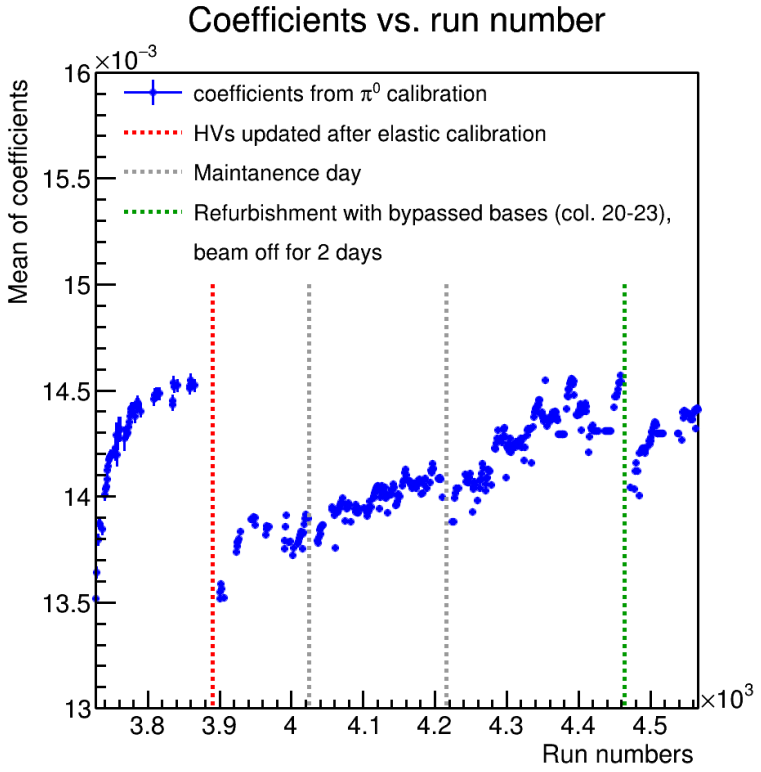


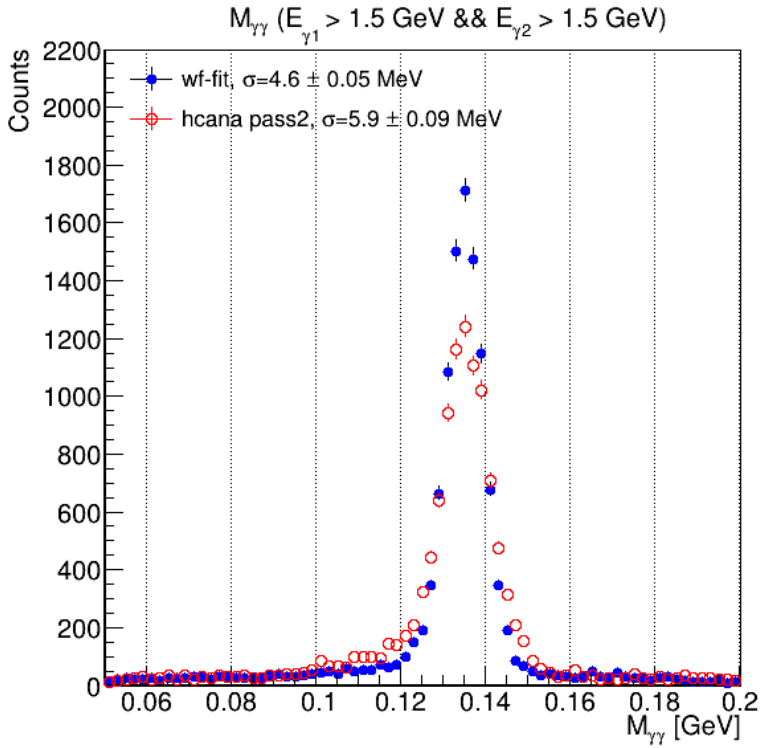
γγ invariant mass after π⁰ calibration



Online calibration results

- Reduced the width of π^0 invariant mass → better energy resolution
- Coefficients as a function of time
  - Increased due to the radiation damages
  - Decrease after updating high voltages or long time of beam OFF

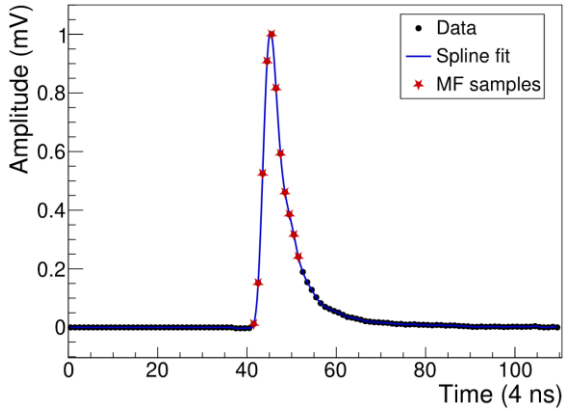




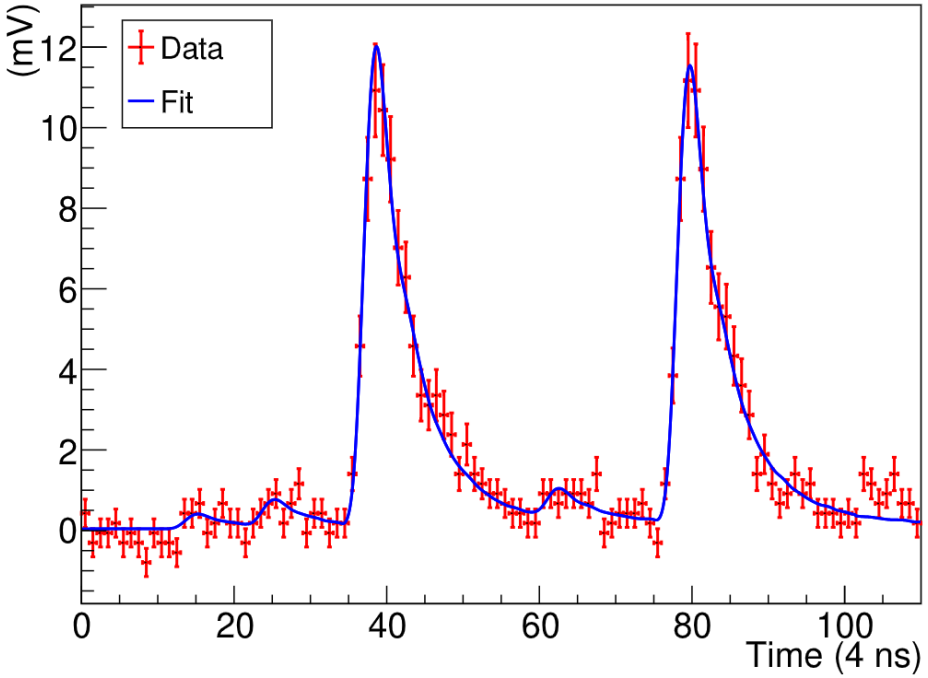
Optimizing E_γ resolution: waveform fit analysis

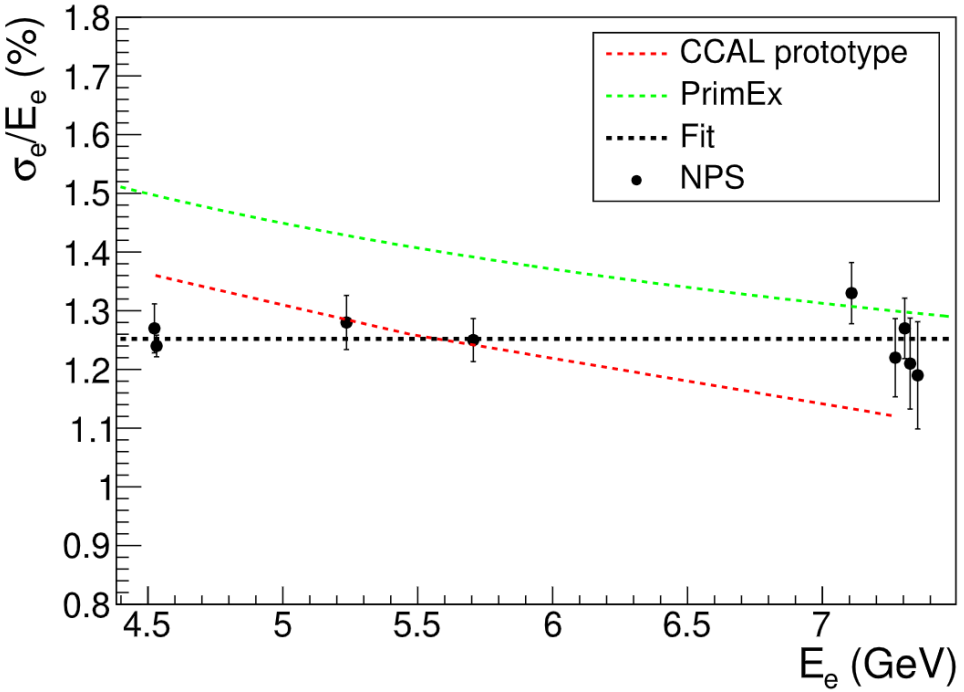
- Waveforms samples were readout (each channel and each event)
- Fitted using reference shapes from elastic data
- More accurate amplitudes are extracted
- Energy resolution (σ_e/E_e): 1.2% to 1.3% between 4.5 GeV and 7.3 GeV

Reference shape for fitting



Waveform fit using the reference shape



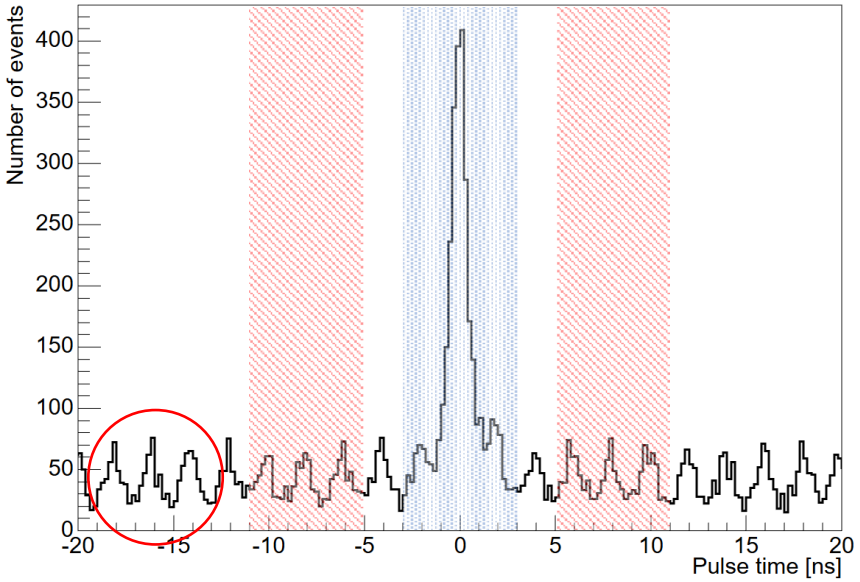


Nucl. Instrum. Methods A 1086 (2026), 171323

Accidental background estimation

➢ Clustering using different pulse timing window

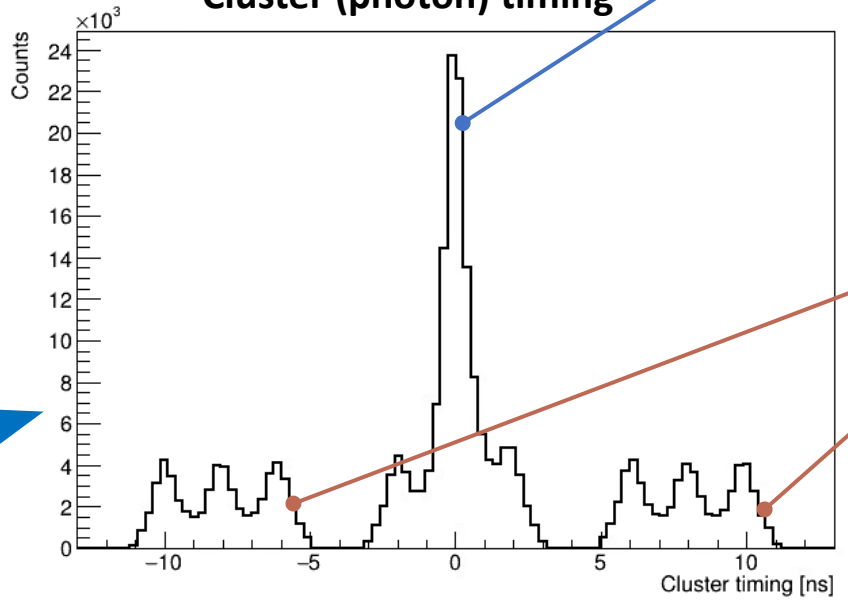
Pulse timing cut (coincidence & accidental)



structure of 500 MHz beam frequency

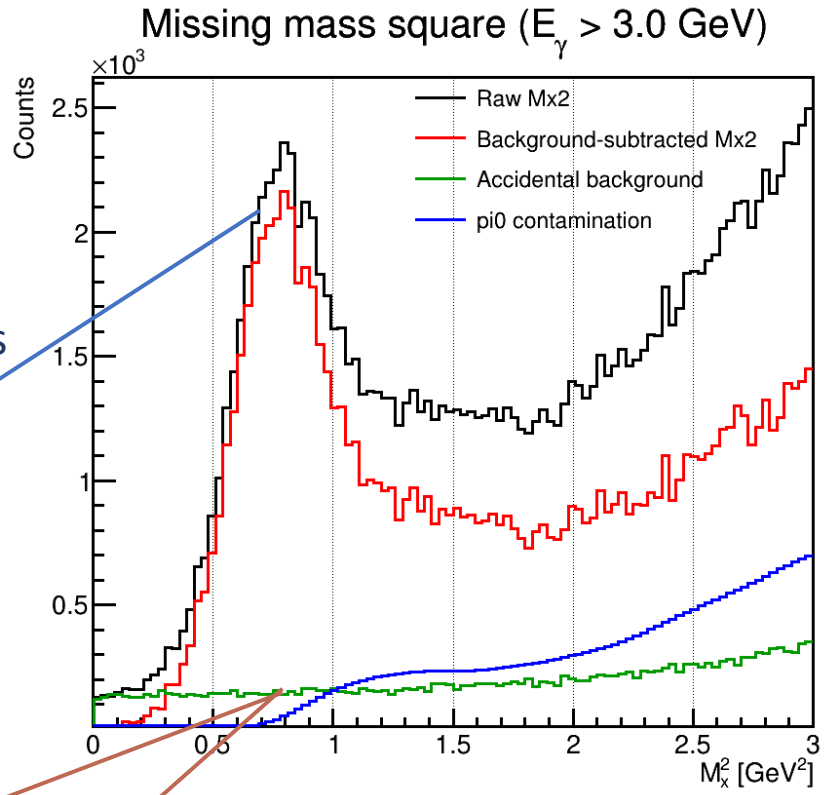
- Clustering
- Photon reconstruction

Cluster (photon) timing



Raw M_x^2
- Timing in [-3, 3] ns

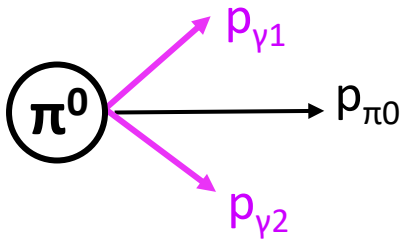
Accidental M_x^2
- Timing in [-11, -5] & [5, 11] ns (average)



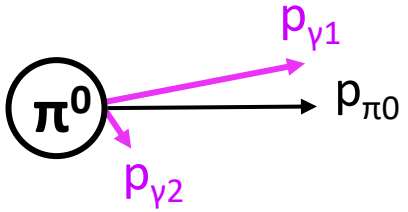
π^0 contamination background

- Photons from asymmetric decay could be identified as DVCS photons

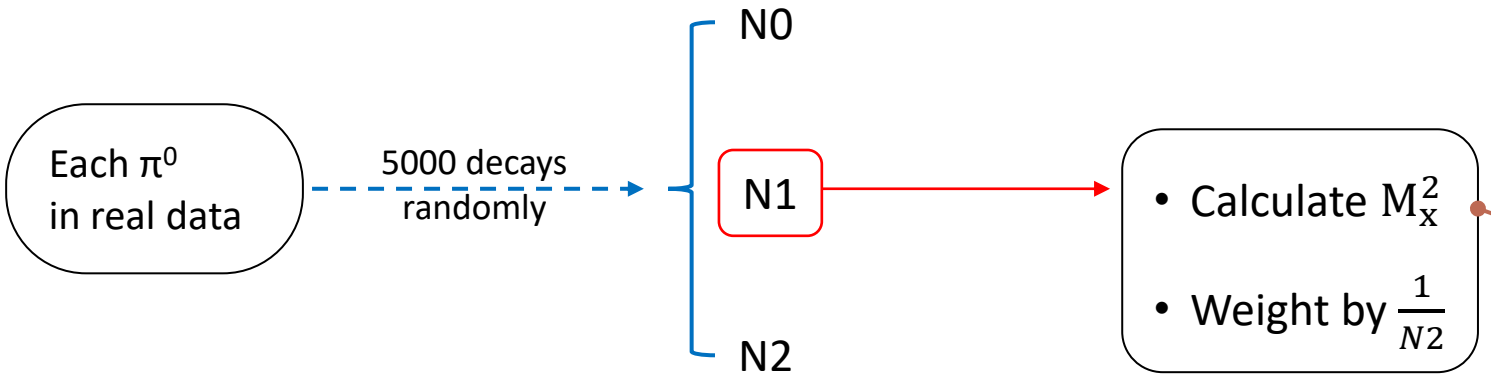
Symmetric decay in lab frame

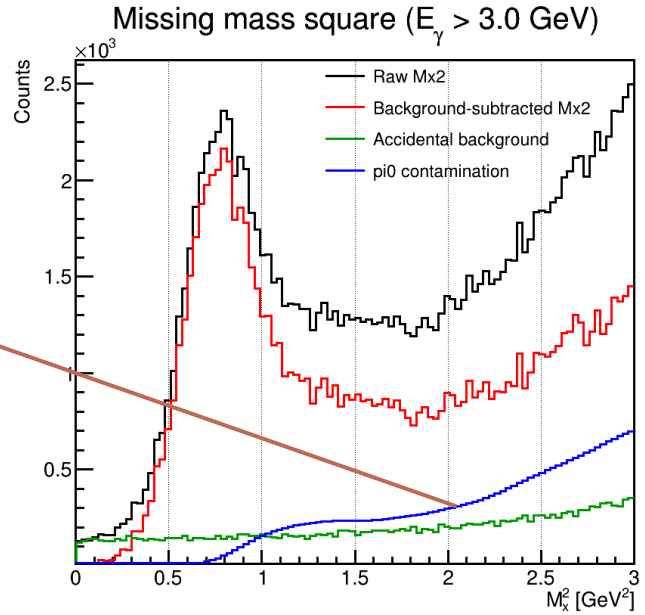


Asymmetric decay in lab frame



- Estimation of π^0 contamination





N0, N1, N2: number of 0, 1 or 2 photons in NPS acceptance

Cross section extraction: parametrization with CFFs

➢ $$\frac{d^4\sigma}{dQ^2 dx_{Bj} dt d\phi} = \frac{\alpha^3 x_{Bj} y^2}{8\pi Q^4 \sqrt{1+\epsilon^2}} \frac{1}{e^6} \left\{ |T_{BH}|^2 + |T_{DVCS}|^2 + I \right\}$$

kinematics pre-factors

- $|T_{BH}|^2 = \frac{e^6}{x_{Bj}^2 y^2 (1+\epsilon^2) t P_1(\phi) P_2(\phi)} \left\{ c_0^{BH} + \sum_{n=1}^{2} c_n^{BH} cos(n\phi) + s_1^{BH} sin(\phi) \right\}$
- $|T_{DVCS}|^2 = \frac{e^6}{y^2 Q^2} \left\{ c_0^{DVCS} + \sum_{n=1}^{2} [c_n^{DVCS} cos(n\phi) + s_n^{DVCS} sin(n\phi) \right\}$
- $I = \frac{\pm e^6}{x_{Bj} y^3 t P_1(\phi) P_2(\phi)} \left\{ c_0^I + \sum_{n=1}^{3} [c_n^I cos(n\phi) + s_n^I sin(n\phi)] \right\}$

➢ Take c_n^I and s_n^I as example:

$$\begin{cases} c_n^I = C_{++}(n) \mathcal{R}e C_{++}^I(n|F) + ... \\ s_n^I = \lambda S_{++}(n) \mathcal{I}m S_{++}^I(n|F) + ... \end{cases} \quad \begin{cases} C_{++}^I(n|F) = C^I(F) + ... \\ S_{++}^I(n|F) = C^I(F) + ... \end{cases}$$

➢ For unpolarized target: $C^I(F) = F_1 \mathcal{H} - \frac{t}{4M^2} F_2 \mathcal{E} + \frac{x_{Bj}}{2 - x_{Bj} + x_{Bj} \frac{t}{Q^2}} (F_1 + F_2) \tilde{\mathcal{H}}$

Compton Form Factors

Phys. Rev. D. 82, 074010, 2010.

Fitted CFF combination from the DVCS term

$$|\mathcal{T}^{\rm DVCS}|^2 = \frac{e^6}{y^2\mathcal{Q}^2}\left\{c_0^{\rm DVCS} + \sum_{n=1}^{2}\left[c_n^{\rm DVCS}\cos(n\phi) + s_n^{\rm DVCS}\sin(n\phi)\right]\right\}, \tag{2.17}$$

with

$$c_{0,\rm unp}^{\rm DVCS} = 2\frac{2-2y+y^2+\frac{\epsilon^2}{2}y^2}{1+\epsilon^2}\mathcal{C}_{\rm unp}^{\rm DVCS}(\mathcal{F},\mathcal{F}^*) + \frac{16K^2}{(2-x_{\rm B})^2(1+\epsilon^2)}\mathcal{C}_{\rm unp}^{\rm DVCS}(\mathcal{F}_{\rm eff},\mathcal{F}_{\rm eff}^*), \tag{2.18}$$

$$\begin{Bmatrix} c_{1,\rm unp}^{\rm DVCS} \\ s_{1,\rm unp}^{\rm DVCS}\end{Bmatrix} = \frac{8K}{(2-x_{\rm B})(1+\epsilon^2)}\begin{Bmatrix}(2-y)\\ -\lambda y\sqrt{1+\epsilon^2}\end{Bmatrix}\begin{Bmatrix}\Re{\rm e}\\ \Im{\rm m}\end{Bmatrix}\mathcal{C}_{\rm unp}^{\rm DVCS}(\mathcal{F}_{\rm eff},\mathcal{F}^*) \tag{2.19}$$

$$\begin{aligned}\mathcal{C}_{\rm unp}^{\rm DVCS} = {} & \frac{\mathcal{Q}^2(\mathcal{Q}^2+x_{\rm B}t)}{((2-x_{\rm B})\mathcal{Q}^2+x_{\rm B}t)^2}\left\{4(1-x_{\rm B})\mathcal{H}\mathcal{H}^* + 4\left(1-x_{\rm B}+\frac{2\mathcal{Q}^2+t}{\mathcal{Q}^2+x_{\rm B}t}\frac{\epsilon^2}{4}\right)\widetilde{\mathcal{H}}\widetilde{\mathcal{H}}^*\right. \\ & -\frac{x_{\rm B}^2(\mathcal{Q}^2+t)^2}{\mathcal{Q}^2(\mathcal{Q}^2+x_{\rm B}t)}(\mathcal{H}\mathcal{E}^*+\mathcal{E}\mathcal{H}^*) - \frac{x_{\rm B}^2\mathcal{Q}^2}{\mathcal{Q}^2+x_{\rm B}t}\left(\widetilde{\mathcal{H}}\widetilde{\mathcal{E}}^*+\widetilde{\mathcal{E}}\widetilde{\mathcal{H}}^*\right) \\ & \left.-\left(\frac{x_{\rm B}^2(\mathcal{Q}^2+t)^2}{\mathcal{Q}^2(\mathcal{Q}^2+x_{\rm B}t)}+\frac{((2-x_{\rm B})\mathcal{Q}^2+x_{\rm B}t)^2}{\mathcal{Q}^2(\mathcal{Q}^2+x_{\rm B}t)}\frac{t}{4M^2}\right)\mathcal{E}\mathcal{E}^* - \frac{x_{\rm B}^2\mathcal{Q}^2}{\mathcal{Q}^2+x_{\rm B}t}\frac{t}{4M^2}\widetilde{\mathcal{E}}\widetilde{\mathcal{E}}^*\right\}\end{aligned} \tag{2.22}$$

Phys. Rev. D. 82, 074010, 2010.

Fitted CFF combination from the interference term

$$\mathcal{I} = \frac{\pm e^6}{x_{\rm B} y^3 t \mathcal{P}_1(\phi)\mathcal{P}_2(\phi)} \left\{ c_0^{\mathcal{I}} + \sum_{n=1}^{3} \left[c_n^{\mathcal{I}} \cos(n\phi) + s_n^{\mathcal{I}} \sin(n\phi) \right] \right\} , \tag{2.34}$$

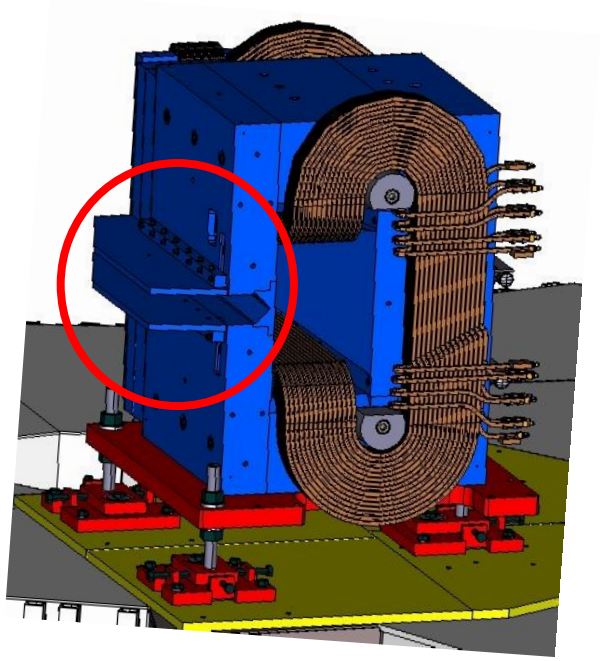
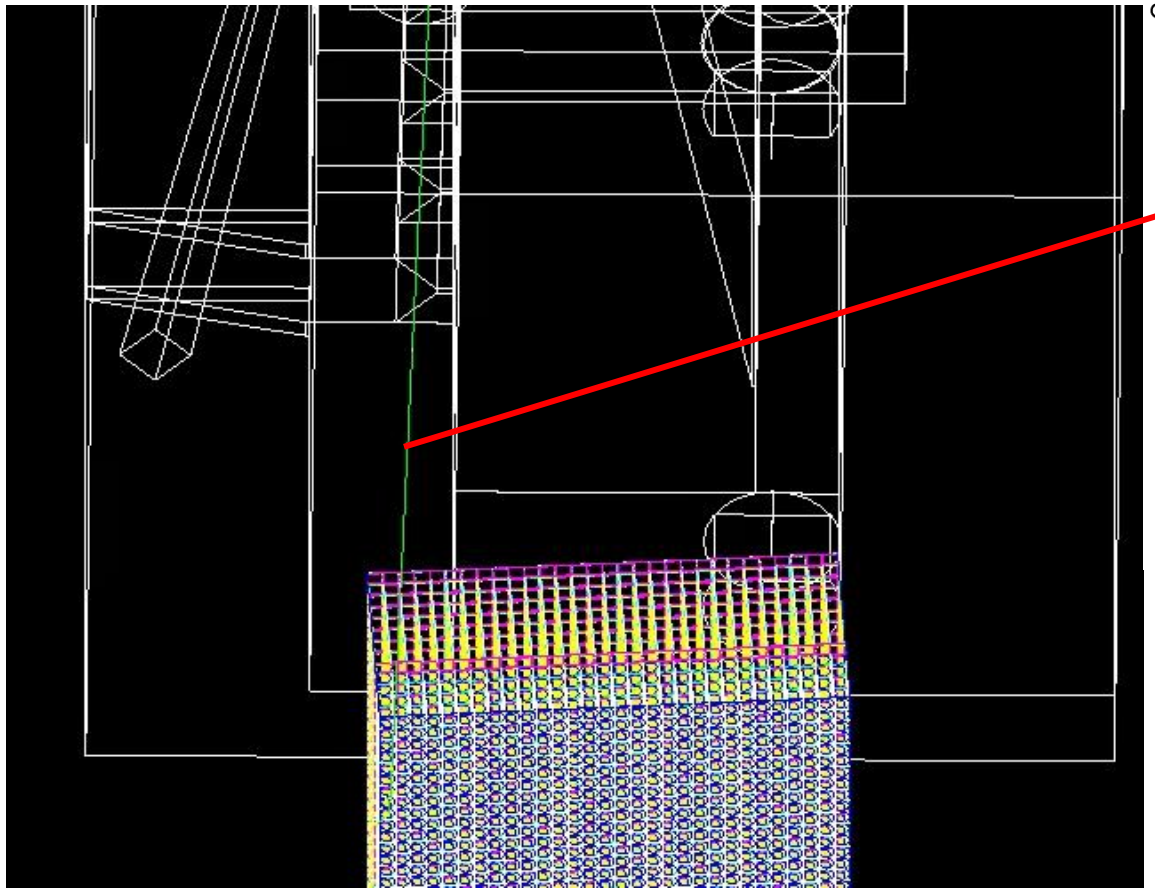
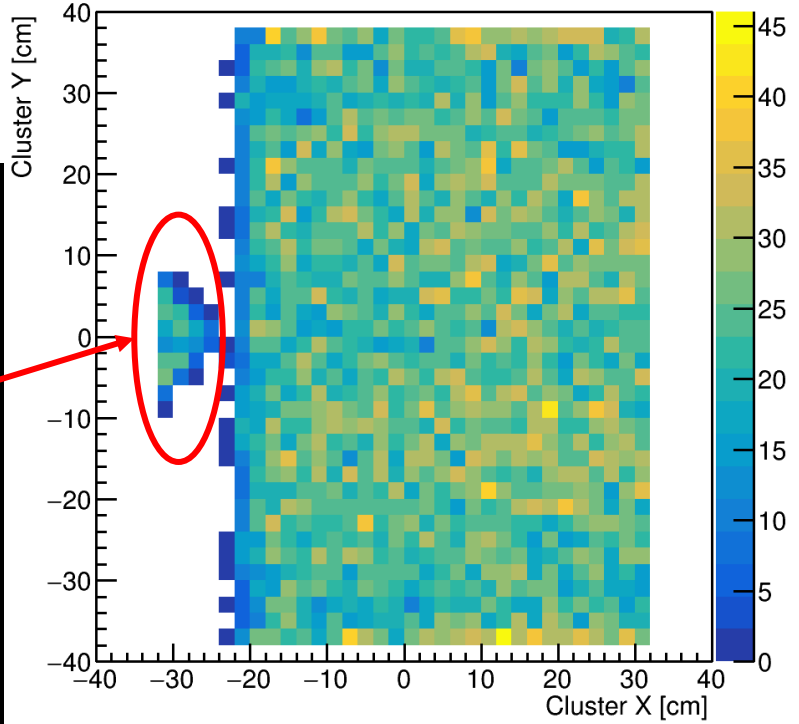
with kinematically power-suppressed contributions exactly accounted for,

$$\begin{aligned} c_n^{\mathcal{I}} &= C_{++}(n)\, \Re\mathrm{e}\, \mathcal{C}_{++}^{\mathcal{I}}\,(n|\mathcal{F}) + C_{0+}(n)\, \Re\mathrm{e}\, \mathcal{C}_{0+}^{\mathcal{I}}\,(n|\mathcal{F}_{\rm eff}) + C_{-+}(n)\, \Re\mathrm{e}\, \mathcal{C}_{-+}^{\mathcal{I}}\,(n|\mathcal{F}_T) \ , \\ s_n^{\mathcal{I}} &= S_{++}(n)\, \Im\mathrm{m}\, \mathcal{S}_{++}^{\mathcal{I}}\,(n|\mathcal{F}) + S_{0+}(n)\, \Im\mathrm{m}\, \mathcal{S}_{0+}^{\mathcal{I}}\,(n|\mathcal{F}_{\rm eff}) + S_{-+}(n)\, \Im\mathrm{m}\, \mathcal{S}_{-+}^{\mathcal{I}}\,(n|\mathcal{F}_T) \ . \end{aligned} \tag{2.35}$$

The above coefficients are defined in terms of the photon helicity-conserving

$$\begin{aligned} \mathcal{C}_{++}^{\mathcal{I}}\,(n|\mathcal{F}) &= \mathcal{C}^{\mathcal{I}}\,(\mathcal{F}) + \frac{C_{++}^{V}(n)}{C_{++}(n)} \mathcal{C}^{\mathcal{I},V}\,(\mathcal{F}) + \frac{C_{++}^{A}(n)}{C_{++}(n)} \mathcal{C}^{\mathcal{I},A}\,(\mathcal{F}) \\ \mathcal{S}_{++}^{\mathcal{I}}\,(n|\mathcal{F}) &= \mathcal{C}^{\mathcal{I}}\,(\mathcal{F}) + \frac{S_{++}^{V}(n)}{S_{++}(n)} \mathcal{C}^{\mathcal{I},V}\,(\mathcal{F}) + \frac{S_{++}^{A}(n)}{S_{++}(n)} \mathcal{C}^{\mathcal{I},A}\,(\mathcal{F}) \end{aligned} \tag{2.36}$$

$$\mathcal{C}_{\rm unp}^{\mathcal{I}}(\mathcal{F}) = F_1 \mathcal{H} - \frac{t}{4M^2} F_2 \mathcal{E} + \frac{x_{\rm B}}{2 - x_{\rm B} + x_{\rm B}\frac{t}{Q^2}} (F_1 + F_2) \widetilde{\mathcal{H}} \, , \tag{2.28}$$

Phys. Rev. D. 82, 074010, 2010.

Additional clusters around x = -30 cm in simulation