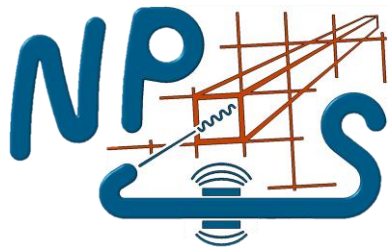


Neutral-Pion Electroproduction and Hadron Femtography with Jefferson Lab Hall C

The 17th edition of the "International Conference on Meson-Nucleon Physics and the Structure of the Nucleon"

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The Catholic University of America



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Flow of the talk

- Physics motivation and previous measurements
- Hall C Experiment
- Event reconstruction and extraction
- Preliminary results

Physics Motivation

The Mass Puzzle

- Light-quark current masses account for only a small fraction of the proton mass; most emerges through QCD dynamics.
 - Dynamical Chiral Symmetry Breaking (DCSB)
 - Gluon fields and quark interactions
 - Confinement
- The pion is exceptionally light because of its pseudo-Nambu–Goldstone character.
- Understanding pion structure and production provides complementary information about nonperturbative QCD.

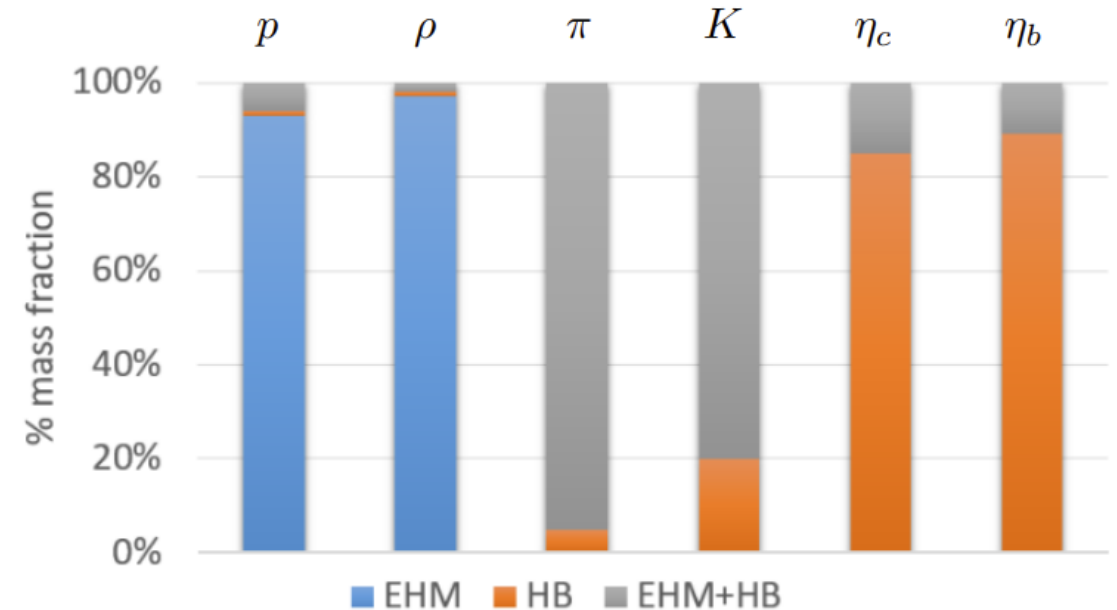


Fig. Hadron-mass budgets illustrating emergent QCD mass generation, Higgs-generated mass, and their interference. [Raya et al., Few-Body Syst. 65, 60 (2024)]

Nucleon structure and π^0

- Exclusive π^0 electroproduction, ($ep \rightarrow e'p'\pi^0$), provides complementary sensitivity to nucleon structure.
- The neutral channel is free of the prominent charged-pion pole contribution.
- Transverse-photon amplitudes can receive significant contributions from chiral-odd GPDs, particularly, H_T and $\bar{E}_T$.
- Measurements of σ_T , σ_{TT} , and σ_{LT} can constrain these contributions within reaction models.

Quantify the role of transverse-photon amplitudes in exclusive π^0 production

QCD Factorization: Exclusive Meson Electroproduction

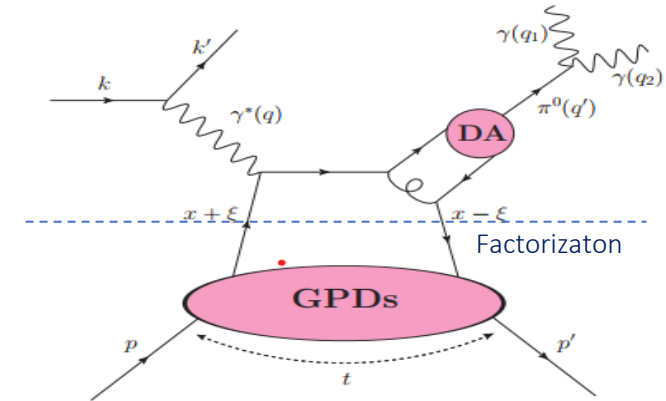
At sufficiently large Q^2 , fixed x_B , and $|t|/Q^2 \ll 1$, the leading longitudinal meson-production amplitude factorizes into a hard-scattering kernel, a nucleon GPD, and a meson distribution amplitude

The scattering amplitude factorizes into three components:

$$A(\gamma * p \rightarrow Mp') = H(Q^2, x, \xi) \otimes F(x, \xi, t) \otimes \phi_M(z)$$

where

- $H(Q^2, x, \xi)$ - perturbatively calculable hard scattering kernel
- $F(x, \xi, t)$ – Non-perturbative (GPD) contribution describing the nucleon structure
- $\phi_M(z)$ - meson distribution amplitude describing the meson wave function.
- Leading-power QCD predicts longitudinal-photon dominance at asymptotically large Q^2 .
- Transverse amplitudes are power suppressed asymptotically, but may be significant at experimentally accessible momentum transfers.
- Chiral-odd GPDs coupled to twist-3 pion distribution amplitudes provide a possible mechanism for enhanced transverse strength.



Collins, Frankfurt and Strikman, Phys. Rev. D 56, 2982 (1997)

Goloskokov and Kroll, Eur. Phys. J. A 47, 112 (2011)

Earlier measurements: CLAS at Jefferson Lab

- CLAS extracted σ_U , σ_{TT} and σ_{LT} over a broad kinematic range
- Sizeable σ_{TT} contributions indicate a significant role for transverse photon amplitudes.
- Calculations incorporating transversity GPDs describe the measurements better than longitudinal-only descriptions.

Supports that π^0 electroproduction is sensitive to the transversity GPDs.

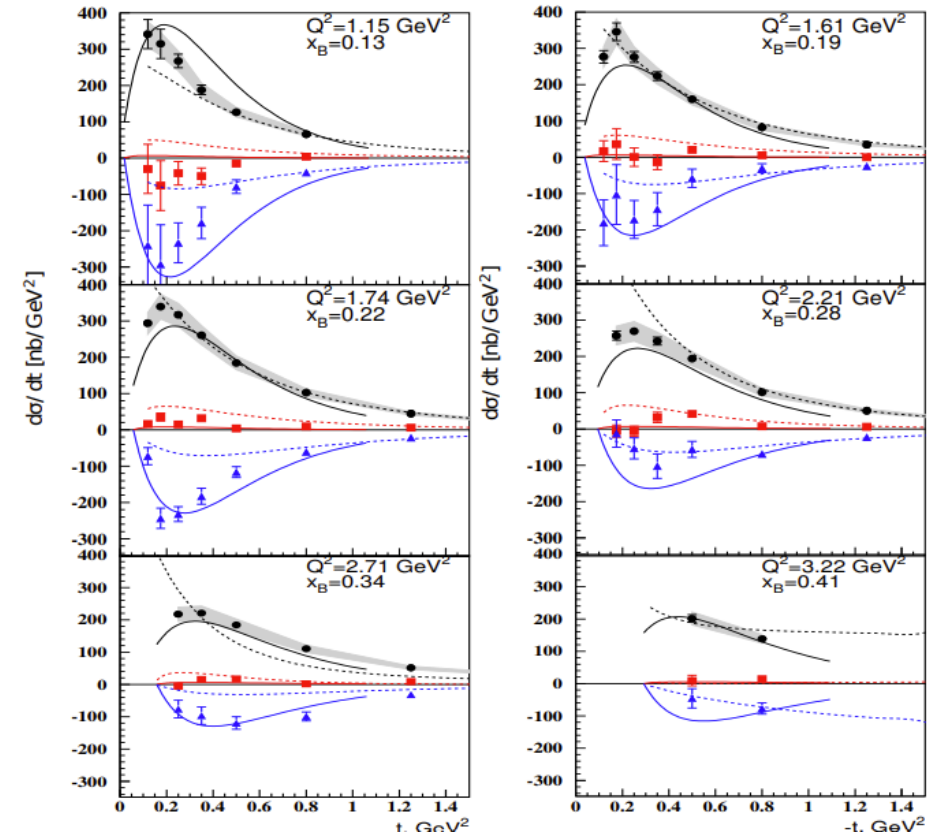


Fig. CLAS measurements of unseparated and interference structure functions compared with GPD-based calculations. (**Black points**): σ_U ; (**Blue points**): σ_{TT} ; (**Red points**): σ_{LT}
[Bedlinskiy et al., Phys. Rev. Lett. 109, 112001 (2012)]

Earlier measurements: E07-007 at Hall A Jefferson Lab

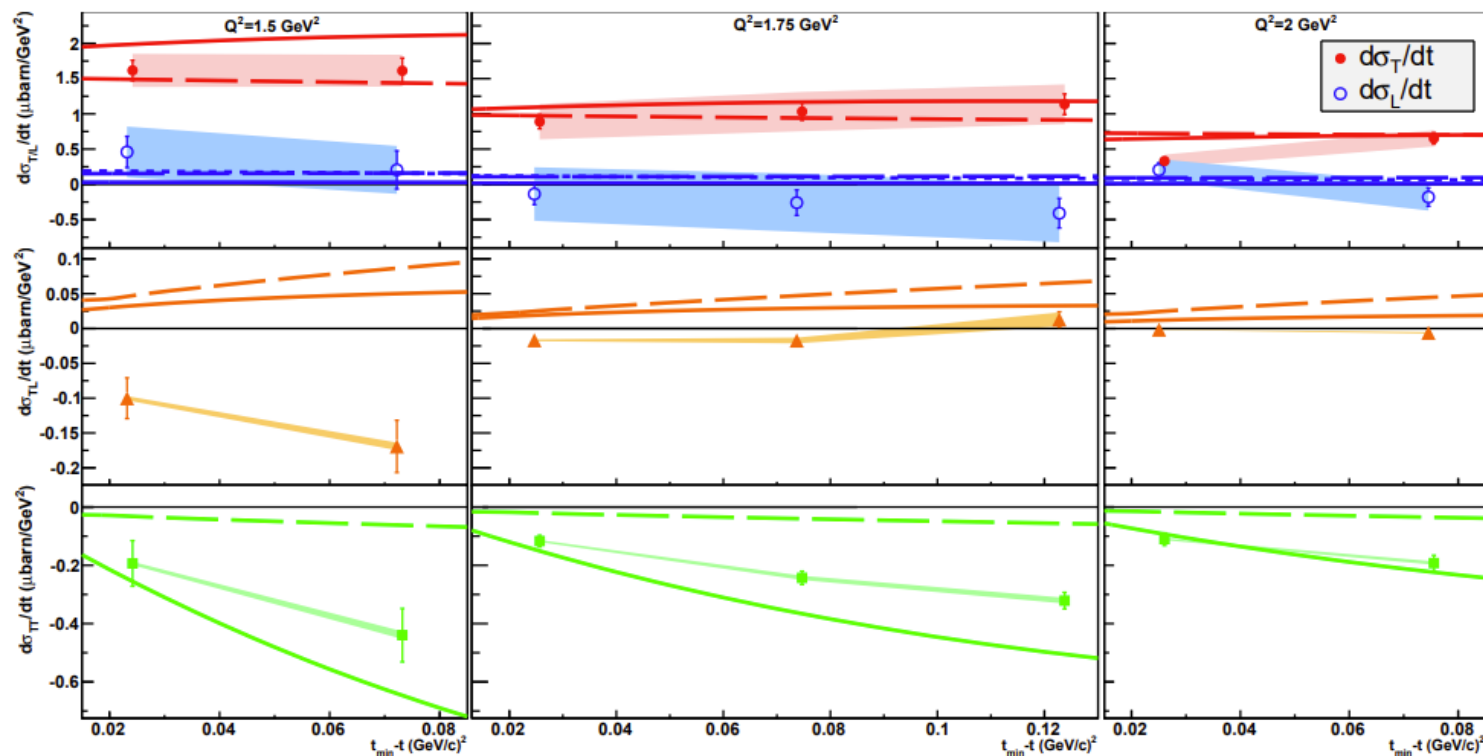
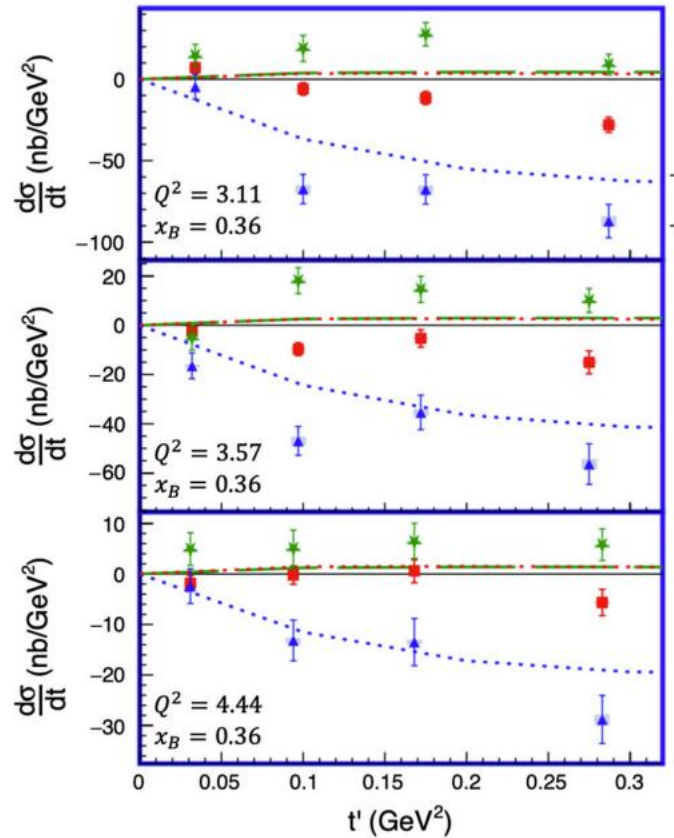


Fig. Hall A Rosenbluth-separated π^0 structure functions at $x_B = 0.36$. Transverse dominance is observed over the measured Q^2 range. [Defurne et al., Phys. Rev. Lett. 117, 262001 (2016)].

- The cross section is dominated by transverse photons, while the separated longitudinal contribution is consistent with zero within uncertainties.
- Nonzero σ_{LT} provides evidence for longitudinal-transverse interference despite the small extracted longitudinal cross section.

$\sigma_T \gg \sigma_L$ gives evidence that the considered kinematic regime was still far from pQCD regime.

Earlier measurements: E12-06-014 at Hall A Jefferson Lab



- Hall A extended exclusive π^0 measurements to $Q^2 = 3.1\text{--}8.4 \text{ GeV}^2$ and $x_B = 0.36\text{--}0.60$.
- Significant σ_{TT} over σ_{LT} responses indicate that transverse-photon contributions and interference effects remain important at higher Q^2 .

However, σ_T and σ_L were not independently separated, motivating Rosenbluth measurements in this kinematic regime.

Fig. Hall A measurements higher Q^2 of the interference structure functions σ_{TT} (blue), σ_{LT} (red), and $\sigma_{LT'}$ (green) at $x_B = 0.36$, compared with transversity-GPD calculations.

[*M. Dlamini et al., Phys. Rev. Lett.* **127**, 152301 (2021)]

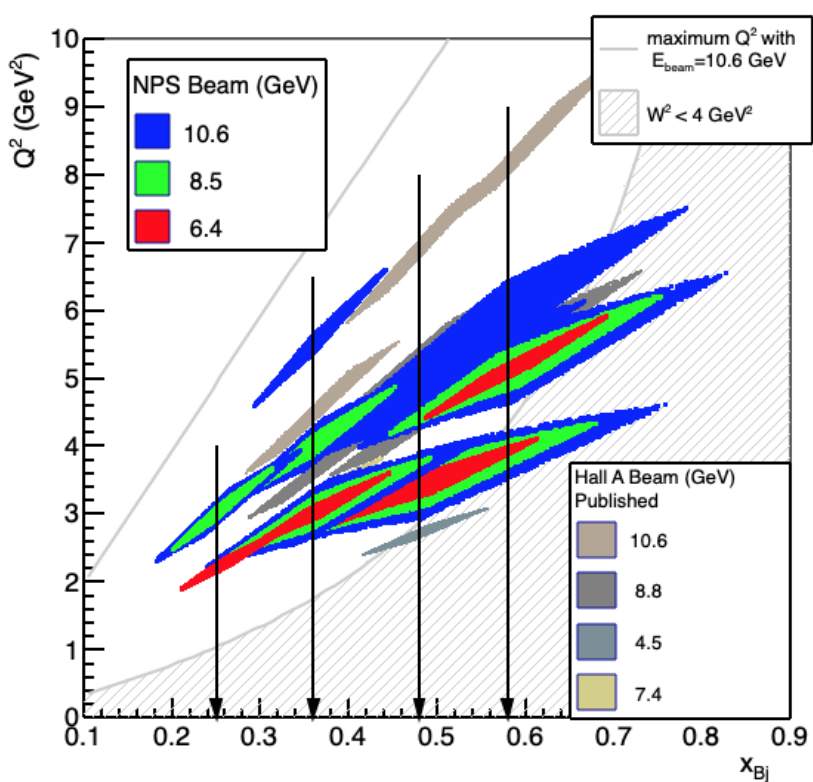
The Experiment

NPS Run Group 1a (Sept 2023 – May 2024)

- E12-13-010: Exclusive Deeply Virtual Compton and Neutral Pion Cross-Section Measurements in Hall C
- E12-13-007: Measurement of Semi-Inclusive π^0 Production as Validation of Factorization
- E12-22-006: Deeply Virtual Compton Scattering off the neutron with the Neutral Particle Spectrometer in Hall C
- E12-23-014: Measurements of the Ratio $R = \sigma_L/\sigma_T$, p/d ratios, Pt dependence, and azimuthal asymmetries in Semi-Inclusive DIS π^0 production from proton and deuteron targets using the NPS in Hall C

Hall C kinematic complements earlier measurements

DVCS 12 GeV Hall A/C



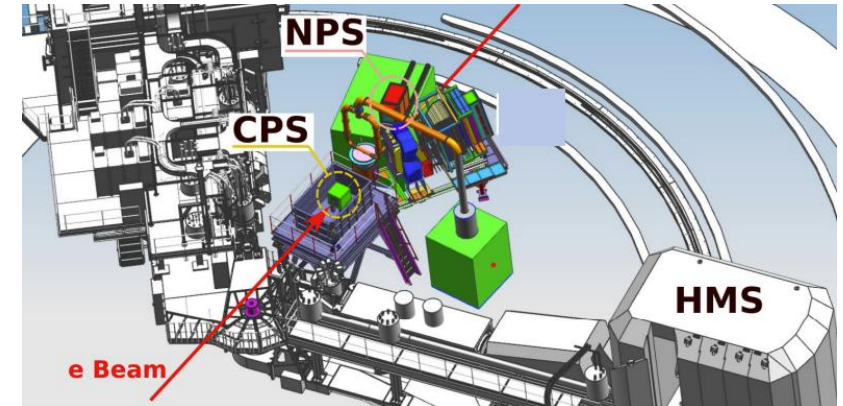
- Courtesy Charles Hyde and Julie Roche

Kinematic Setting	Beam Pass	Coulomb Goal Per Target	LH2 % of Goal	LD2 % of Goal
KinC_x36_1	3	1.2	119.33%	134.08%
KinC_x36_2	4	1.1	37.12%	20.67%
KinC_x36_2'	4	1.1	44.78%	25.22%
KinC_x36_2''	4	1.1	34.77%	25.17%
KinC_x36_3	5	0.6	107.21%	119.06%
KinC_x36_4	4	2.7	36.67%	19.16%
KinC_x36_5	5	1.4	121.88%	88.58%
KinC_x36_5'	5	0.5	137.28%	106.98%
KinC_x36_6	5	4.3	43.95%	36.85%
KinC_x50_0a	3	2	55.18%	48.35%
KinC_x50_0b	3	2	40.73%	47.39%
KinC_x50_1	4	1.9	100.14%	81.01%
KinC_x50_1'	4	1.9	94.84%	80.17%
KinC_x50_2	5	2.05	121.33%	89.67%
KinC_x50_2'	5	0.57	109.81%	90.19%
KinC_x50_2''	5	0.61	94.90%	104.86%
KinC_x50_3	5	4.85	117.56%	86.04%
KinC_x50_3'	5	0.68	80.86%	119.14%
KinC_x50_3''	5	0.7	88.31%	111.69%
KinC_x60_1	3	10	32.48%	29.36%
KinC_x60_2	4	4.75	24.59%	22.70%
KinC_x60_2'	4	4.75	18.67%	20.05%
KinC_x60_3	5	3.17	112.50%	99.41%
KinC_x60_3'	5	1.26	85.76%	114.24%
KinC_x60_3a	5	1.83	57.62%	82.17%
KinC_x60_3b	5	1.83	83.94%	72.65%
KinC_x60_4a	5	3.88	85.56%	77.40%
KinC_x60_4b	5	3.88	83.39%	77.13%
KinC_x25_1	3	0.5	53.14%	34.10%
KinC_x25_3	4	2.6	27.73%	18.02%
KinC_x25_4	5	2.6	41.78%	33.59%

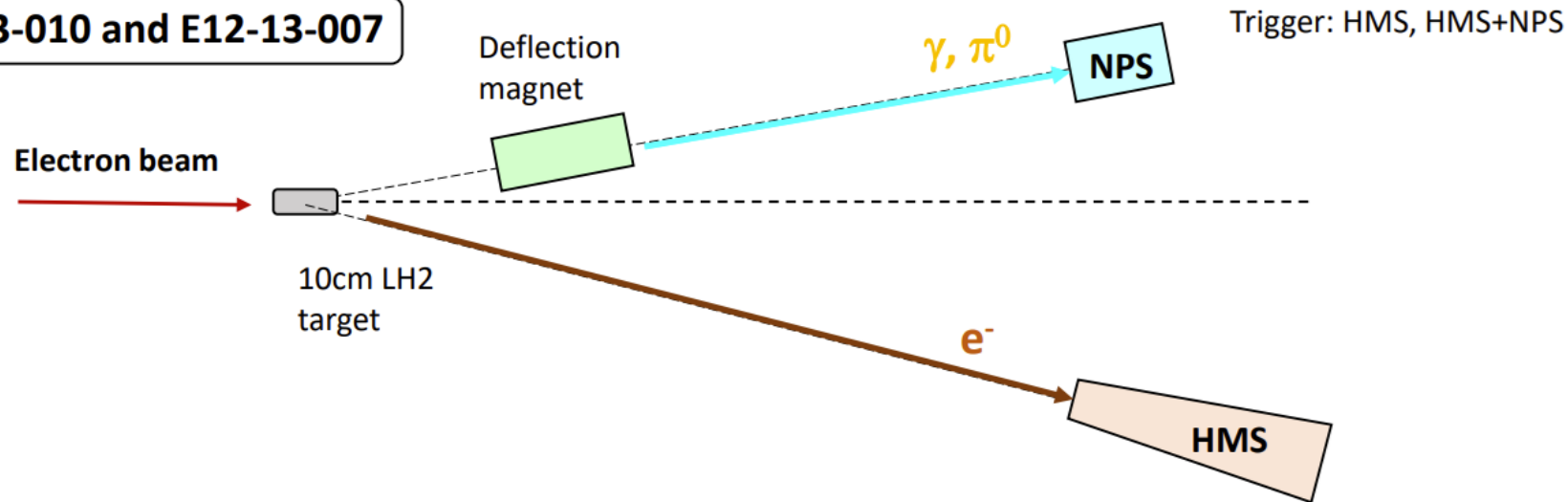
x _b	Q ² (GeV ²)	Energy (MeV)
0.24	2.1	6600
0.26	3.0	8800
0.26	3.1	11000
0.36	3.0	6600
0.36	3.0	8800
0.36	3.0	11000
0.36	4.0	8800
0.36	4.0	11000
0.36	5.5	11000
0.48	3.3	6600
0.48	3.4	8800
0.46	3.3	11000
0.48	4.8	11000
0.58	5.1	6600
0.58	5.1	4400
0.58	5.1	6600
0.58	6.0	8800

Experimental Setup — HMS and Neutral Particle Spectrometer

- The HMS measures the scattered electron and determines the electron-scattering kinematics.
- The NPS detects the two photons from $\pi^0 \rightarrow \gamma\gamma$.
- The recoil proton is identified kinematically using the missing mass.
- The NPS contains 1080 PbWO₄ calorimeter crystals, enabling high-resolution neutral-particle detection.



E12-13-010 and E12-13-007



Kinematic Settings

- Two complementary settings gives an epsilon lever arm which gives the possibility of separating the longitudinal and transverse contributions to the cross-section.

$$\epsilon = \left[1 + 2 \left(1 + \frac{\nu^2}{Q^2} \right) \tan^2 \left(\frac{\theta_e}{2} \right) \right]^{-1}, \quad \nu = E - E', \quad Q^2 = 4EE' \sin^2 \left(\frac{\theta_e}{2} \right)$$

Parameter	Low ϵ	High ϵ
Setting	KinC_x36_4	KinC_x36_5_407
Q^2	$\approx 4.0 GeV^2$	$\approx 4.0 GeV^2$
x_B	≈ 0.36	≈ 0.36
ϵ	≈ 0.52	≈ 0.71

Azimuthal Dependence and L/T Separation

Cross section for $e(k) + p(p) \rightarrow e(k') + p(p') + \pi^0(q_\pi)$ is given as:

$$\frac{d^4}{dt d\phi dQ^2 dx_B} = \frac{1}{2\pi} \Gamma_{\gamma^*}(Q^2, x_B, E) \frac{d^2\sigma}{dt d\phi}$$

$$= \frac{1}{2\pi} \Gamma_{\gamma^*}(Q^2, x_B, E) \left[\underbrace{(\sigma_T + \epsilon\sigma_L)}_{\sigma_U} + \epsilon\sigma_{TT} \cos 2\phi + \sqrt{2\epsilon(1+\epsilon)}\sigma_{LT} \cos \phi \right]$$

where, $\sigma_i = \frac{d\sigma_i}{dt}$.

- The azimuthal (ϕ) dependence determines σ_U , σ_{LT} , and σ_{TT} .
- The longitudinal and the transverse components can then be separated using the relation $\sigma_U = (\sigma_T + \epsilon\sigma_L)$.
- This requires the data to be taken at a minimum of two complementary (with a common kinematic phase space coverage) ϵ settings.

$$\sigma_{high}^U = \sigma_T + \epsilon_{high}\sigma_L, \quad \sigma_{low}^U = \sigma_T + \epsilon_{low}\sigma_L$$

$$\sigma_L = \frac{\sigma_U^{high} - \sigma_U^{low}}{\epsilon_{high} - \epsilon_{low}}, \quad \sigma_T = \frac{\epsilon_{high}\sigma_U^{low} - \epsilon_{low}\sigma_U^{high}}{\epsilon_{high} - \epsilon_{low}}.$$

e' in HMS

$\gamma\gamma$ in NPS

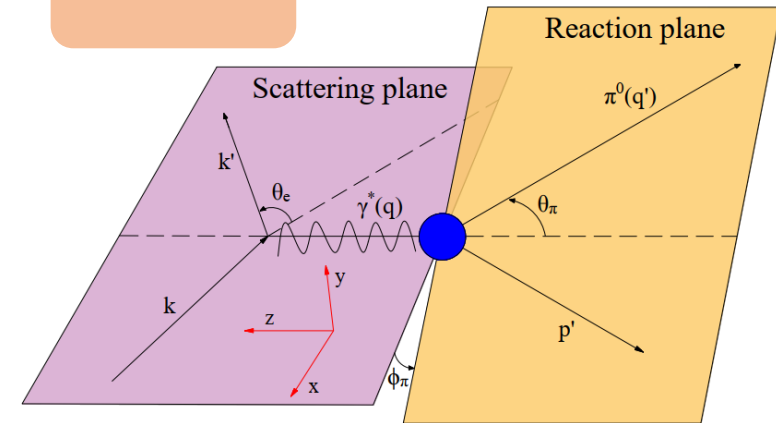


Fig. Scattering Kinematic schematic

[S. Ali, Ph.D. thesis, JLAB-PHY-21-3402]

Analysis

Acceptance and Particle Identification (PID) event cuts

- Acceptance and particle-identification requirements are applied consistently to select the scattered electron and reconstructed photon candidates.
- The same selection definitions are used when evaluating the detector response in simulation.

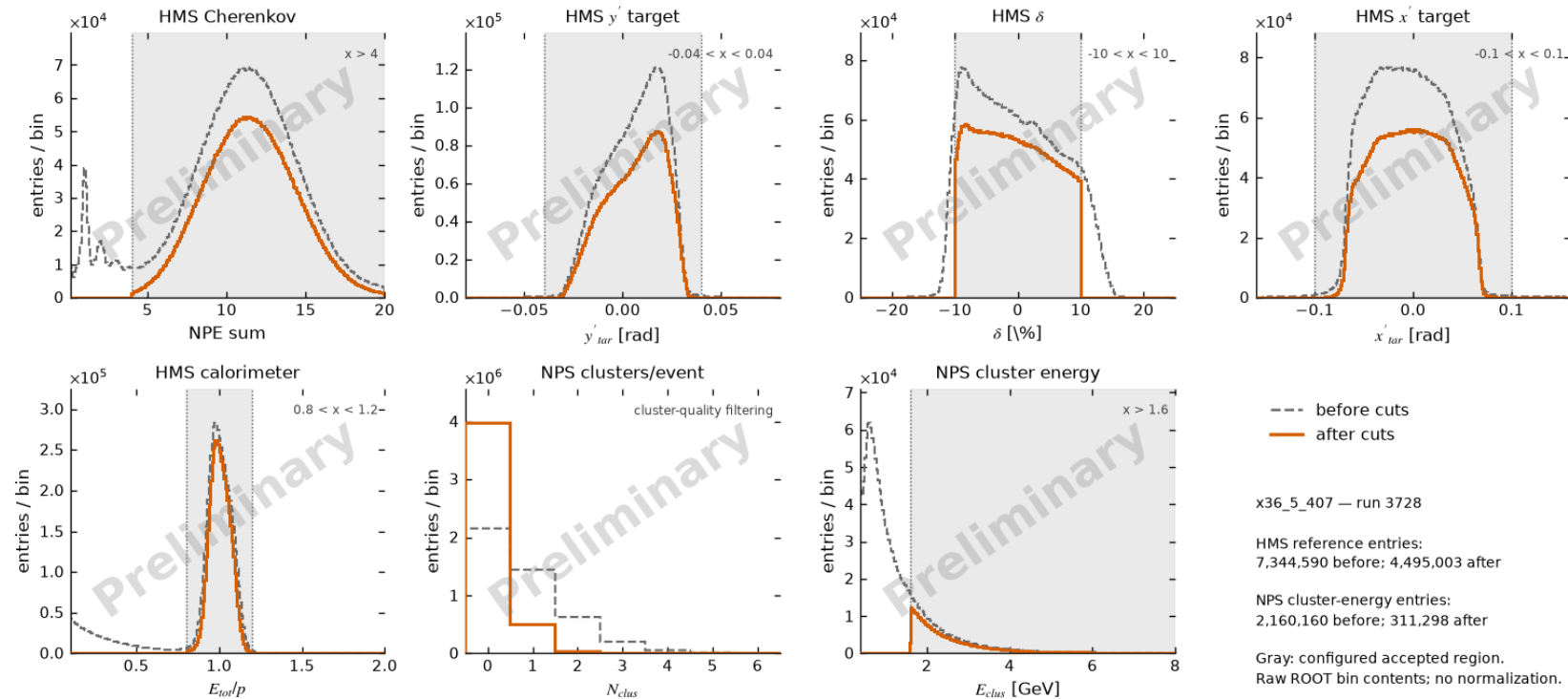
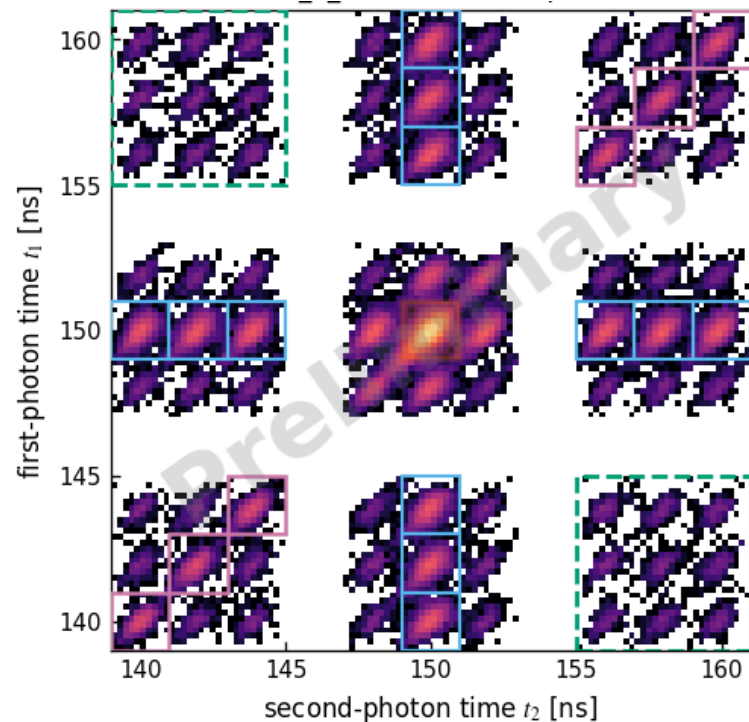


Fig. Distributions from Run 3728 (chosen for reference from KinC_x36_5_407) showing the event selection through acceptance and PID cuts.

Pion reconstruction and background subtraction

- The prompt timing region selects $(e'\gamma\gamma)$ coincidence candidates.
- Off-time regions characterize accidental combinations involving one or both photons.



Region	Timing interpretation
Center	All three particles in coincidence: (e, γ_1, γ_2)
Diagonal	(γ_1) and (γ_2) coincident with each other, but not with (e)
Horizontal band	$(e - \gamma_1)$ coincidence; (γ_2) out of time
Vertical band	$(e - \gamma_2)$ coincidence; (γ_1) out of time
Off-diagonal	Both photons out of time with (e) , with no mutual timing coincidence

Fig. Two photon timing spectrum relative to the scattered electron. The prompt region identifies triple coincidences, while off-time structures characterize accidental backgrounds.

Reconstructed π^0 invariant mass and Proton missing mass

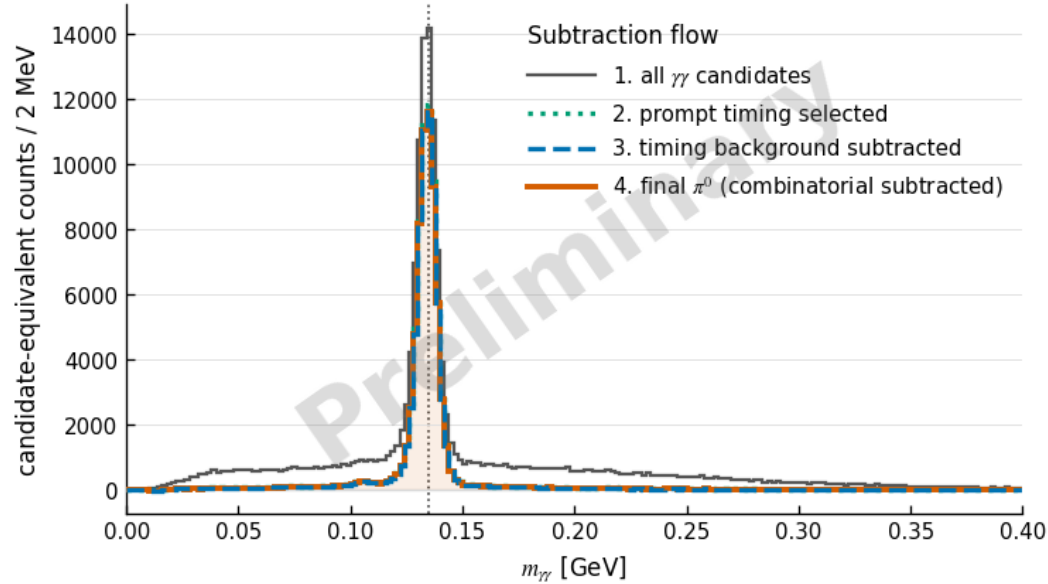


Fig. π^0 reconstructed from the two photon clusters detected on the NPS for the setting KinC_x36_5_407

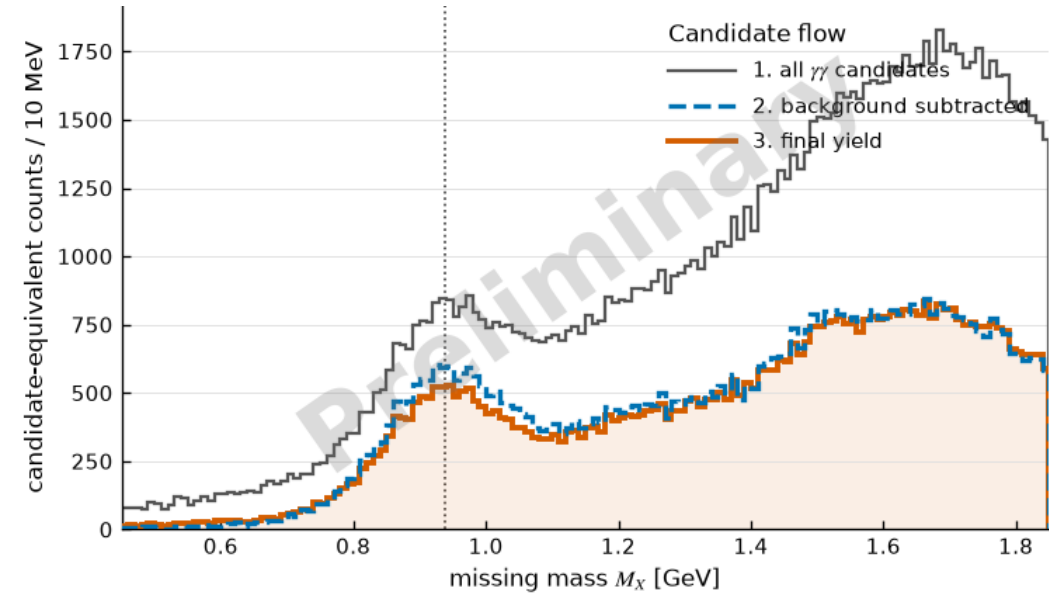


Fig. The corresponding missing-mass distribution missing mass (M_X) for KinC_x36_5_407 reconstructed for the reaction $e + p \rightarrow e + \pi^0 + X$ using the clean π^0 candidates. The exclusive proton peak can be seen near the proton mass 938 MeV.

Exclusive event selection

- A common ellipse in the reconstructed $((m_{\gamma\gamma}, M_X))$ plane defines the exclusive candidate sample in both settings.

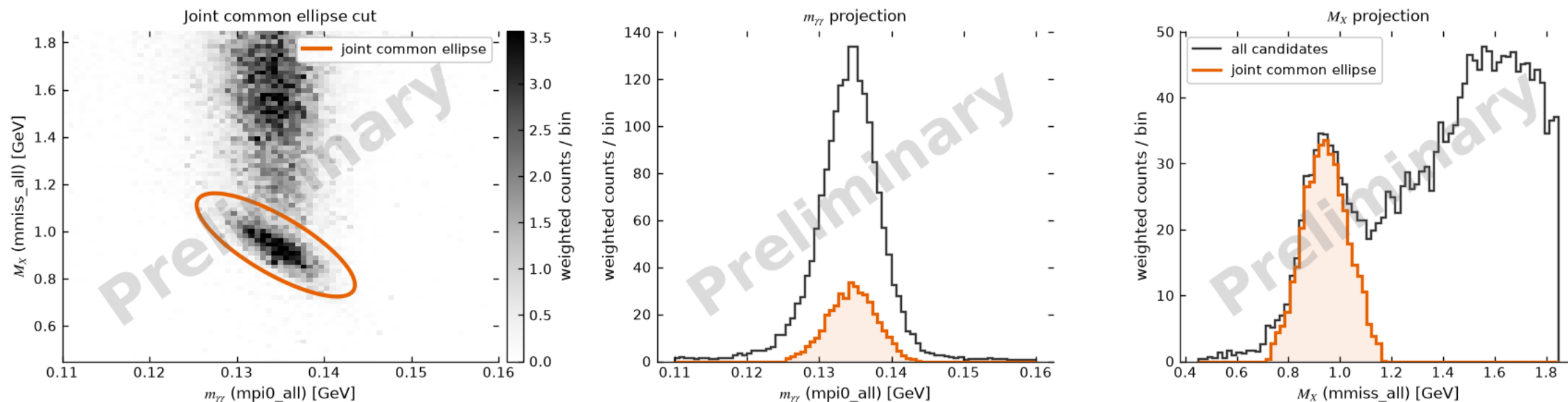


Fig. KinC_x36_5_407: (2D plot) Missing mass (M_X) vs Invariant mass ($m_{\gamma\gamma}$) distribution showing the correlation between the two. (1D plots) The one dimensional projection of the M_X and $m_{\gamma\gamma}$ distributions with and without the exclusive events selected by the ellipse cut.

Kinematic Phase Space Coverage

- With all the relevant event selection applied
 - Acceptance cuts and PID cuts
 - Background subtraction in the π^0 signal
 - Exclusive event selection
- The two data sets are restricted to a common kinematic region to support the joint extraction at fixed Q^2 , x_B , t' and ϕ .

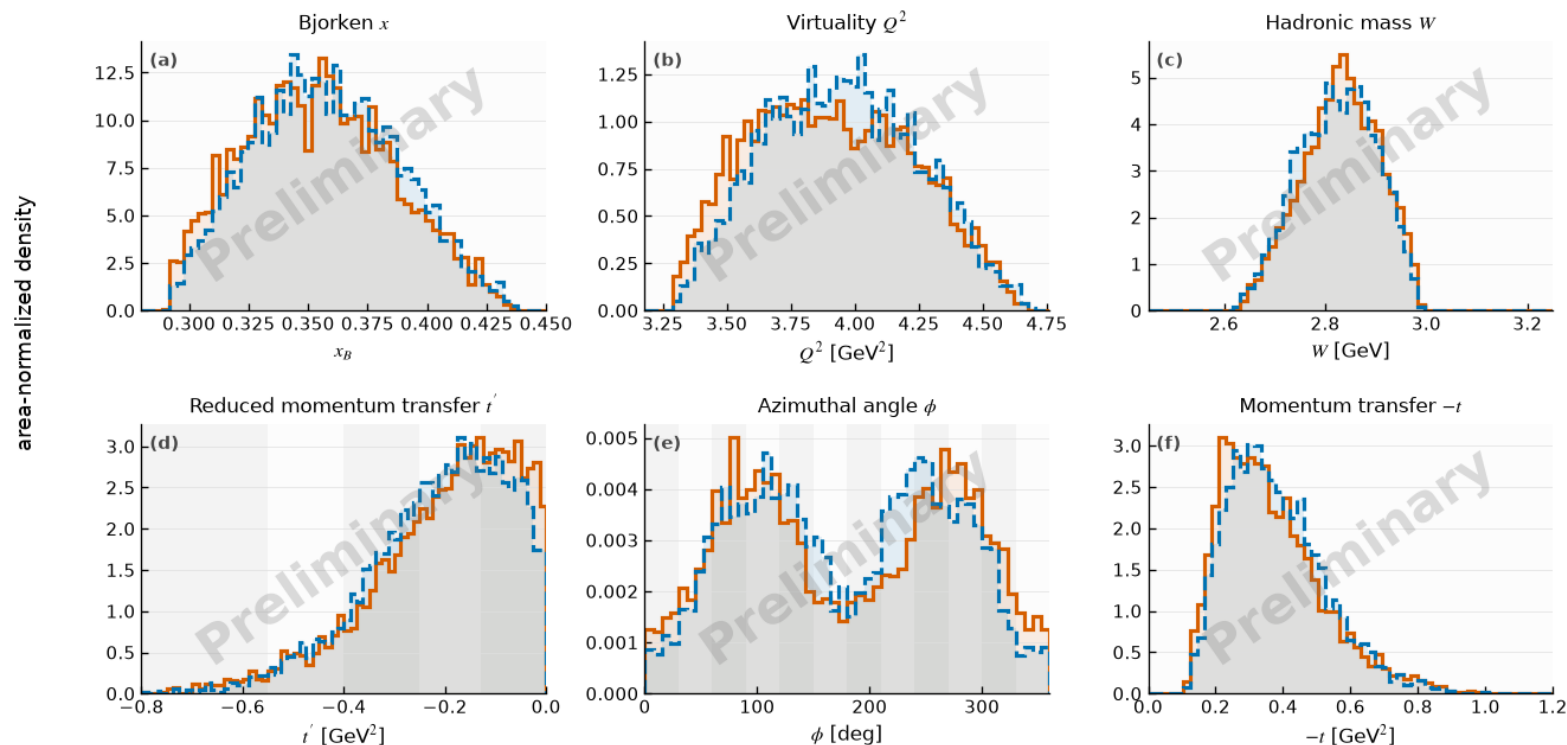
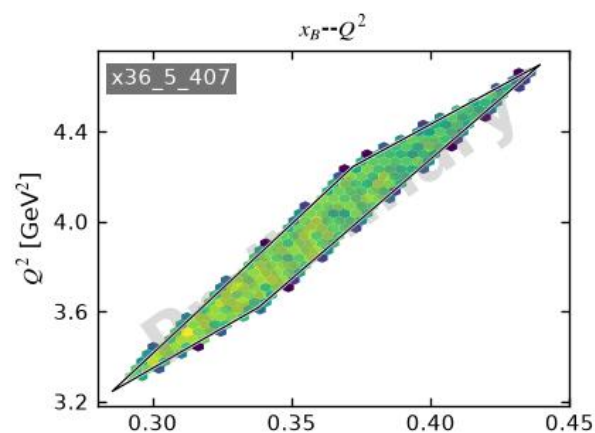
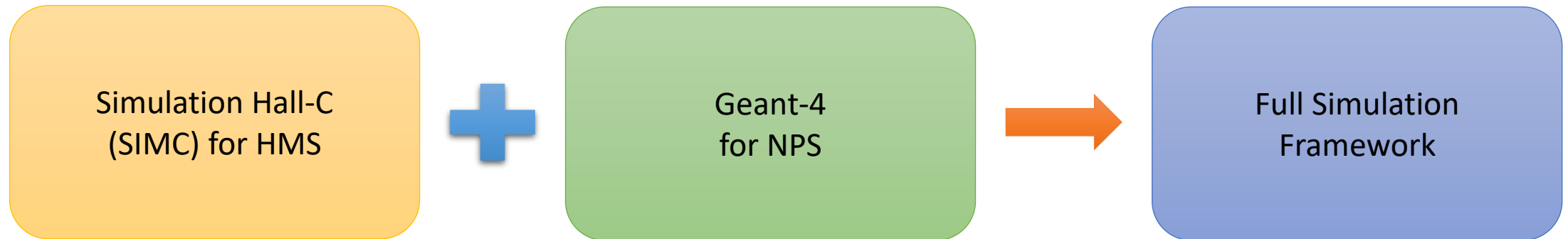


Fig. (Left) Q^2 vs x_B phase space “diamond cut” selected events for phase space matching. (Right) area-normalized distributions for the high- ϵ and low- ϵ samples, illustrating their kinematic overlap of KinC_x36_5_407 (orange) and KinC_x36_4 (blue).

Simulation

- The experimental cross section doesn't just need the experimental data but also requires a good simulation of the process.
- The simulation maps generated kinematics to reconstructed yields, accounting for acceptance, resolution, radiative effects, and migration between bins.



- Primary scattering events with xsec model and radiative corrections.
- Simulates HMS spectrometer acceptance and full HMS side kinematics.
- Provides the event generator for the hadron side, serving as input to Geant4.

- Simulates particle transport and energy deposition in the NPS calorimeter.

Data–Simulation Validation

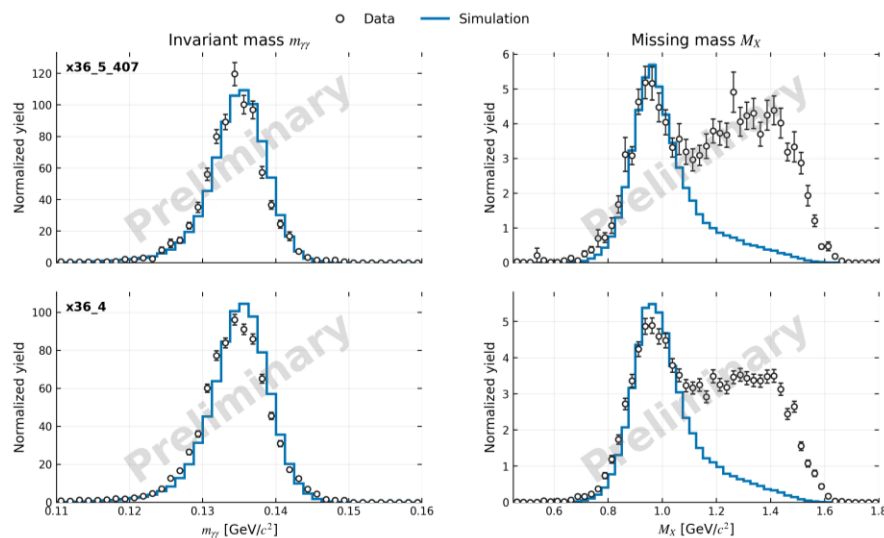
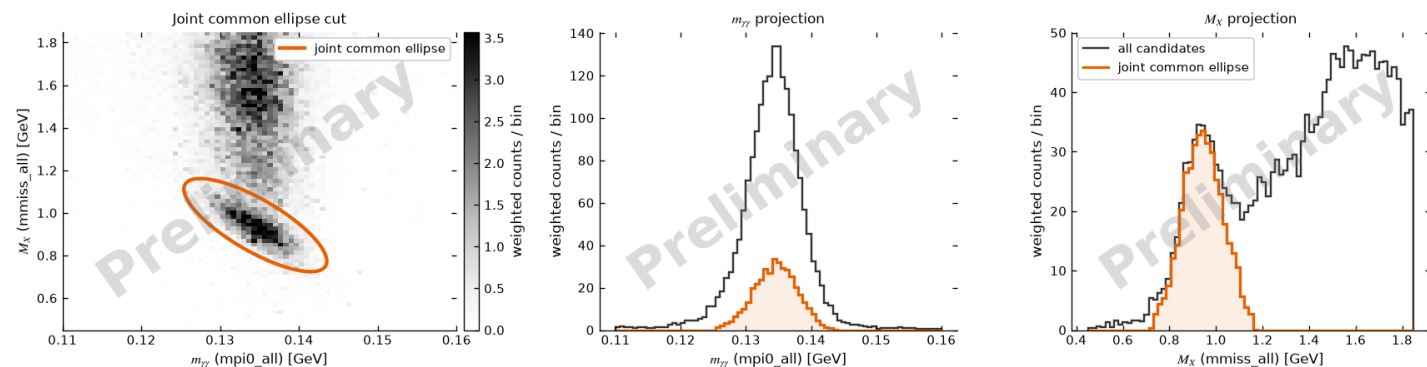
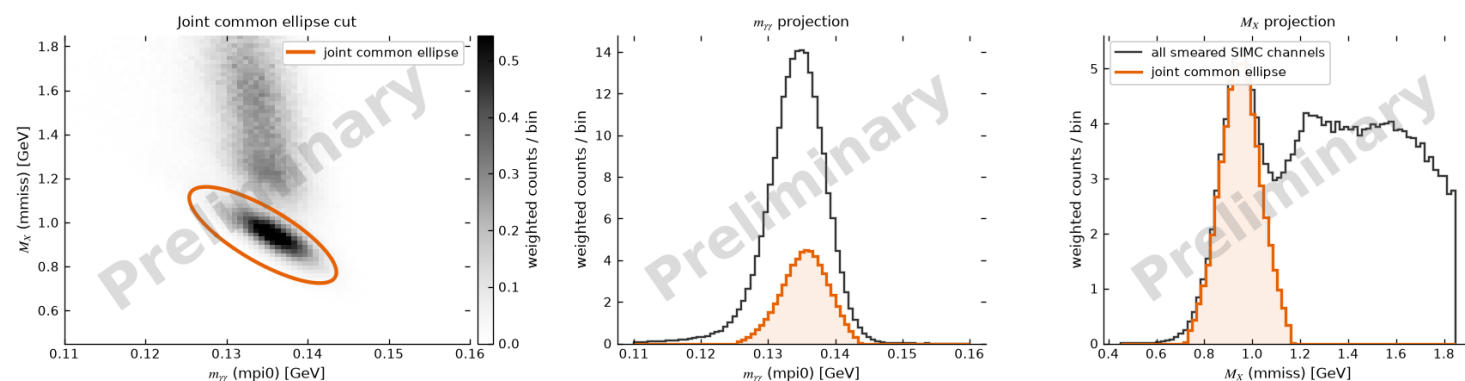


Fig. (Left) Data and Simulation M_X and $m_{\gamma\gamma}$ overlay plots, normalized to the same scales for comparison. (Top) Data (M_X vs $m_{\gamma\gamma}$) and their 1d projections. (Bottom) Simulated (M_X vs $m_{\gamma\gamma}$) and their 1d projections.



- The reconstructed π^0 and exclusive-proton signal regions provide validation of the simulated detector response used in the cross-section extraction.



Extraction from the Azimuthal Yield Distributions

The high- and low- ϵ simulations are fitted simultaneously to the corresponding data using the azimuthal dependence of exclusive π^0 production.

$$\frac{d^2\sigma}{dtd\phi} = (\sigma_T + \epsilon\sigma_L) + \epsilon\sigma_{TT}\cos 2\phi + \sqrt{2\epsilon(1+\epsilon)}\sigma_{LT}\cos\phi$$

Fitting parameters to the functional form:

$$\mathbf{E} + \mathbf{F}(\epsilon\cos 2\phi) + \mathbf{G}\sqrt{2\epsilon(1+\epsilon)}\cos\phi$$

- The unseparated responses are determined independently at the two ϵ settings.
- The σ_{TT} and σ_{LT} responses are shared between the settings at matched kinematics.

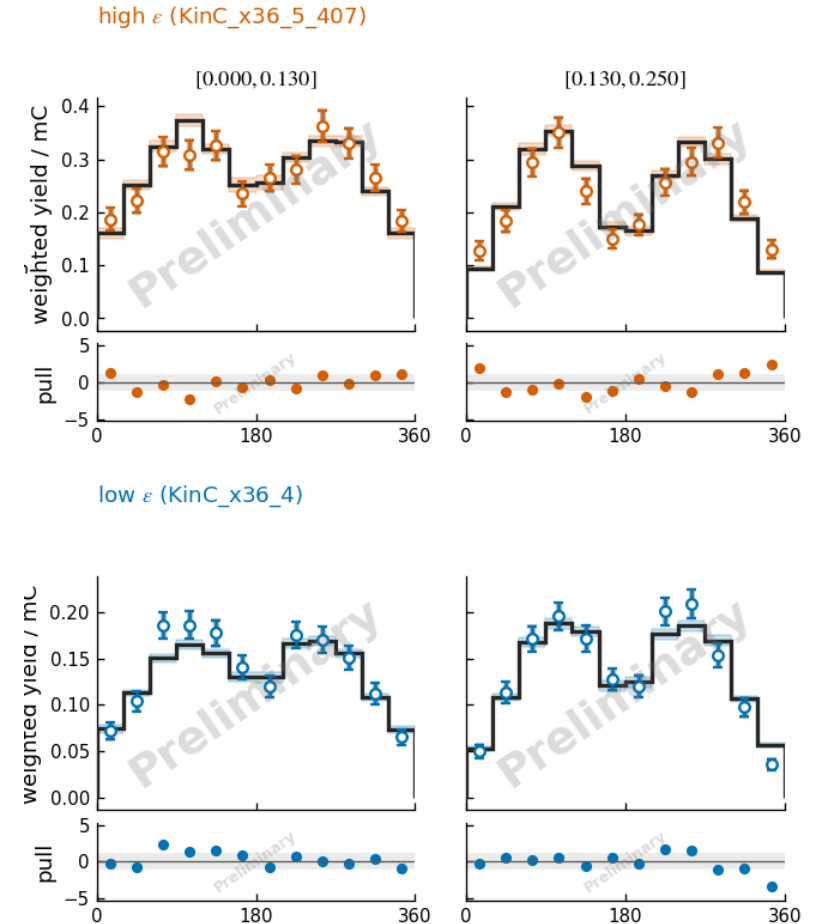


Fig. Simulated yields (solid line) fitted to data yields for t' bins with further 12 ϕ bins each.

Preliminary Results

Preliminary Unseparated and Interference cross-sections

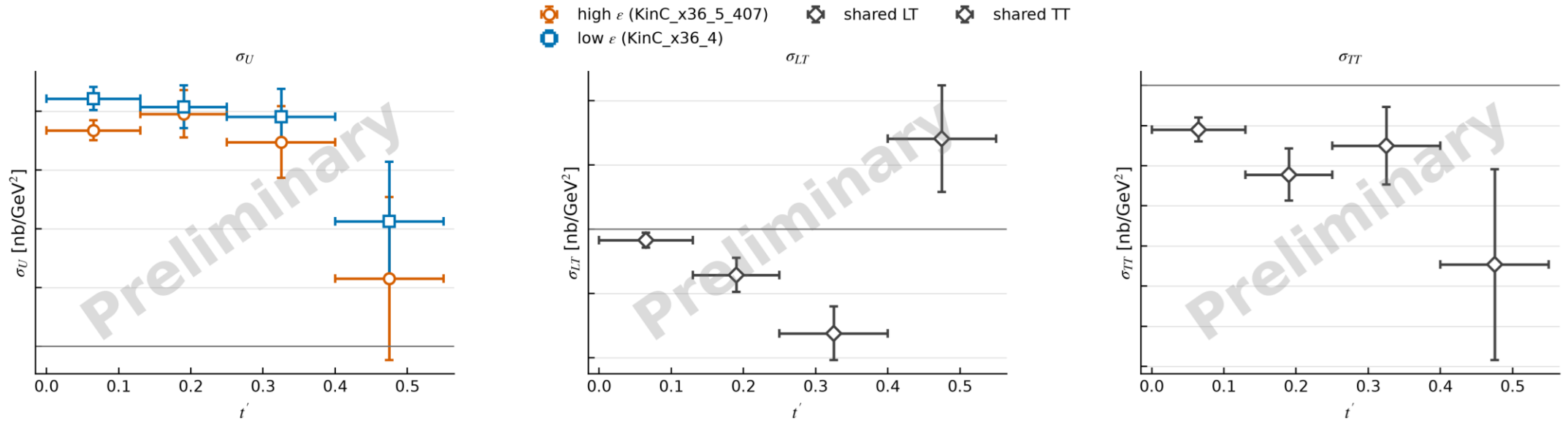
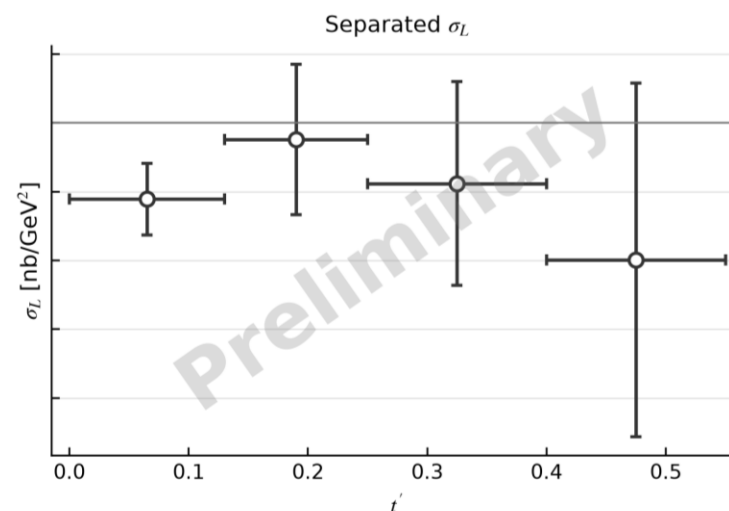
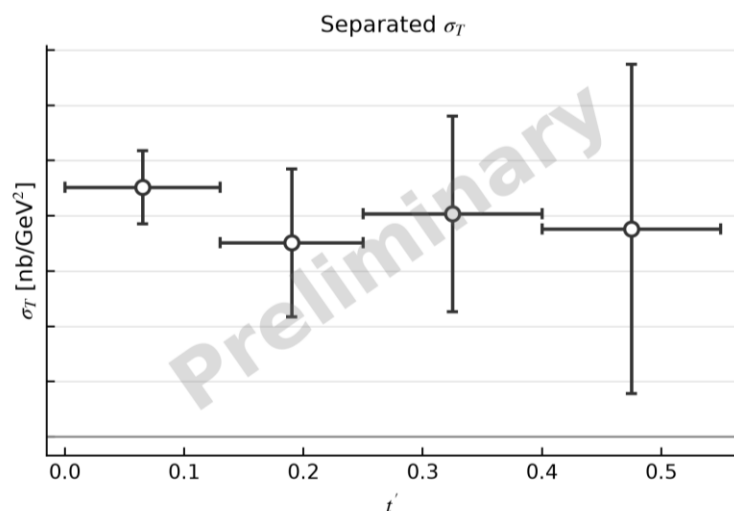


Fig. Preliminary cross section results for $Q^2 \approx 4.0 \text{ GeV}^2$ and $x_B \approx 0.36$ from the two settings KinC_x36_5_407 ($\epsilon \approx 0.71$) and KinC_x36_4 ($\epsilon \approx 0.52$).

Preliminary Rosenbluth Separation



$$\sigma_L = \frac{\sigma_U^{\text{high}} - \sigma_U^{\text{low}}}{\epsilon_{\text{high}} - \epsilon_{\text{low}}}$$

$$\sigma_T = \frac{\epsilon_{\text{high}}\sigma_U^{\text{low}} - \epsilon_{\text{low}}\sigma_U^{\text{high}}}{\epsilon_{\text{high}} - \epsilon_{\text{low}}}$$

Fig. Preliminary L/T separation results for $Q^2 \approx 4.0 \text{ GeV}^2$ and $x_B \approx 0.36$ from the two settings KinC_x36_5_407 ($\epsilon \approx 0.71$) and KinC_x36_4 ($\epsilon \approx 0.52$).

- The preliminary L/T separation is particularly sensitive to relative normalization and kinematic matching between the two settings. These effects, along with the statistical and systematic uncertainties, are undergoing further validation..

Closing remarks

- Previous CLAS and Hall A measurements have demonstrated the importance of transverse-photon contributions in exclusive π^0 electroproduction.
- The Hall C NPS experiment extends the opportunity for L/T separation to higher momentum transfer.
- Preliminary results from E12-13-010 near $Q^2 \approx 4.0 \text{ GeV}^2$ and $x_B \approx 0.36$ undergoing validations and cross checks.
- A direct, simultaneous extraction from the two ε settings has yielded preliminary unseparated, interference, and L/T-separated cross-section estimates.
- Further validation of normalization and uncertainties is underway before drawing final physics conclusions.

The finalized separated cross sections will provide new constraints on transverse reaction mechanisms and help test the approach toward longitudinal dominance at higher Q^2 .

Thank you for your time and attention!

Backup

Exclusive Processes and Nucleon Structure

- How are quarks and gluons distributed in momentum and transverse position inside the nucleon?
- Parton distribution functions (PDFs) describe longitudinal momentum distributions, while generalized parton distributions (GPDs) provide information correlating longitudinal momentum with transverse spatial structure.
- Hard exclusive reactions, such as deeply virtual Compton scattering (DVCS) and deeply virtual meson production (DVMP), provide complementary experimental constraints on GPDs.

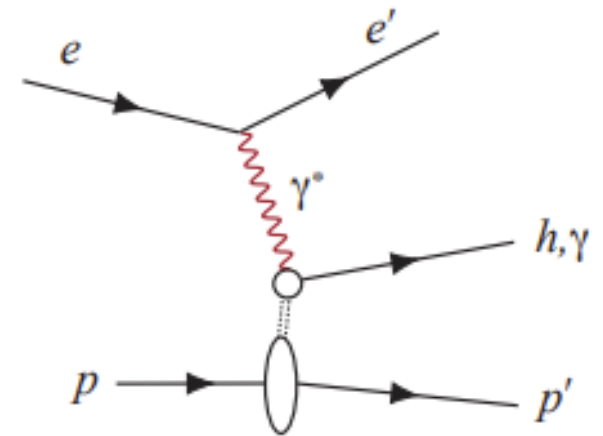


Fig. Exclusive DIS

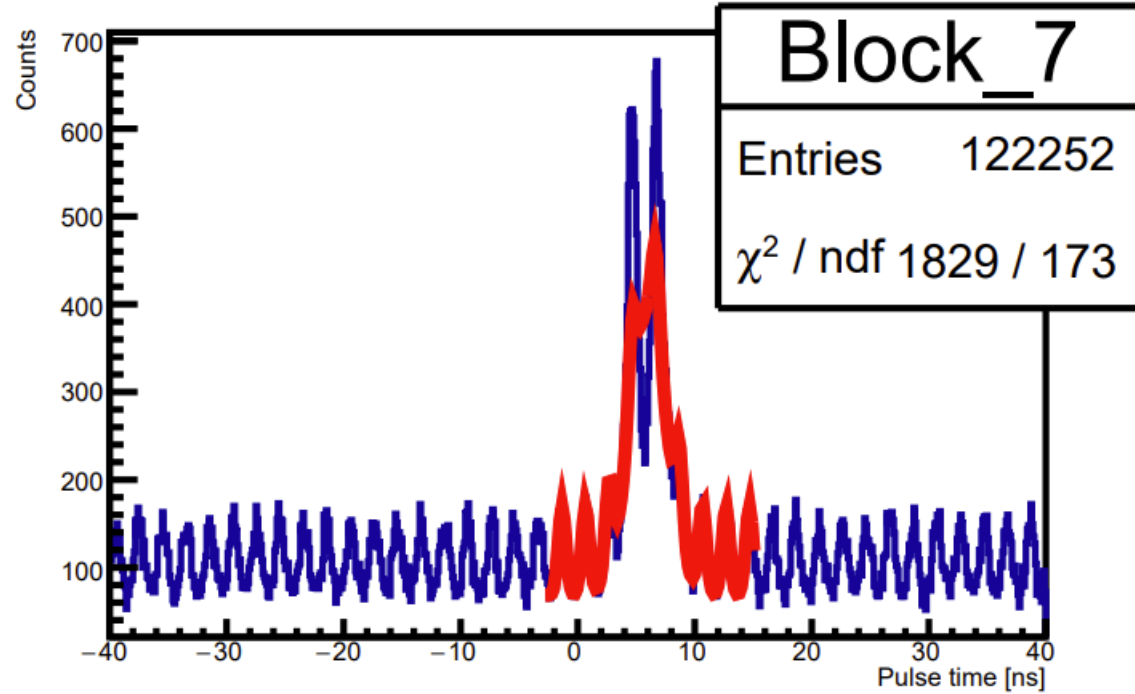


Fig. A block with a double-peak in the timing spectrum.

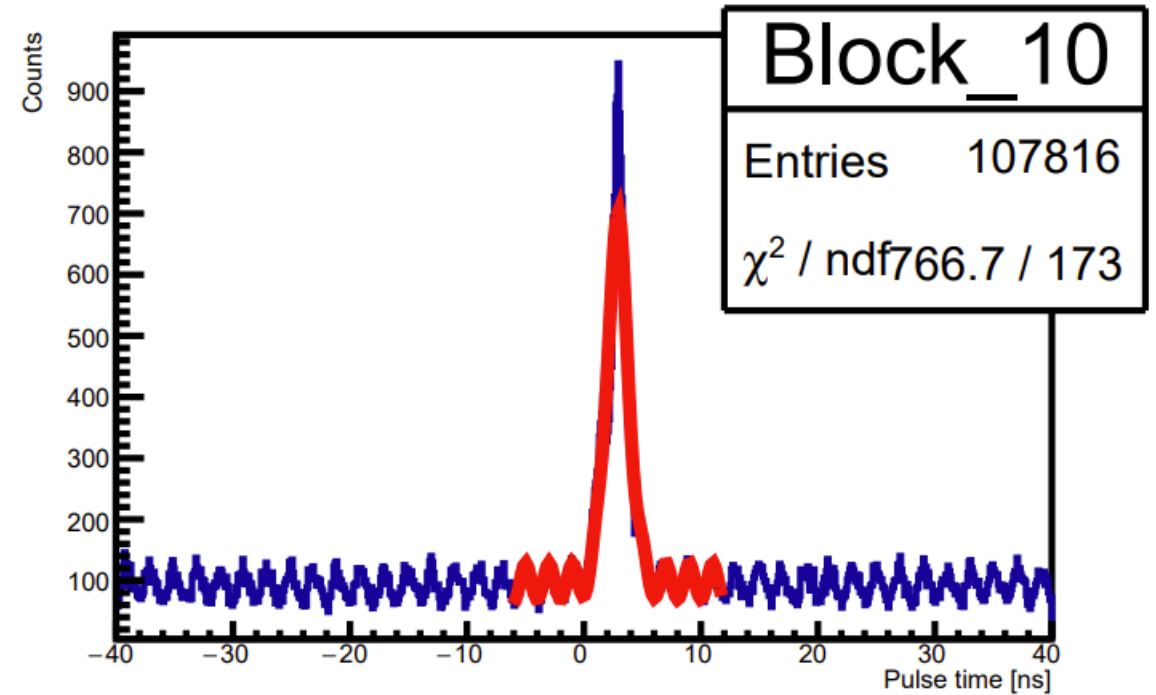


Fig. A block with a clean peak in the timing spectrum.

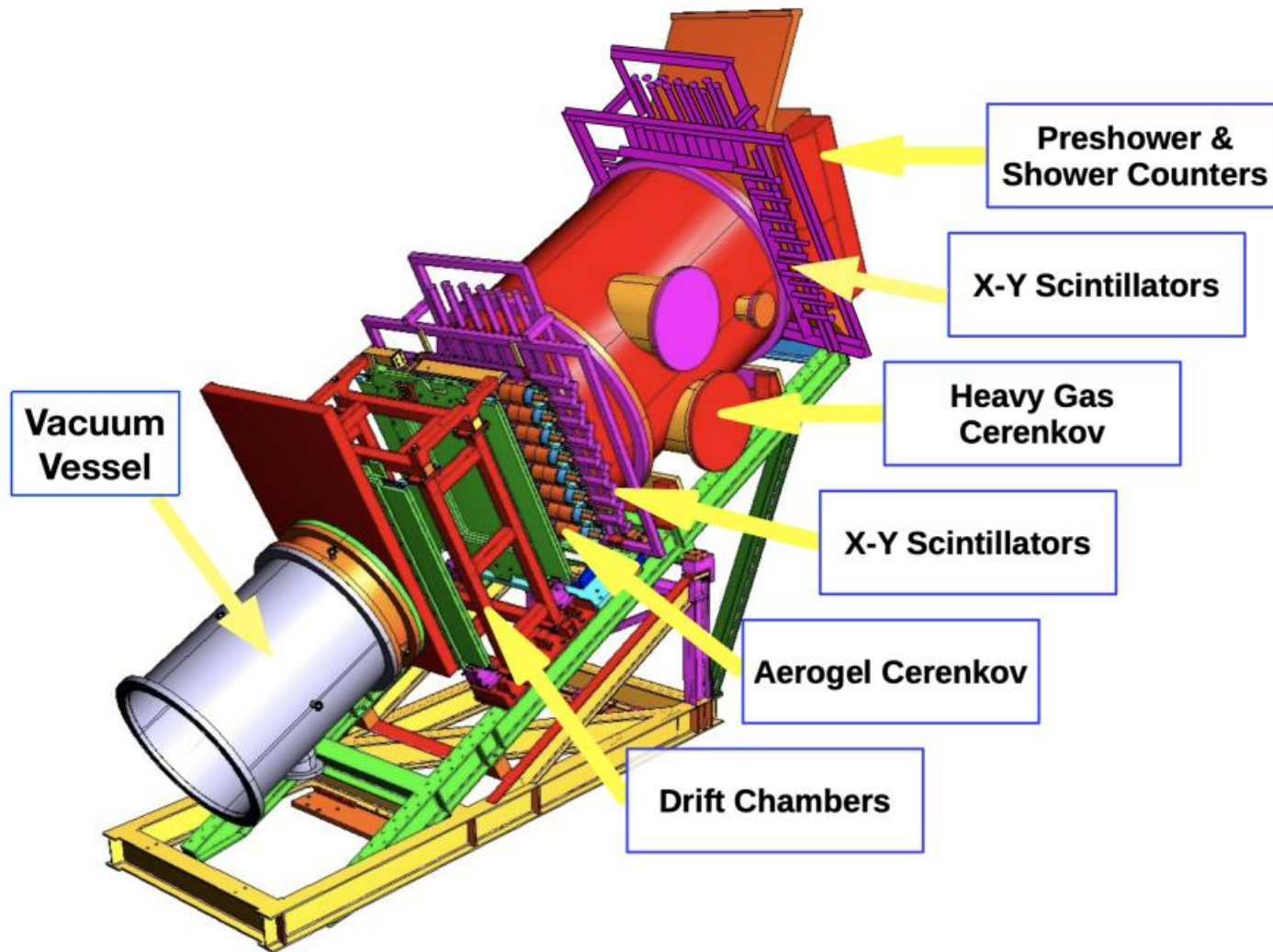


Fig. Schematic diagram of High Momentum Spectrometer (HMS) Detector at Hall C

Kinematic	Runs used in analysis	Run Range(s)	Correction Factor	Relative Error
x36_5_3	3734 (LH2) 6931 (dummy)	3728-3782	0.6889 +/- 0.0108	1.56%
x60_4	4300 (LH2) 4309 (dummy)	4239-4568	0.732 +/- 0.024	3.28%
x36_4	6407 (LH2)	6407-6421	0.646 +/- 0.018	2.79%
	6477 (LH2)	6432-6487	0.699 +/- 0.018	2.56%
	6559 (LH2)	6504-6569	0.852 +/- 0.021	2.46%
	6427 (dummy) 6490 (LH2 positrons)			

Table: Target density correction factors applied to the data yield.

Data included in the extraction

	High ϵ	Low ϵ
Selected events	3939	4658
Runs	12	51
x_B , central 90%	0.306–0.409	0.310–0.409
Q^2 , central 90% [GeV ²]	3.43–4.44	3.48–4.44
W , central 90% [GeV]	2.70–2.95	2.70–2.94
Mean t' [GeV ²]	−0.203	−0.212

Table 1: The two settings cover nearly the same kinematic region.

Analysis range: $0.29 < x_B < 0.44$, $3.3 < Q^2 < 4.7 \text{ GeV}^2$, and $-0.8 < t' < 0 \text{ GeV}^2$.

Corrections versus beam current: high ϵ

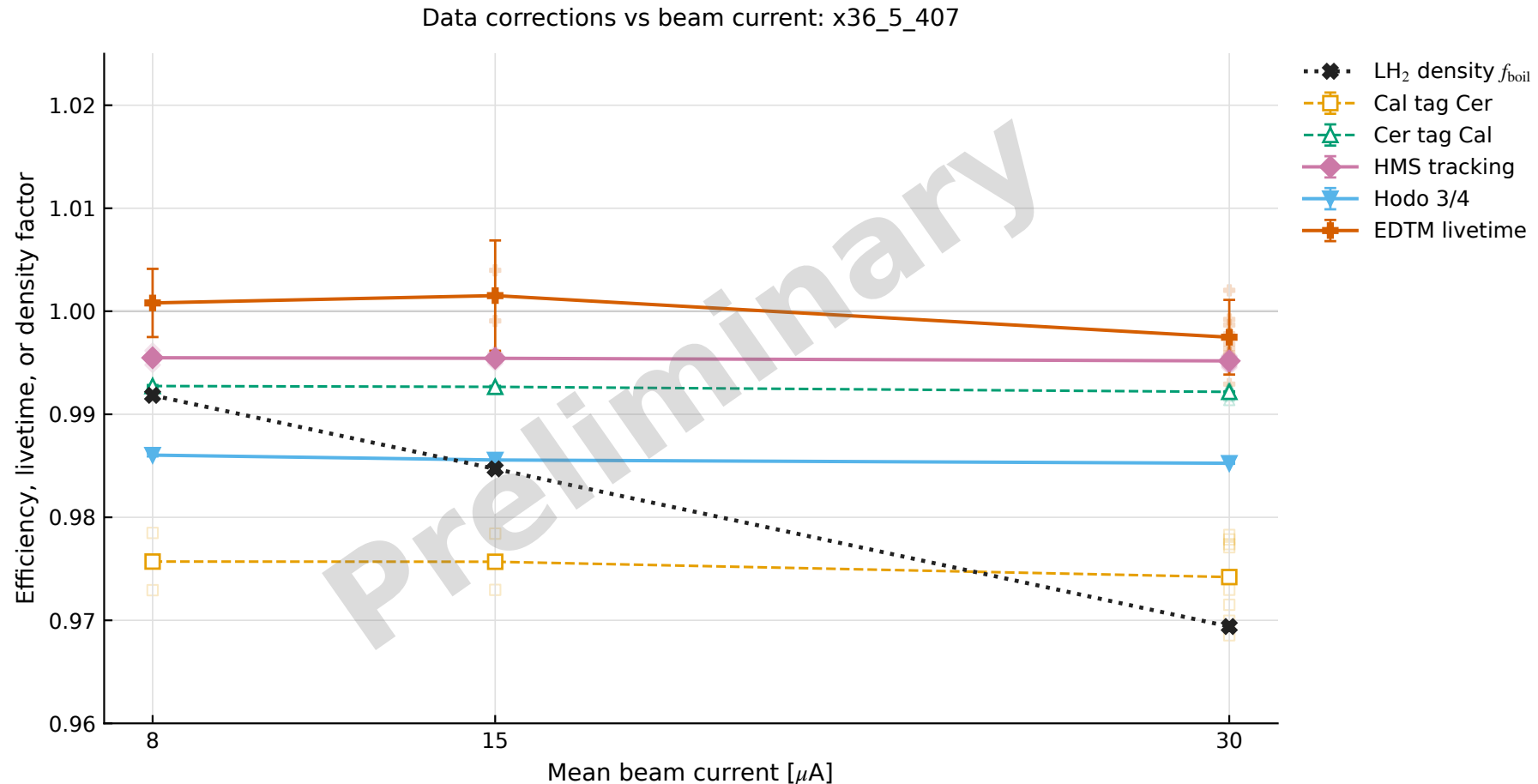


Figure 1: Efficiency, livetime, and target-density checks at 8, 15, and 30 μA . Tracking, hodoscope, and livetime values are used in the yield correction.

Corrections versus beam current: low ϵ

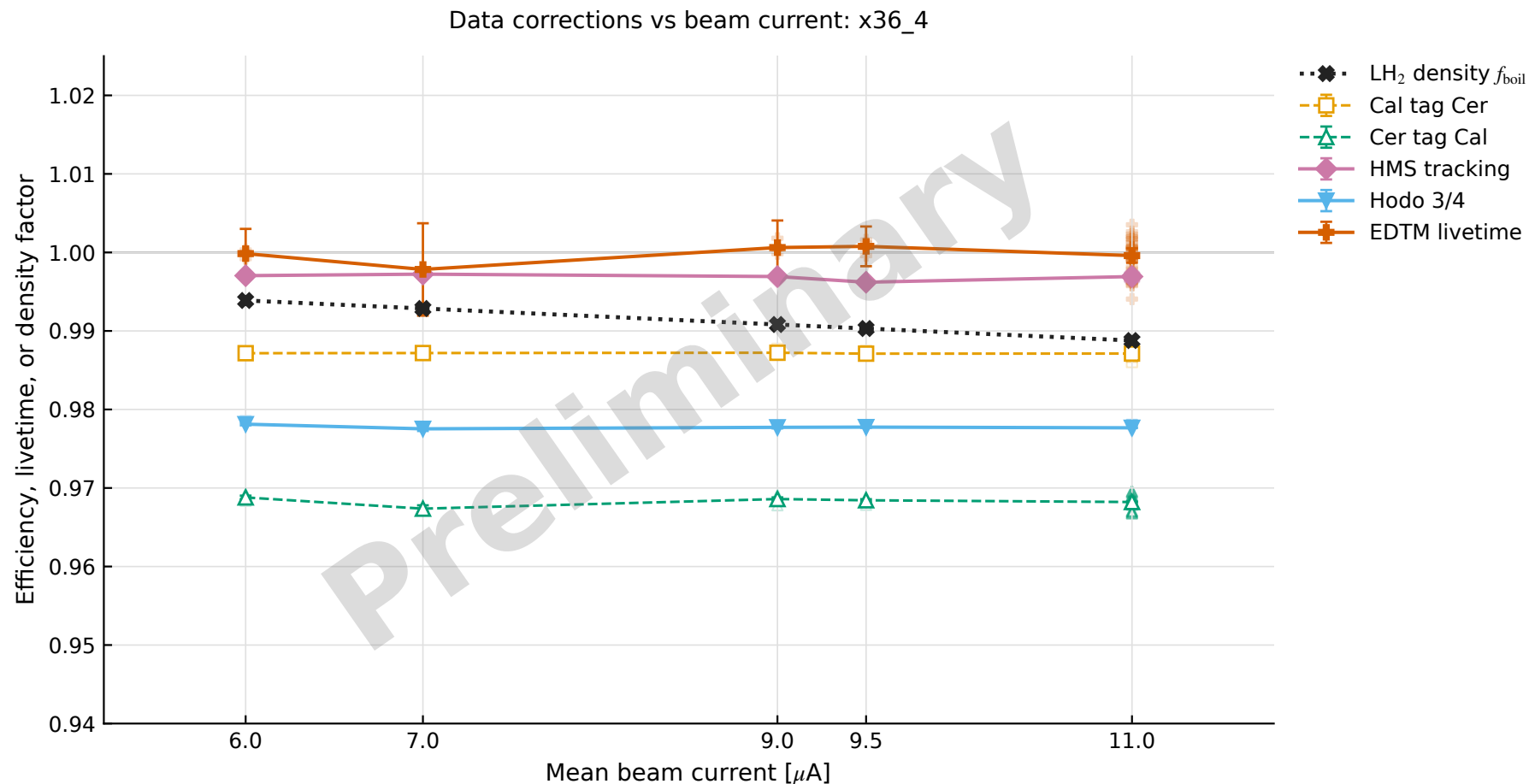


Figure 2: The same checks at the six low- ϵ current settings. The correction values remain stable across the measured current range.

Measured and predicted yields: high ϵ

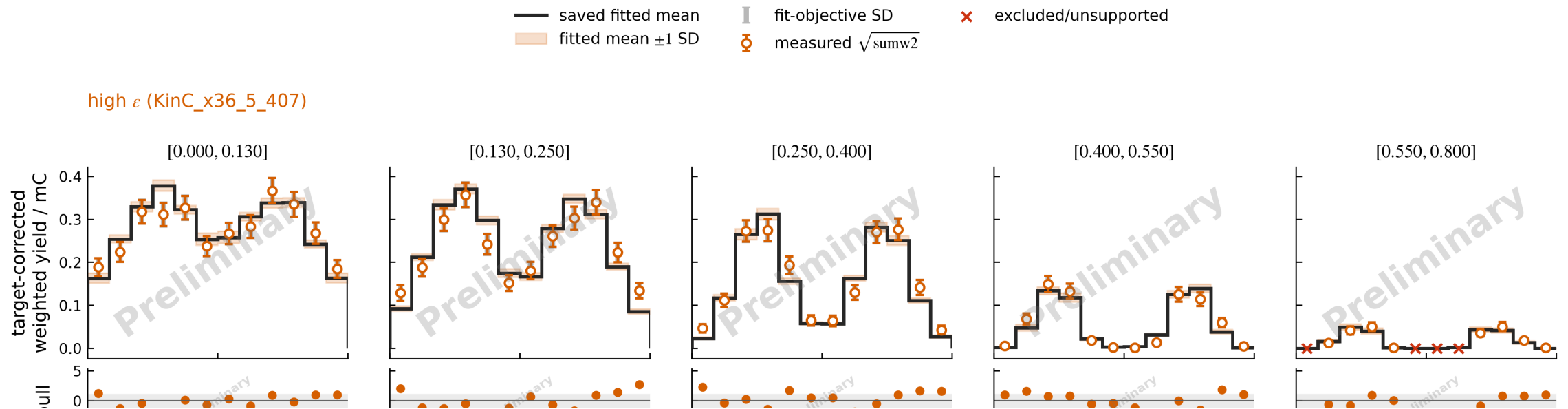


Figure 3: Markers are the measured yield versus azimuth in all five $-t'$ bins. Black steps show the simulation-based prediction after detector acceptance and bin migration. Red crosses mark bins that are not used.

Measured and predicted yields: low ϵ

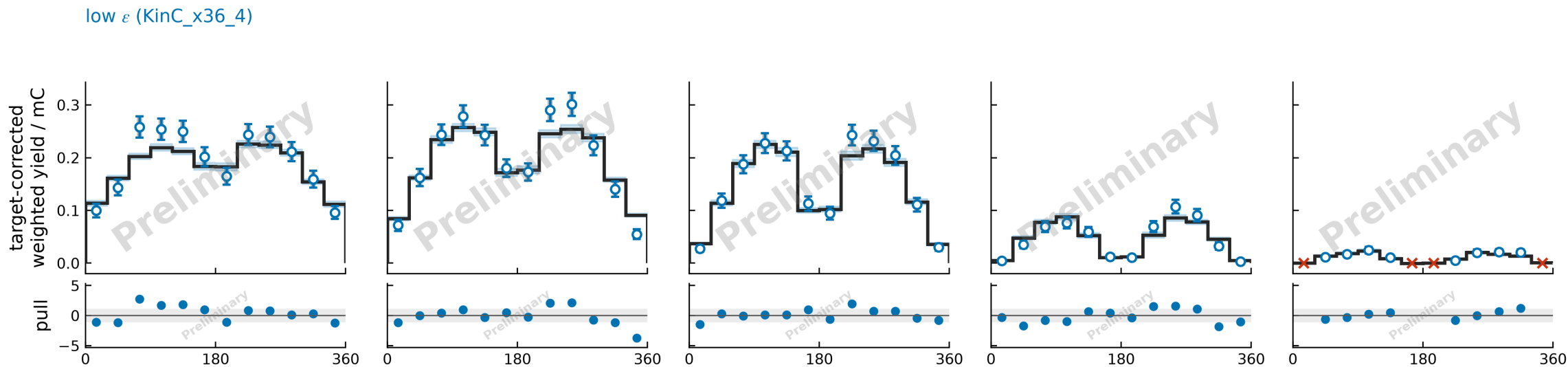


Figure 4: The low- ϵ data use the same five $-t'$ bins. The lower strips show the difference between each measurement and its simulation-based prediction in units of the expected spread.

Uncertainties included so far

Source	Treatment in the displayed bars
Measured event counts	Included
Limited detector-response sample	Included
Efficiencies and livetime	Applied as fixed corrections
Target density	Applied; its uncertainty is not yet included
Background subtraction	Its uncertainty is not yet included
Detector calibration and bin choice	Not yet included
Matching the two beam settings	Not yet included

Table 2: The bars are statistical estimates, not the final uncertainty.