First look at π^- asymmetries off CLAS12 RG-C longitudinally polarized ND_3 target

CLAS12 Collaboration Meeting
March 11, 2026

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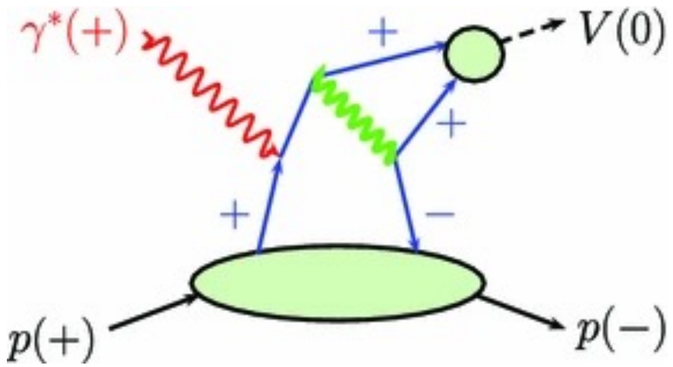
Overview: DVπ^-P, $en \rightarrow ep\pi^-$

- Complementary to exclusive π^+ production analysis (see prev.)
  - Effects of nuclear target (Fermi motion)
  - First DVπ^-P BSA results from CLAS12
  - Potential new access to chiral odd GPDs of neutron from transversely polarized contributions
- Results still very preliminary!

DV$\pi^\pm$P diagram



S. V. Goloskokov and P. Kroll, “Transversity in exclusive vector-meson leptoproduction,” *Eur. Phys. J. C*, vol. 74, p. 2725, 2014.

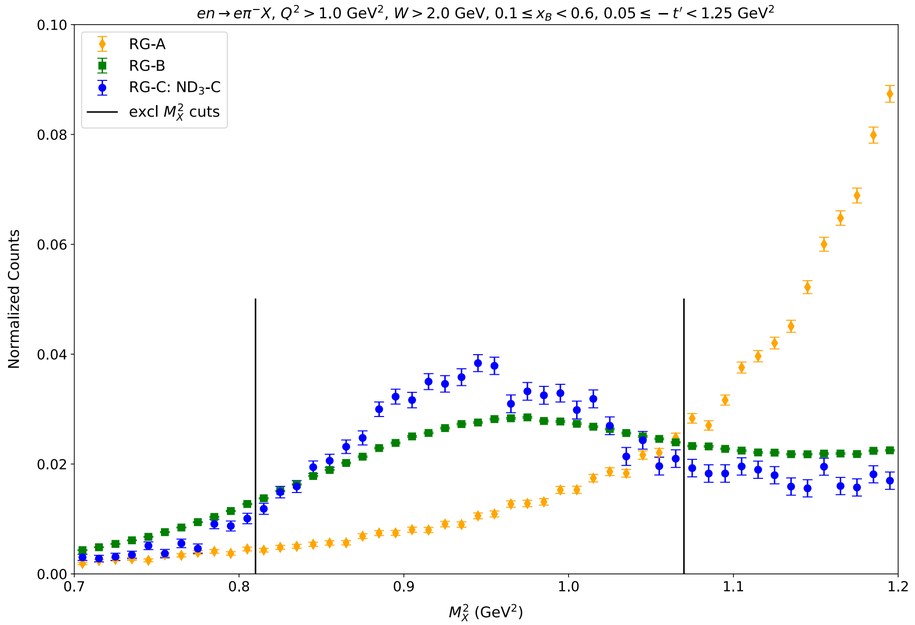
	U	L	T
U	$\mathcal{H}$		$\mathcal{E}_T$
L		$\widetilde{\mathcal{H}}$	$\widetilde{\mathcal{E}}_T$
T	$\mathcal{E}$	$\widetilde{\mathcal{E}}$	$\mathcal{H}_T, \widetilde{\mathcal{H}}_T$

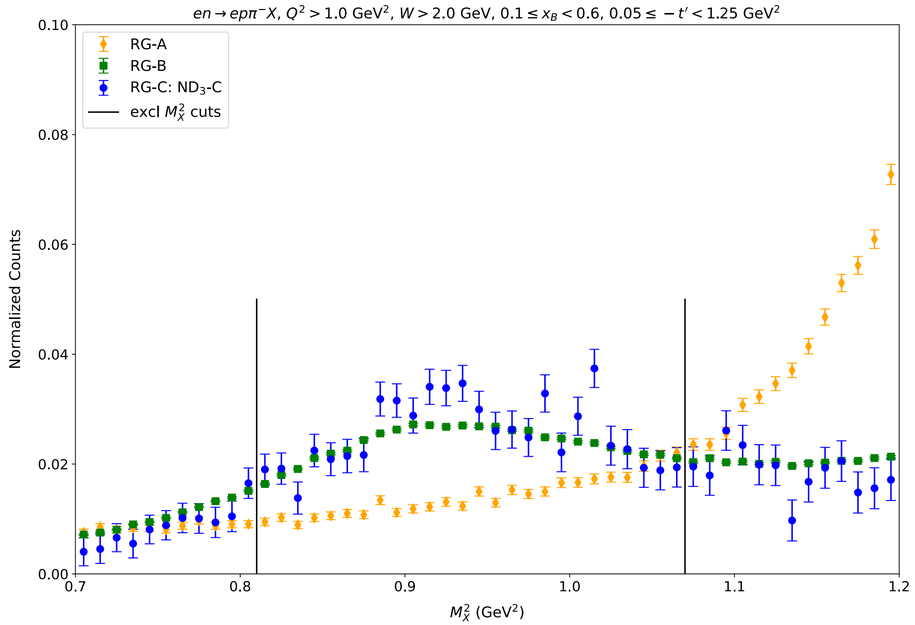
chiral odd GPDs

Final state

$Q^2 > 1.0$ GeV^2
$W > 2.0$ GeV
$y < 0.75$
0.81 GeV$^2 < M_X^2 < 1.07$ GeV^2

Two-dimensional binning to match π^+ analysis:
$x_B \in [0.10,0.25,0.35,0.45,0.60)$
$-t' \in [0.05,0.25,0.45,0.65,1.05,1.25)$ GeV^2





$en \to e\pi^- X$: higher statistics, mirrors π^+ analysis, poorer resolution

$en \to ep\pi^- X$: lower statistics, cross-check with two particle final state, alternative methods for calculating kinematics

→ Subtracting "nuclear component" replicates RG-B M_X^2 peaks for both channels

Comparing two and three particle final state yields

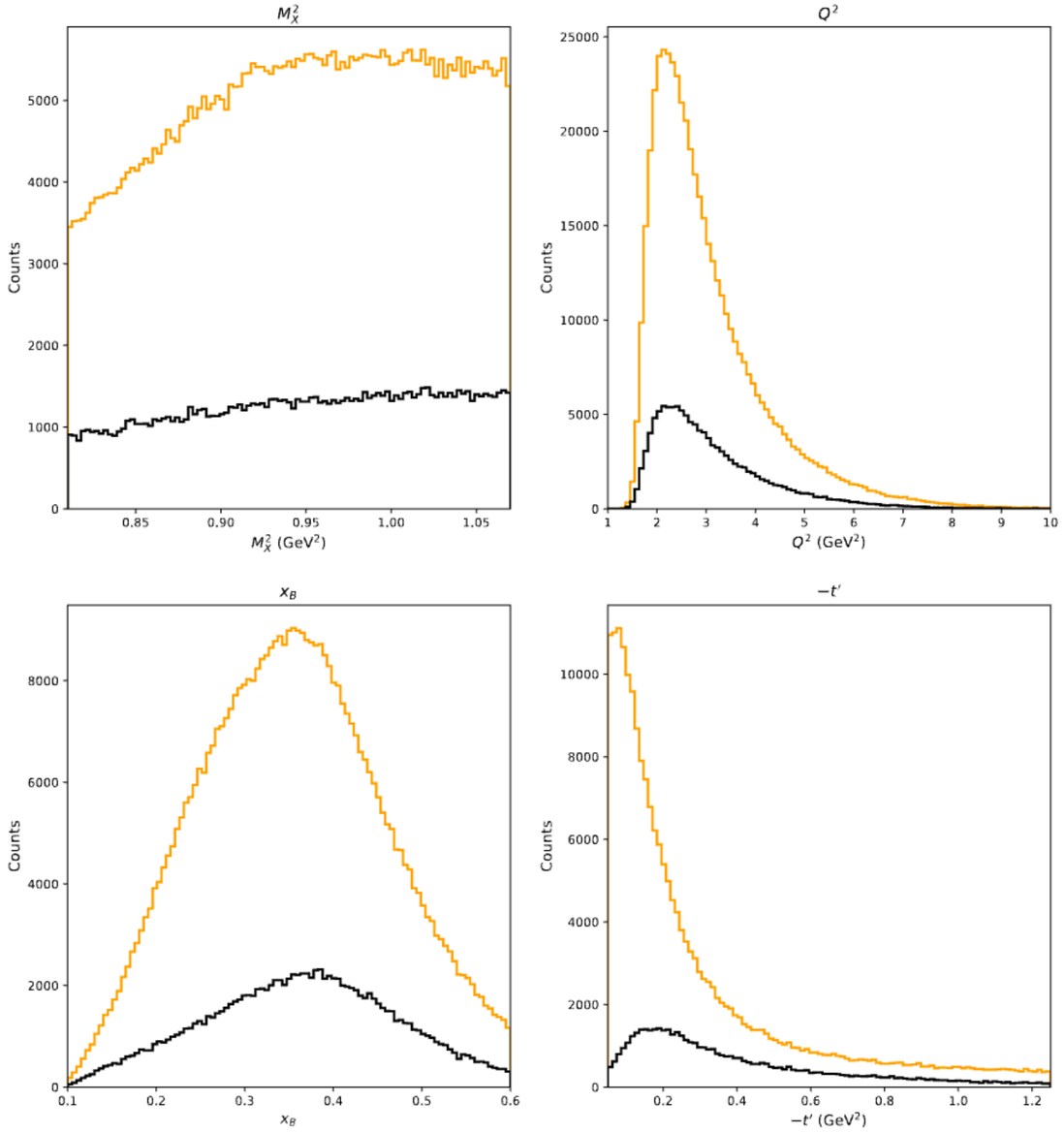
Yields for three particle final state ~25% of two particle final state count total

Multiple strategies to extract t:

1) $t = \left(p - p'\right)^2$: sensitivity to Fermi motion

2) $t = \left(q - p_\pi\right)^2$: sensitivity to resolution effects, used for π^+ analysis, shown here

→ Similar kinematics with lower statistics in three particle final state



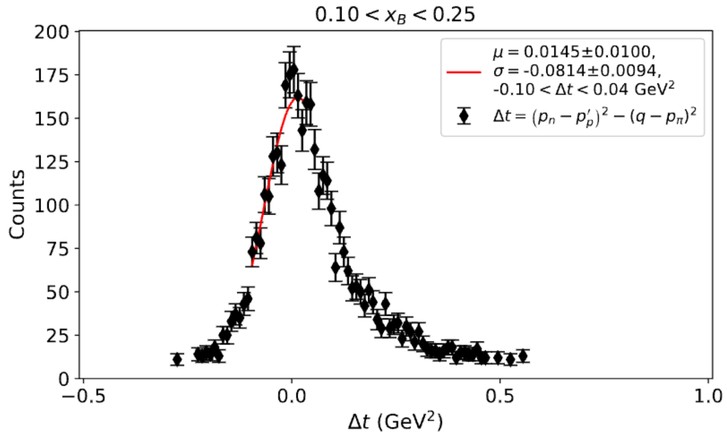
$en \rightarrow e(p)\pi^-$

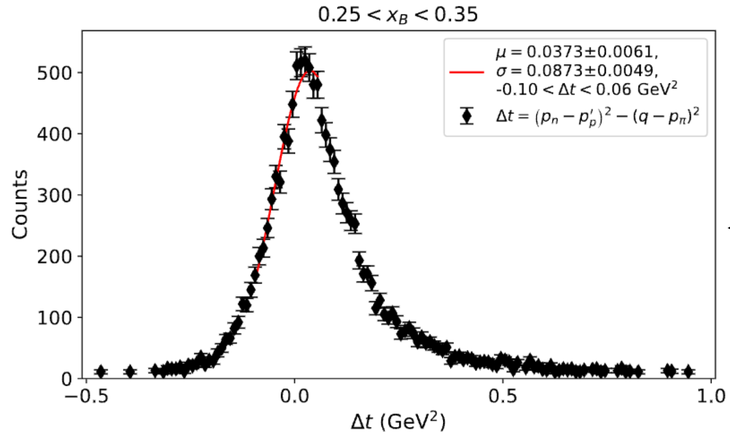
$en \rightarrow ep\pi^-$

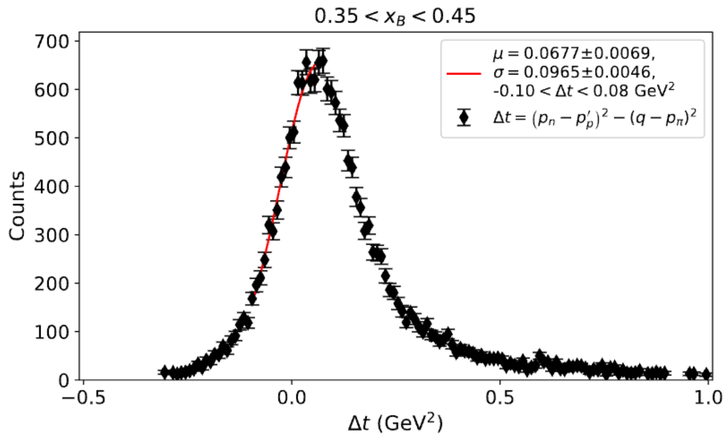
Alternate calculations for $-t \rightarrow -t'$

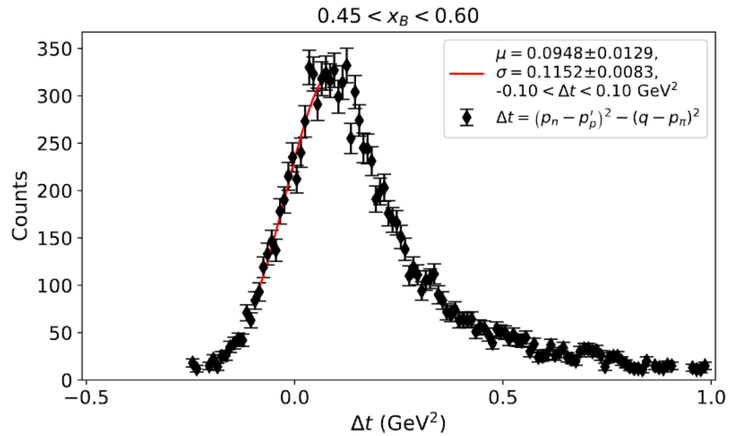
$t' = t - t_{min}$

$\Delta t = \left(p - p'\right)^2 - \left(q - p_\pi\right)^2$ distributions for RG-C Fa22, on ND_3 (nuclear target with heightened Fermi motion)









← width of distributions enhanced by Fermi motion, these are likely events occurring off nitrogen

→ How we use kinematics accessible with three particle final state to constrain Fermi motion?

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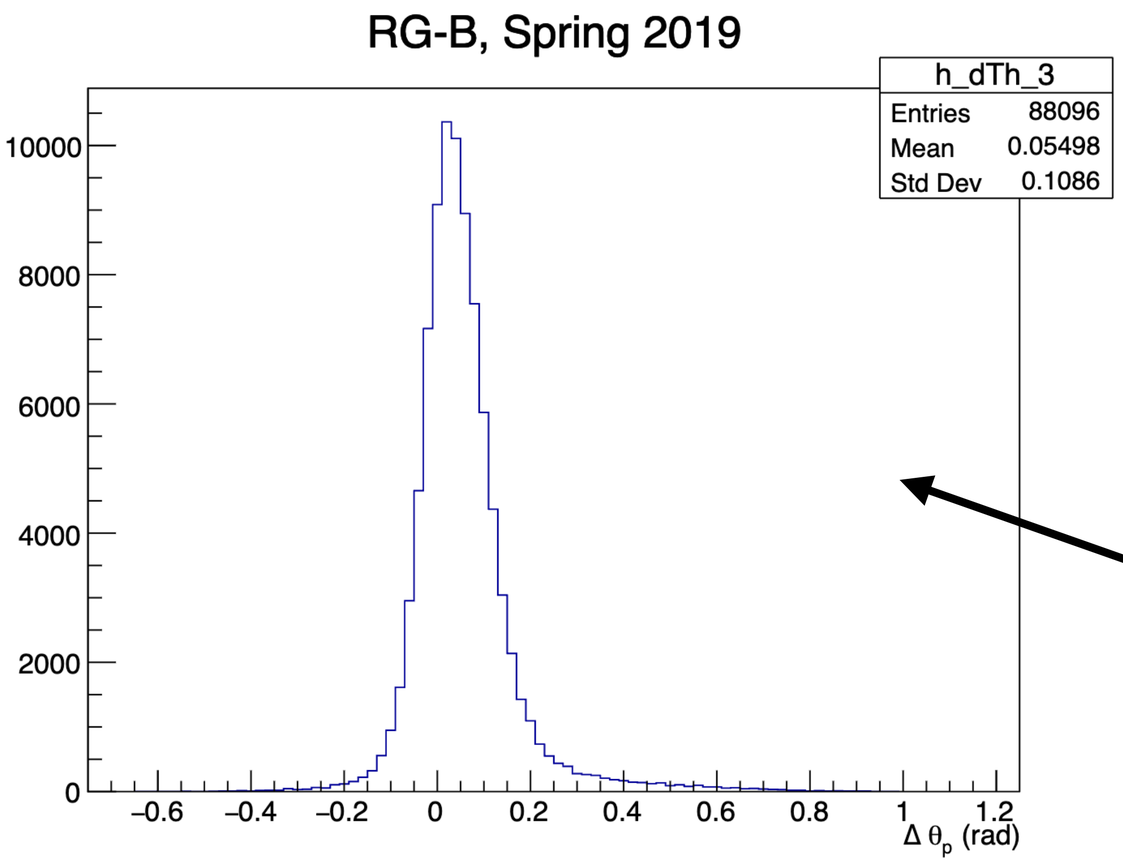
Cone angle cut



- Measuring difference between detected and reconstructed (using π^- and e^-) proton θ
- When calculating proton 4-vector, we assume no Fermi motion
- Discrepancy provides insight on Fermi motion contributions
- Can use RG-B as baseline for expected distribution from deuterons (unpolarized LD_2 target)

RG-B Sp19
$\mu = 0.05496$
$\sigma = 0.1086$

vs.

RG-C
$\mu \sim 0.24$
$\sigma \sim 0.27$

→ RG-B data helps us define a cone angle cut to select events off of deuterons for RG-C (RG-B $\mu \pm \sigma$)

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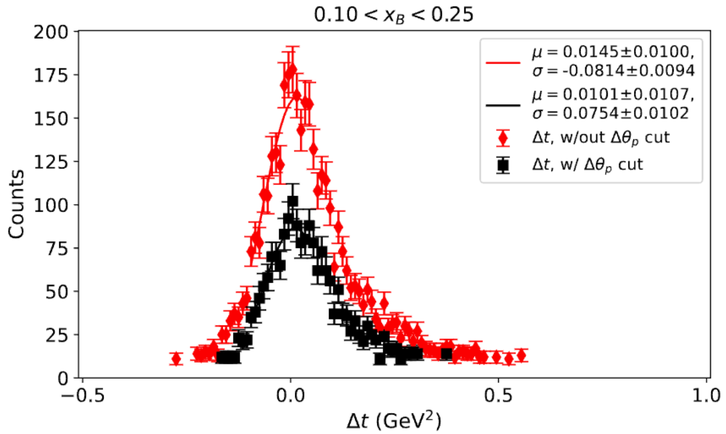
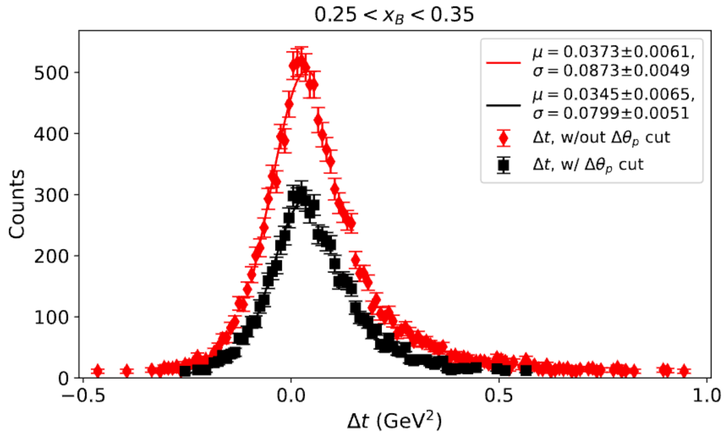
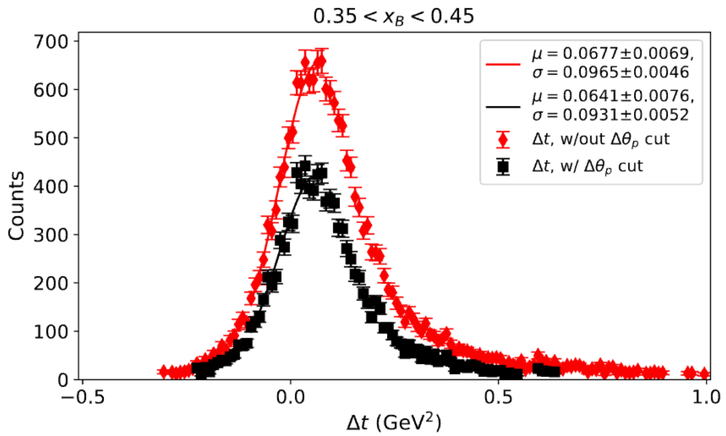
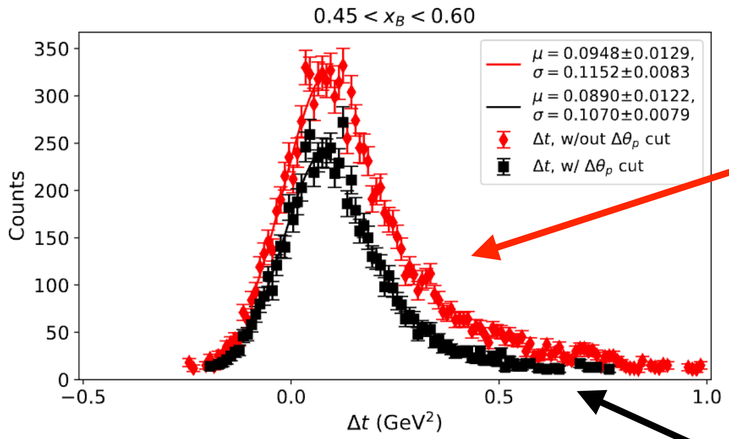
Alternate calculations for $-t \rightarrow -t'$

$$t' = t - t_{min}$$









Constraining $\Delta\theta_p$ narrows Δt distribution, removing events identified as being nuclear in origin due to high Fermi motion

without $\Delta\theta_p$ cut

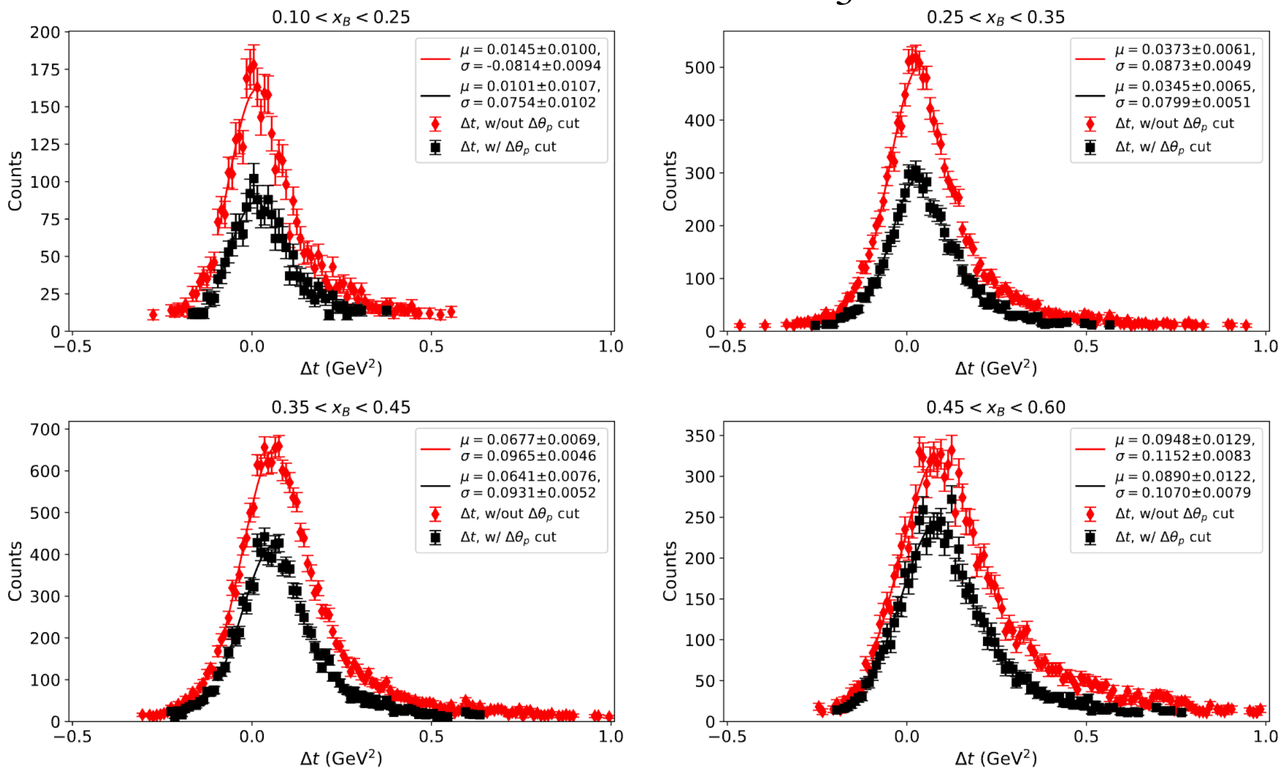
with $\Delta\theta_p$ cut

Alternate calculations for $-t \rightarrow -t'$

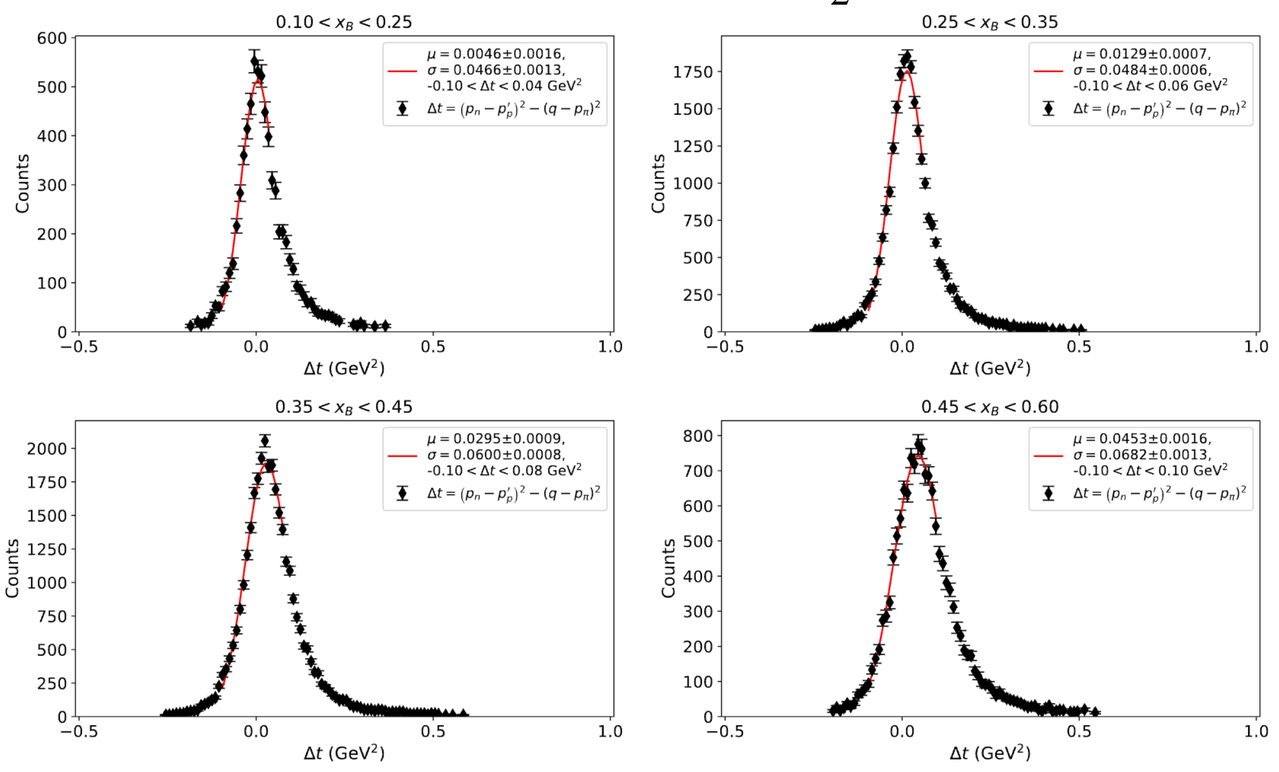
$t' = t - t_{min}$

Still not as narrow as RG-B Δt distributions!

RG-C Fa22, on ND_3



RG-B Sp19, on LD_2



$\rightarrow \Delta\theta_p$ cuts removes some Fermi motion effects, but not all (other effects as well)

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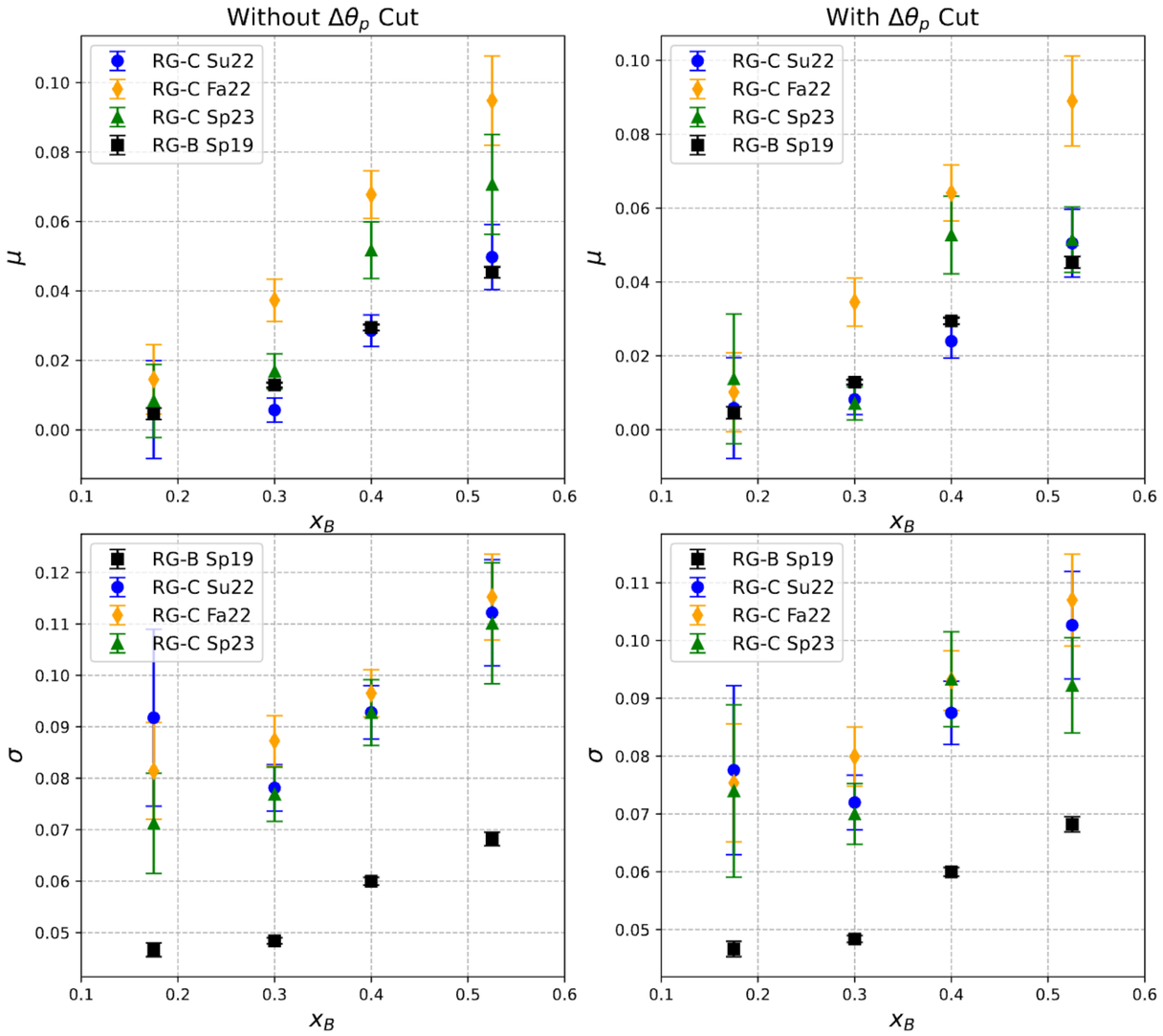
Alternate calculations for $-t \rightarrow -t'$

$t' = t - t_{min}$

Direct comparison using fits to Gaussian:



→ μ: resolution of "reconstructed" t; relatively consistent (using same CLAS12 detectors)

→ σ: Fermi motion; clear differences between RG-B and RG-C, even with $\Delta\theta_p$ cut

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Dilution factor and packing fraction

Dilution factor, packing fraction calculations and methodology by Sebastian Kuhn and Derek Holmberg

- Dilution factor scales results to reflect polarized components of target

$n_A \rightarrow$ (polarized) ND_3

$n_{MT} \rightarrow He$

$n_{CD} \rightarrow CD_2$

$n_C \rightarrow C$

$n_F \rightarrow$ Foils (completely empty target)

where $n_X = \dfrac{N_X}{F_X^{CC}}$

$$DF = \frac{(n_A - n_{MT})\,(n_{CD} - 0.757666 n_C - 0.005200 n_{MT} - 0.237132 n_F)}{n_A\,(n_{CD} - 0.168370 n_C - 0.865973 n_{MT} + 0.03434 n_F)}$$

$$PF = 0.442453 \frac{n_A - n_{MT}}{n_{CD} - 0.168370 n_C - 0.865973 n_{MT} + 0.03434 n_F}$$

- Measures of how tightly molecules are “packed” into the target cell
- Should be uniform across processes → useful for comparison
- Can also be used to construct dilution factor, yielding a near identical result with somewhat higher uncertainty

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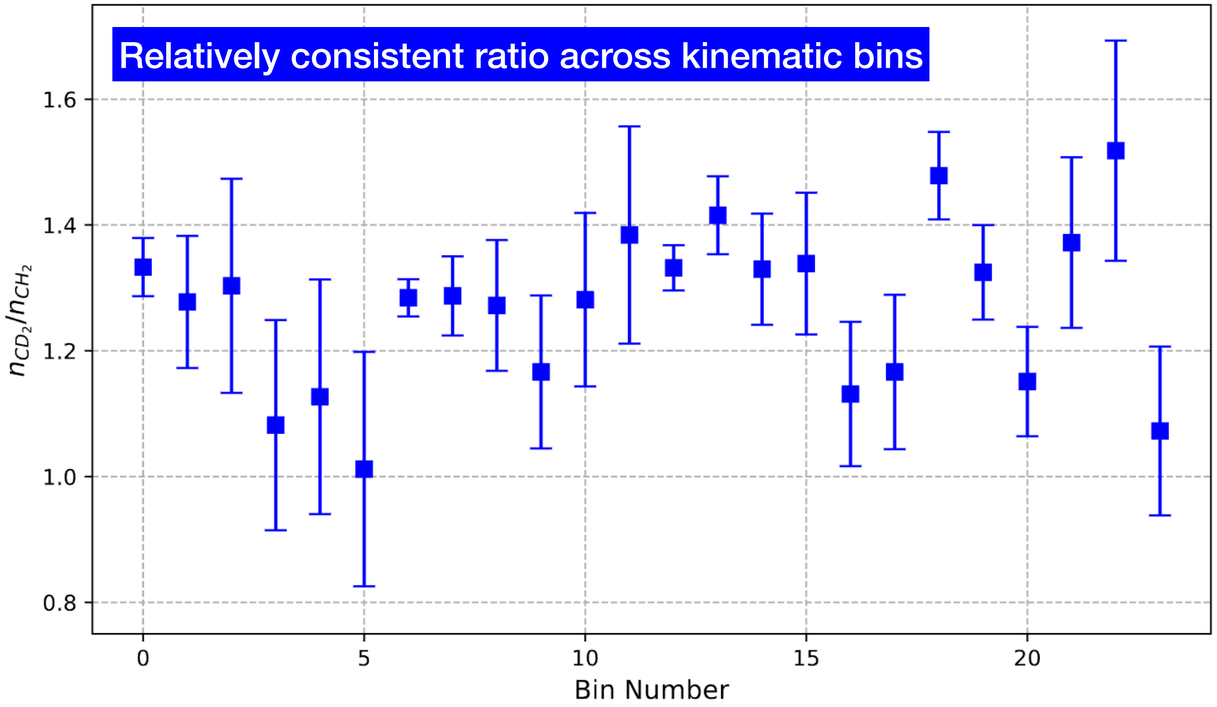
$CH_2 \rightarrow CD_2$ conversion technique

- Sp23 only RG-C run period with data off entire target set for dilution factor
  - Su22 & Fa22 missing data off of CD_2 target so manipulation required to calculate these dilution factors



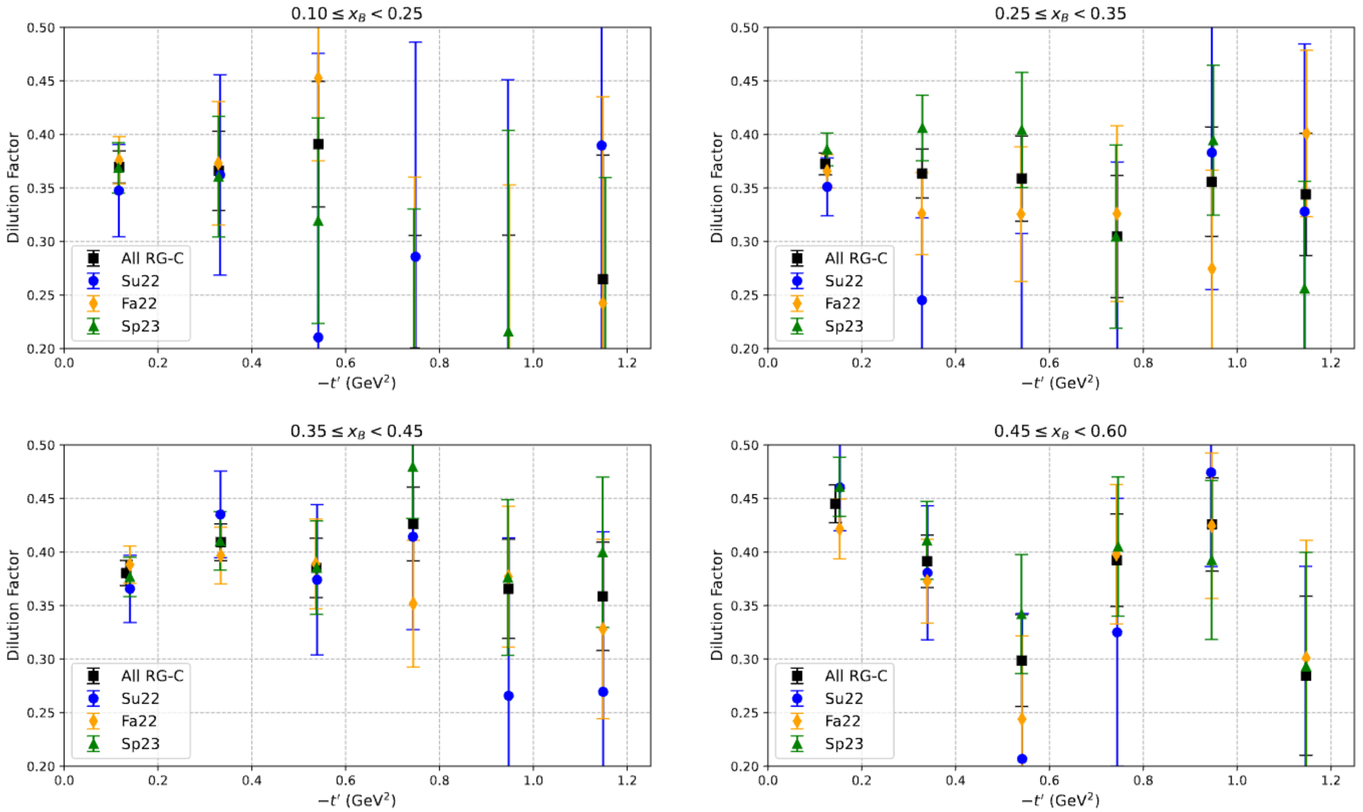
1. Calculate charge-normalized counts per kinematic bin for Sp23 CH_2 and CD_2 targets
2. Construct ratio (per kinematic bin) of CH_2 to CD_2 using Sp23 data
3. Apply ratio to charge-normalized counts per kinematic bin of Su22, Fa22 CH_2 data

→ Despite missing CD_2 data in two periods, we can manipulate CH_2 data to still analyze full RG-C data set

Dilution factor studies

$$en \rightarrow e(p)\pi^-$$

Results over two-dimensional kinematic binning



Su22	Fa22	Sp23
0.372 ± 0.013	0.376 ± 0.010	0.391 ± 0.010

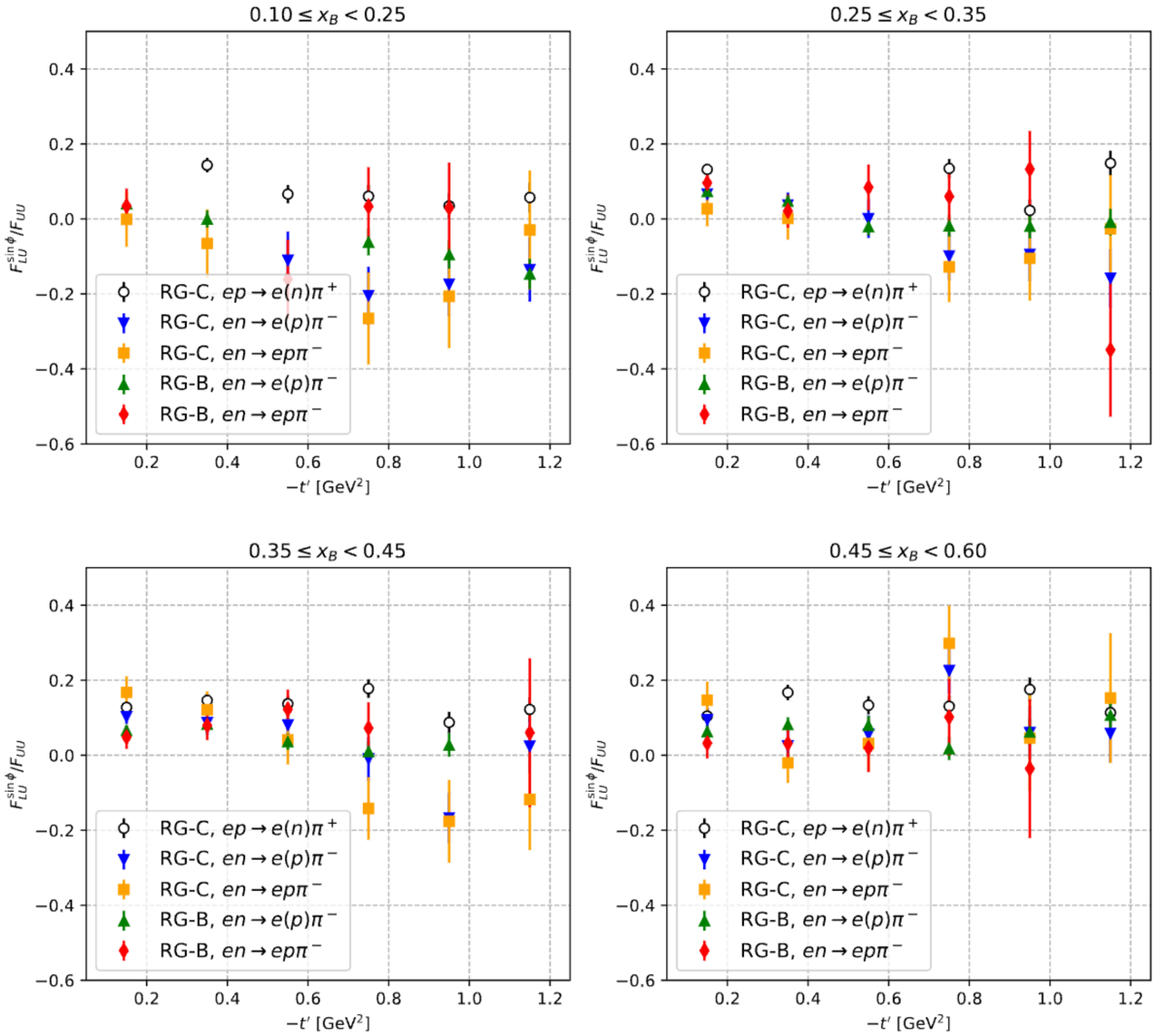
$A_{LU} \rightarrow F_{LU}^{\sin\phi}/F_{UU}$ results

$$A_{LU} = C_{LU} + \frac{\frac{W}{A}\frac{F_{LU}^{\sin\phi}}{F_{UU}}\sin\phi}{1 + \frac{V}{A}\frac{F_{UU}^{\cos\phi}}{F_{UU}}\cos\phi + \frac{B}{A}\frac{F_{UU}^{\cos 2\phi}}{F_{UU}}\cos 2\phi}$$

(denominator set to 1 for this study)

Comparing results from Fa22 RG-C π^+, Fa22 RG-C, Sp19 RG-B π^- & pπ^-

π^+ $F_{LU}^{\sin\phi}/F_{UU}$ amplitude fit possibly slightly larger than for π^-/pπ^- but run period π^-/pπ^- are overall consistent



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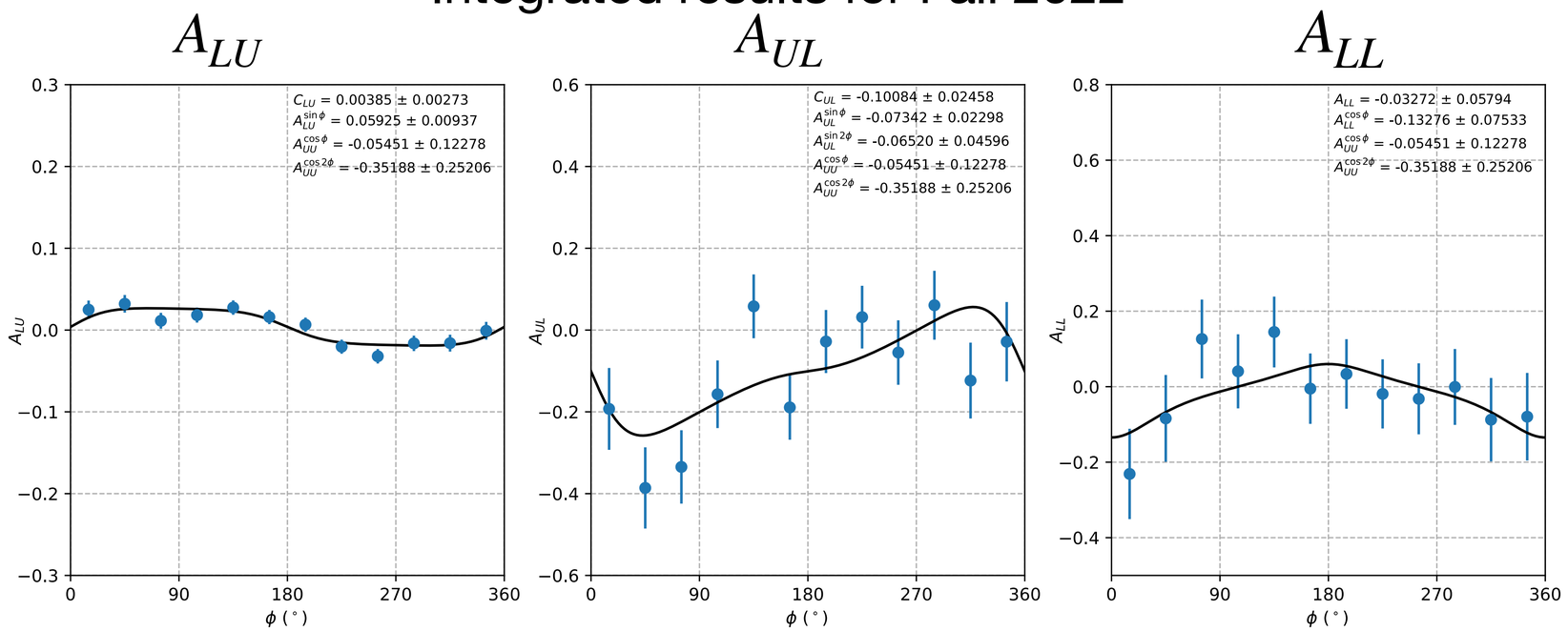
Preliminary spin asymmetry set results

Integrated results for Fall 2022

BSA looks as expected →



← Difficult to comment on DSA until issues with TSA resolved

1) TSA C_{UL} should be consistent with zero if charge normalized counts are accurate
   $\rightarrow \sim 4\sigma$ deviation in Fall22, also difficulties in other run periods with inconsistent offsets and distribution shapes for TSA

   - Working with RG-C collaborators to identify potential runs with issues

2) Preliminary observations for TSA shape → possible non-zero $\sin 2\phi$ modulations for DVπ^-P (as seen in DVπ^+P)

Summary and outlook

- ✓ RG-C DVπ^-P channel complementary to DVπ^+P analysis
- ✓ Interesting avenue to study Fermi motion effects in RG-C data through three particle final state
- ✓ Efforts to test and validate packing fraction/dilution factor for ND_3, including conversion ratio to analyze all RG-C run periods
- ✓ Preliminary 2D BSA studies results suggest consistency between two and three particle final states, RG-B, DVπ^+P & preliminary integrated TSA interesting but work remains to clean up results
- Working with RG-C collaborators on troubleshooting and identifying target behaviour issues to progress towards consistent TSA and DSA results across run periods
- Binning for TSA and DSA in 1D, 2D (may not be possible with statistics)
- Three particle final state TSA and DSA studies (may not be possible with statistics)
- Similar systematic studies to RG-C DVπ^+P analysis

See also:

- T. Hayward, *Exclusive π^+ Spin Asymmetries from RGC and Fermi Motion Smearing Studies* (prev.)

- N. Pilleux, *DVCS on longitudinally polarized protons in deuterium with RGC* (2026/03/12)

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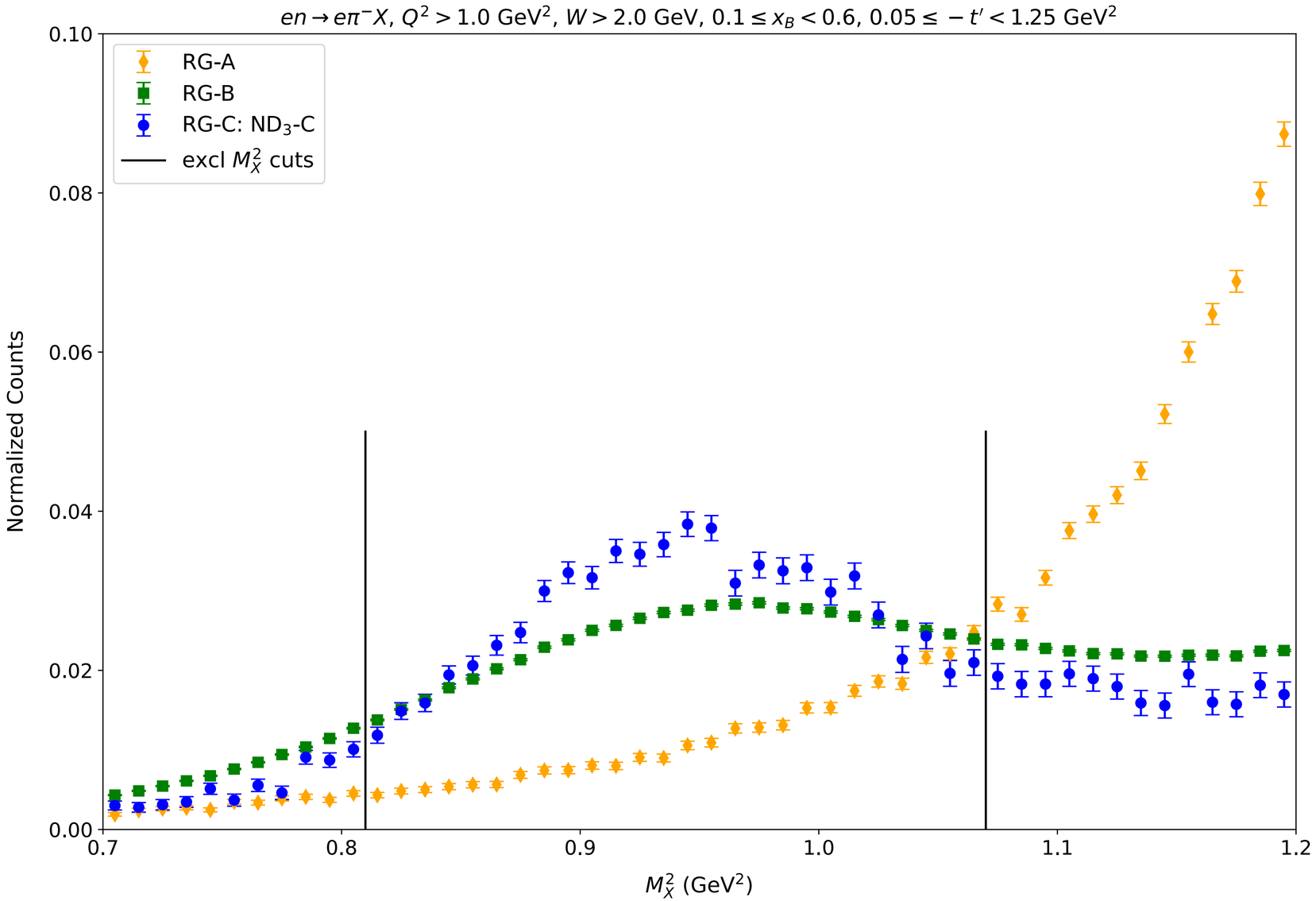
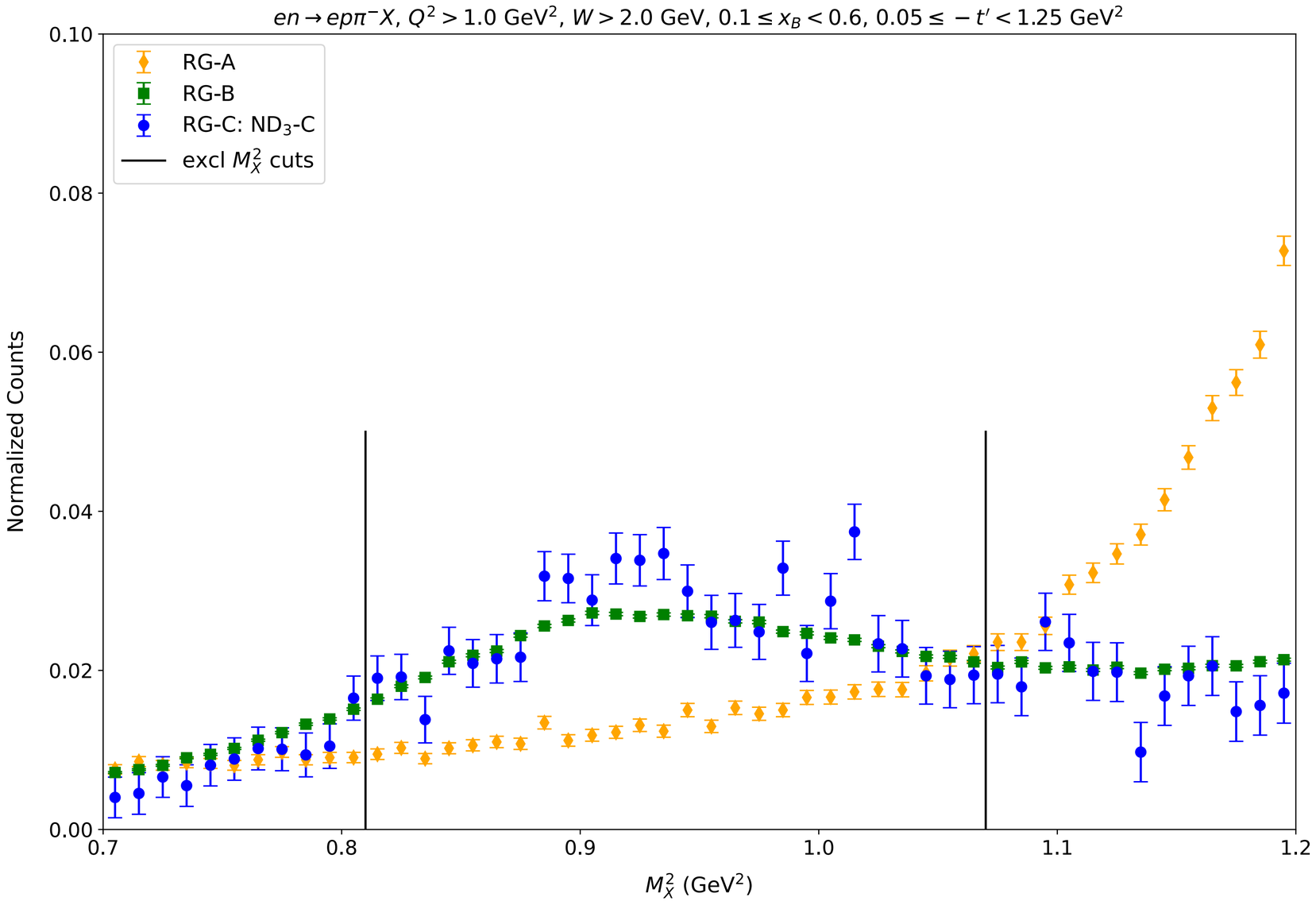
Thank you, questions?

Back-up slides

Two particle final state across run periods



Three particle final state across run periods



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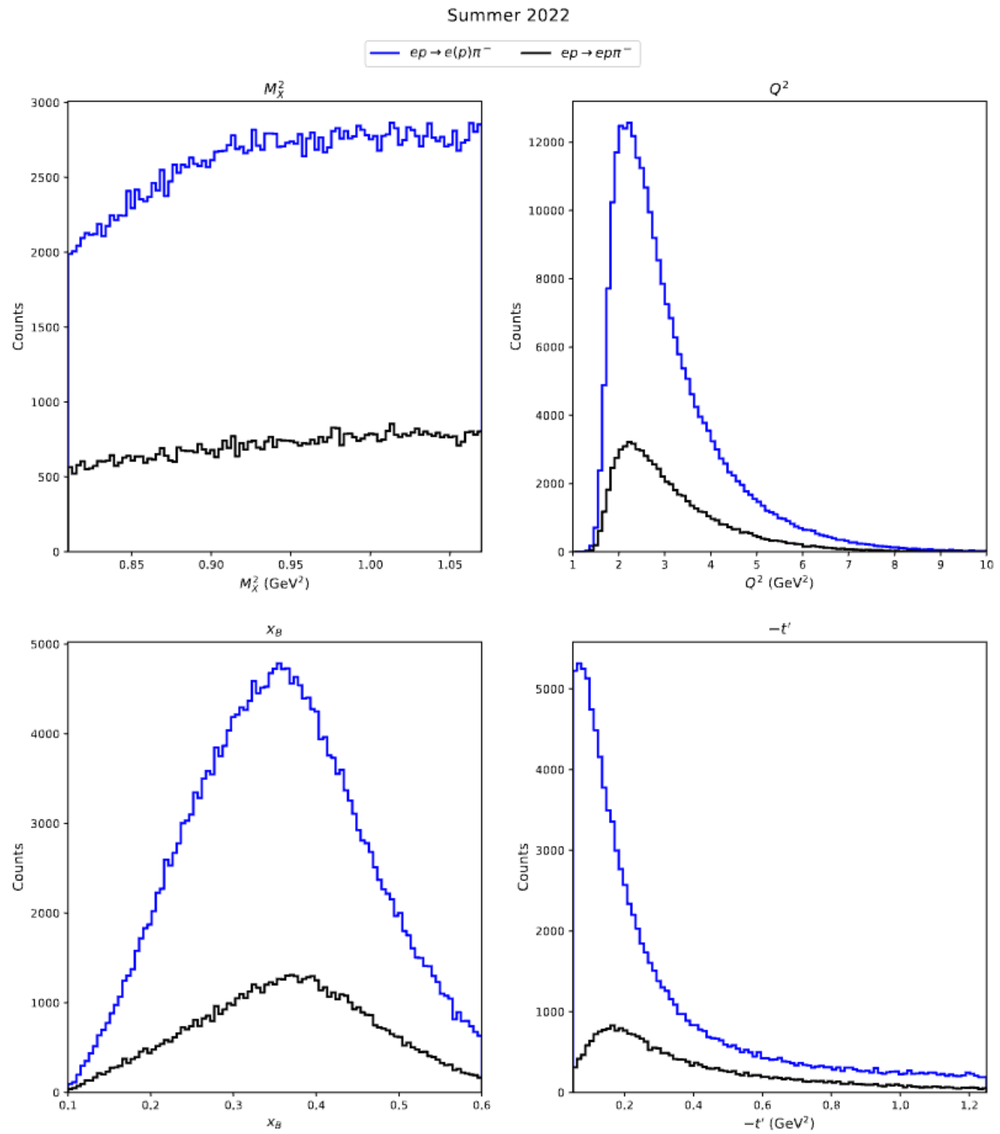
Summer 2022 Yields



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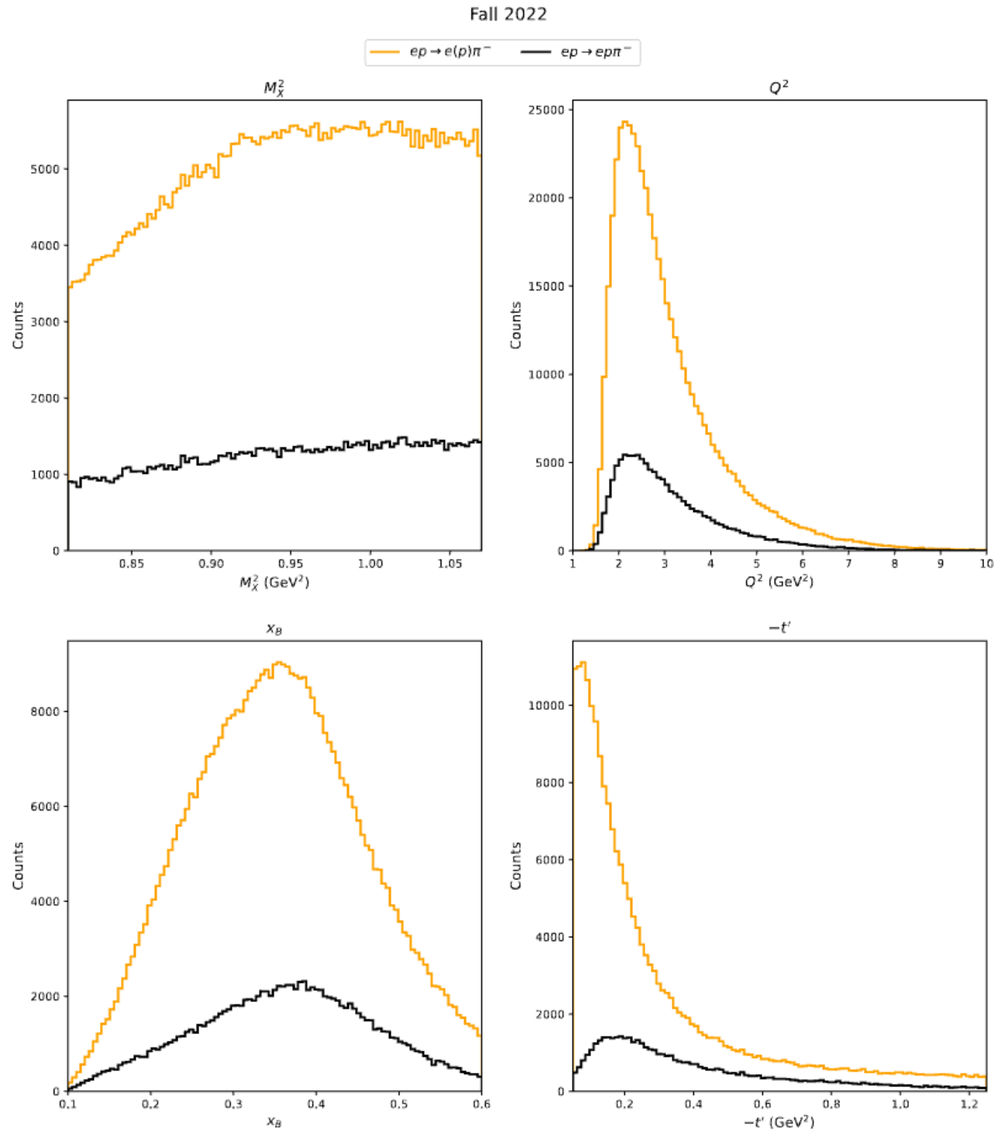
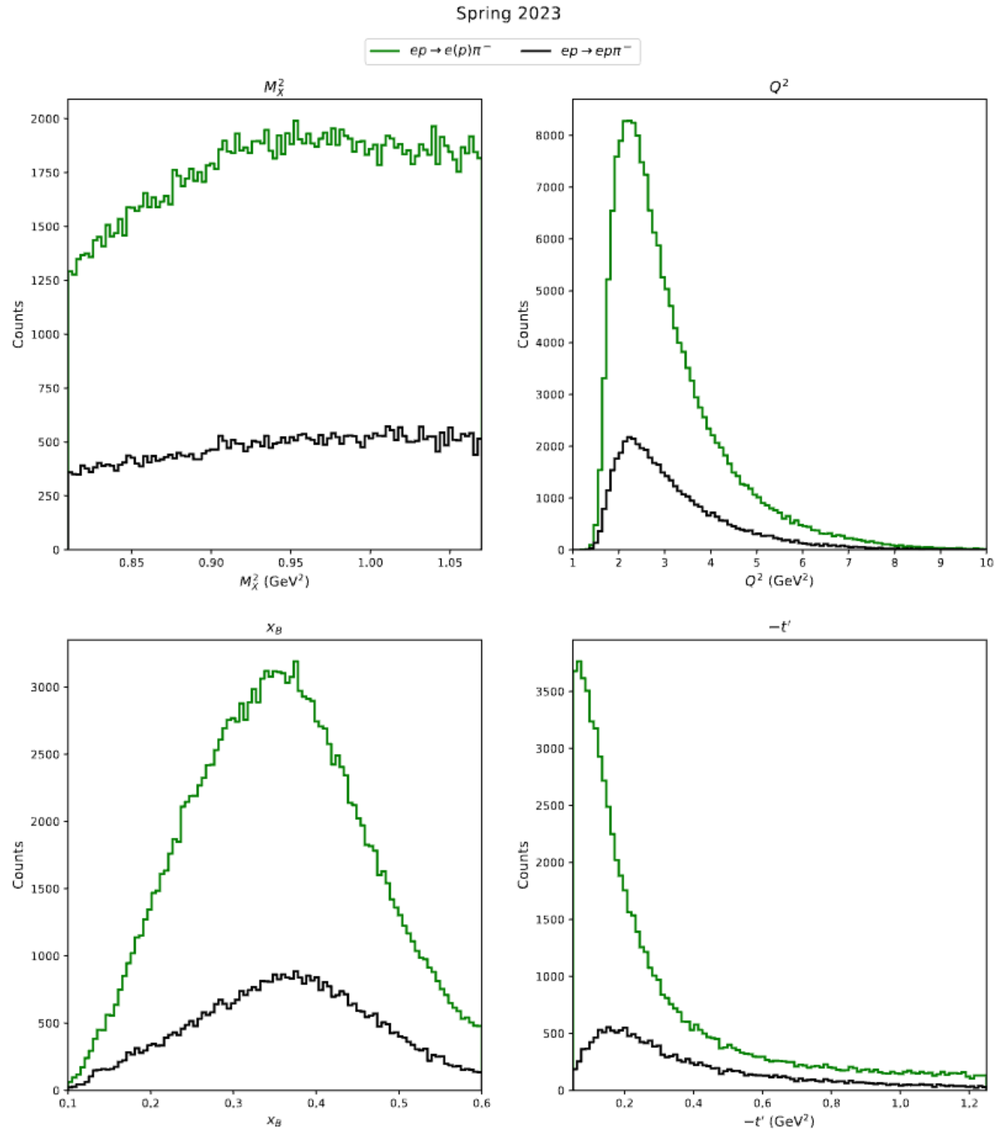
Fall 2022 Yields



Spring 2023 Yields



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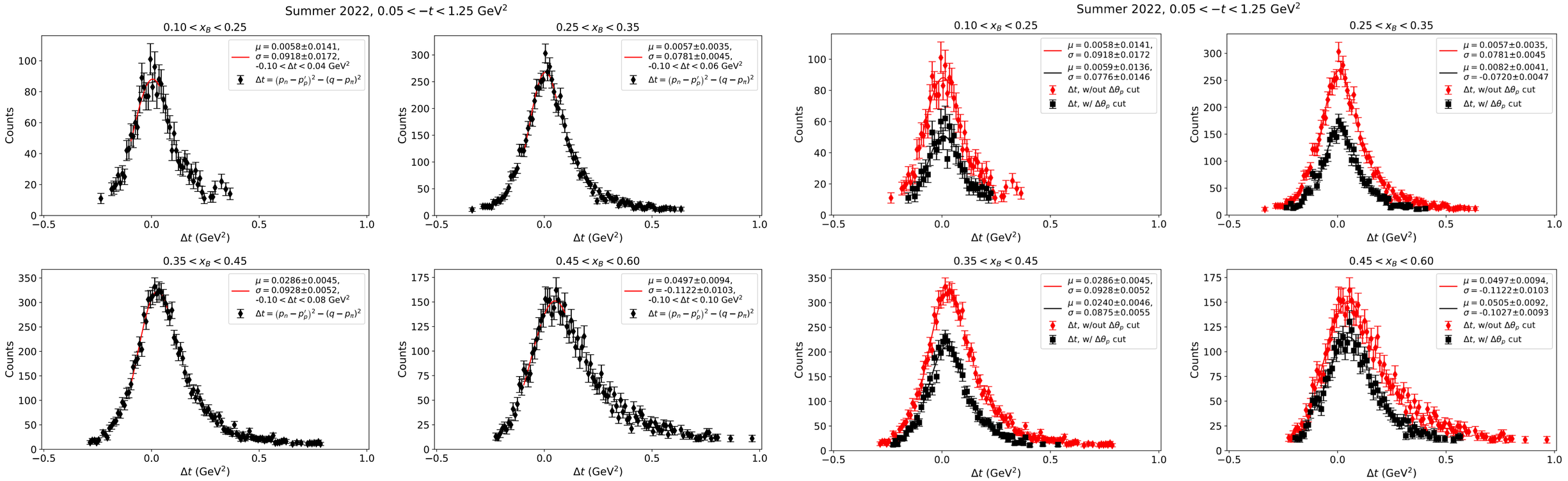
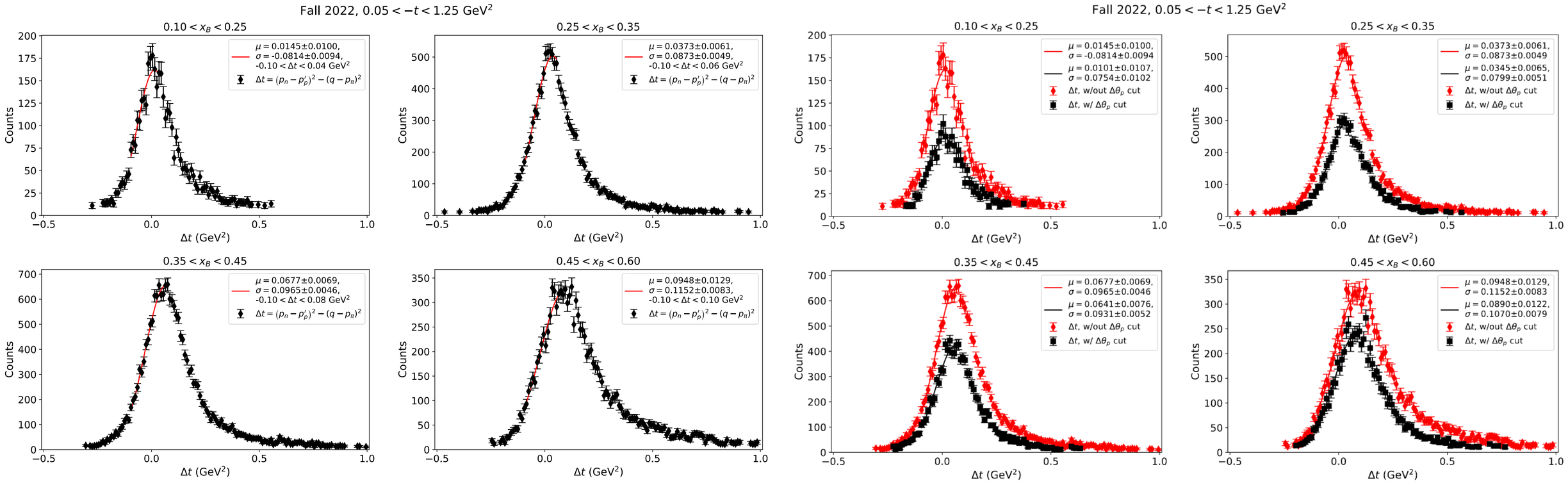
Summer 2022 Δt



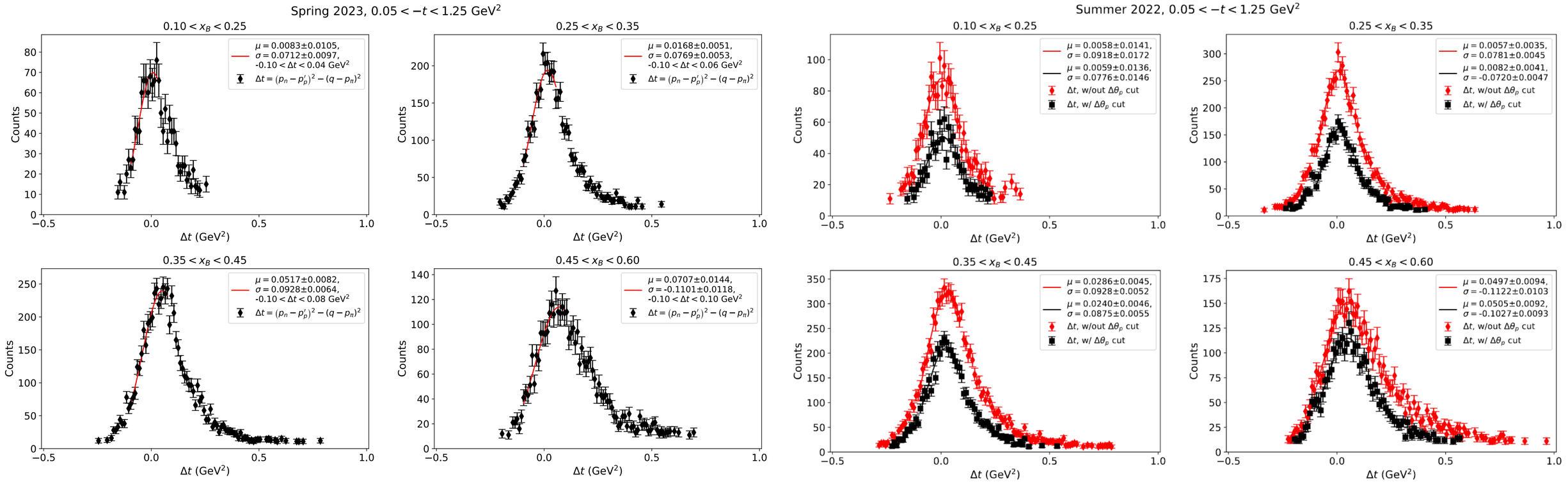
CEBAF Large Acceptance Spectrometer

Fall 2022 Δt



CEBAF Large Acceptance Spectrometer

Spring 2023 Δt



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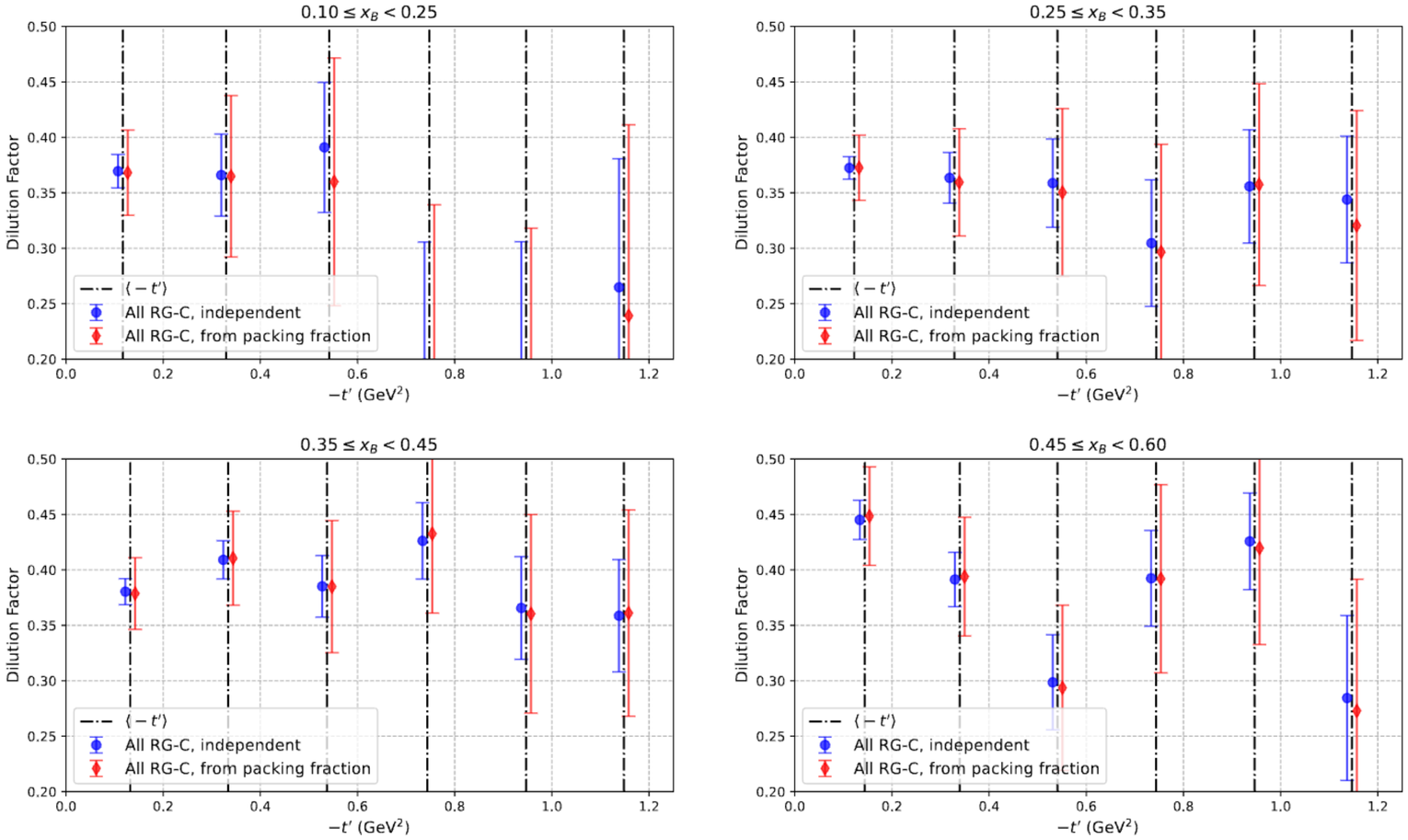
Alternate dilution factor calculation techniques

$$DF = \frac{(n_A - n_{MT})\,(n_{CD} - 0.757666 n_C - 0.005200 n_{MT} - 0.237132 n_F)}{n_A\,(n_{CD} - 0.168370 n_C - 0.865973 n_{MT} + 0.03434 n_F)}$$

vs.

$$DF = 2.260129 \frac{PF}{n_A}\,(n_{CD} - 0.757666 n_C - 0.005200 n_{MT} - 0.237132 n_F)$$

shown for $en \rightarrow e(p)\pi^-$



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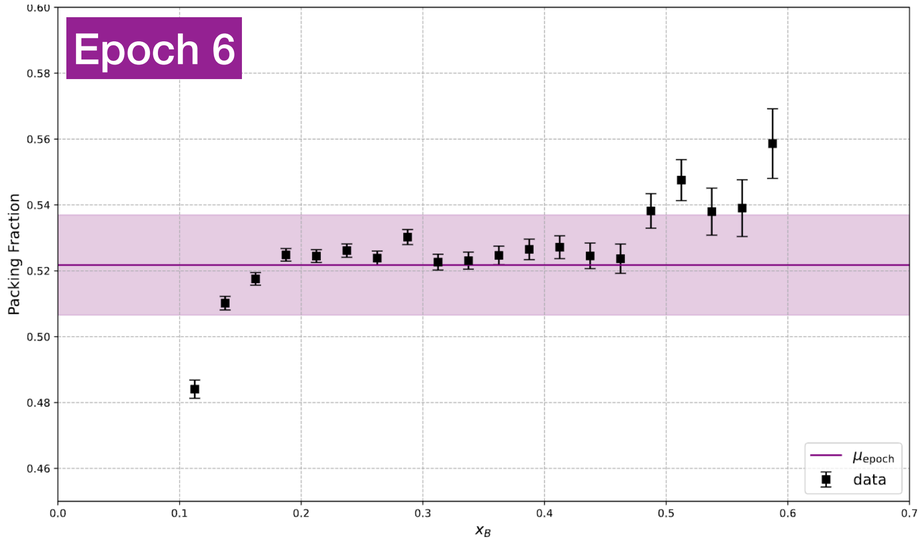
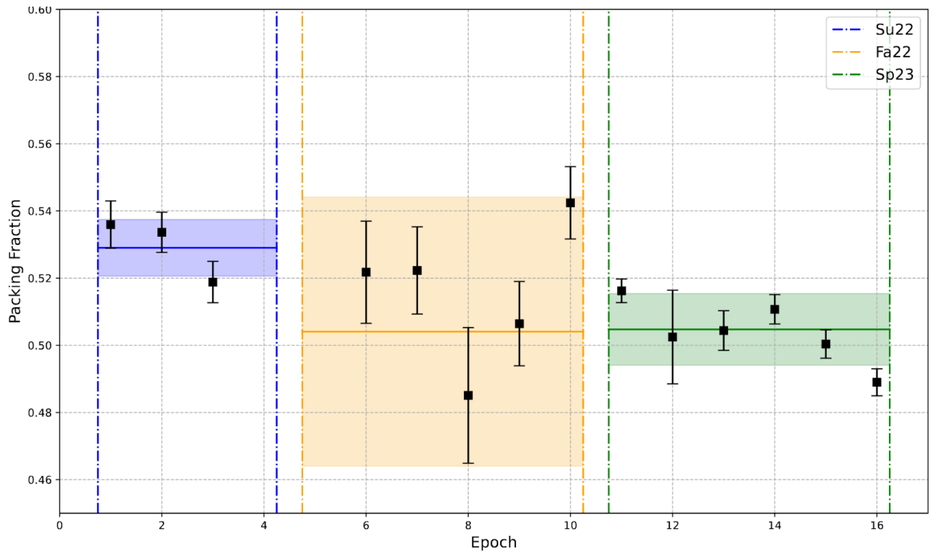
Packing fraction studies

Also useful to extract packing fraction of each run period epoch to measure consistency, shown here without M_X^2 cuts for larger sample size





Individual epoch, $Pf(x_B)$

Averages across all epochs in run-period

→ Still a work in progress to get perfect agreement in epoch packing fraction results across run group, but in general consistent to order of ~5%

Asymmetry observables → structure functions

$$A_{LU} = C_{LU} + \frac{\frac{W}{A} A_{LU}^{\sin\phi} \sin\phi}{1 + \frac{V}{A} A_{UU}^{\cos\phi} \cos\phi + \frac{B}{A} A_{UU}^{\cos 2\phi} \cos 2\phi} = \frac{1}{P_b} \frac{P_t^- \left(n^{++} - n^{-+}\right) + P_t^+ \left(n^{+-} - n^{--}\right)}{P_t^- \left(n^{++} + n^{-+}\right) + P_t^+ \left(n^{+-} + n^{--}\right)}$$

$$A_{UL} = C_{UL} + \frac{\frac{V}{A} A_{UL}^{\sin\phi} \sin\phi + \frac{B}{A} A_{UL}^{\sin 2\phi} \sin 2\phi}{1 + \frac{V}{A} A_{UU}^{\cos\phi} \cos\phi + \frac{B}{A} A_{UU}^{\cos 2\phi} \cos 2\phi} = \frac{1}{D_f} \frac{\left(n^{++} + n^{-+}\right) - \left(n^{+-} + n^{--}\right)}{P_t^- \left(n^{++} + n^{-+}\right) + P_t^+ \left(n^{+-} + n^{--}\right)}$$

$$A_{LL} = \frac{\frac{C}{A} A_{LL}^{\cos 0\phi} + \frac{W}{A} A_{LL}^{\cos\phi} \cos\phi}{1 + \frac{V}{A} A_{UU}^{\cos\phi} \cos\phi + \frac{B}{A} A_{UU}^{\cos 2\phi} \cos 2\phi} = \frac{1}{P_b D_f} \frac{\left(n^{++} - n^{-+}\right) + \left(-n^{+-} + n^{--}\right)}{P_t^- \left(n^{++} + n^{-+}\right) + P_t^+ \left(n^{+-} + n^{--}\right)}$$

$$n^{bt} = \frac{N^{bt}}{F_{CC}^{bt}}$$

simultaneous fit to extract consistent structure functions

+ transversely polarized photon contributions to A_{UL}, A_{LL}

A, B, C, V, W depolarization factors →

$$A(\epsilon, y) \equiv \frac{y^2}{2(1-\epsilon)} = \frac{1}{1+\gamma^2}\left(1 - y + \frac{1}{2}y^2 + \frac{1}{4}\gamma^2 y^2\right) \approx \left(1 - y + \frac{1}{2}y^2\right),$$
$$B(\epsilon, y) \equiv \frac{y^2}{2(1-\epsilon)}\epsilon = \frac{1}{1+\gamma^2}\left(1 - y - \frac{1}{4}\gamma^2 y^2\right) \approx (1 - y),$$
$$C(\epsilon, y) \equiv \frac{y^2}{2\,(1-\epsilon)}\sqrt{1-\epsilon^2} = \frac{y}{\sqrt{1+\gamma^2}}\left(1 - \frac{1}{2}y\right) \approx y\left(1 - \frac{1}{2}y\right),$$
$$V(\epsilon, y) \equiv \frac{y^2}{2\,(1-\epsilon)}\sqrt{2\epsilon(1+\epsilon)} = \frac{2-y}{1+\gamma^2}\sqrt{1 - y - \frac{1}{4}\gamma^2 y^2} \approx (2 - y)\sqrt{1-y},$$
$$W(\epsilon, y) \equiv \frac{y^2}{2\,(1-\epsilon)}\sqrt{2\epsilon(1-\epsilon)} = \frac{y}{\sqrt{1+\gamma^2}}\sqrt{1 - y - \frac{1}{4}\gamma^2 y^2} \approx y\sqrt{1-y},$$

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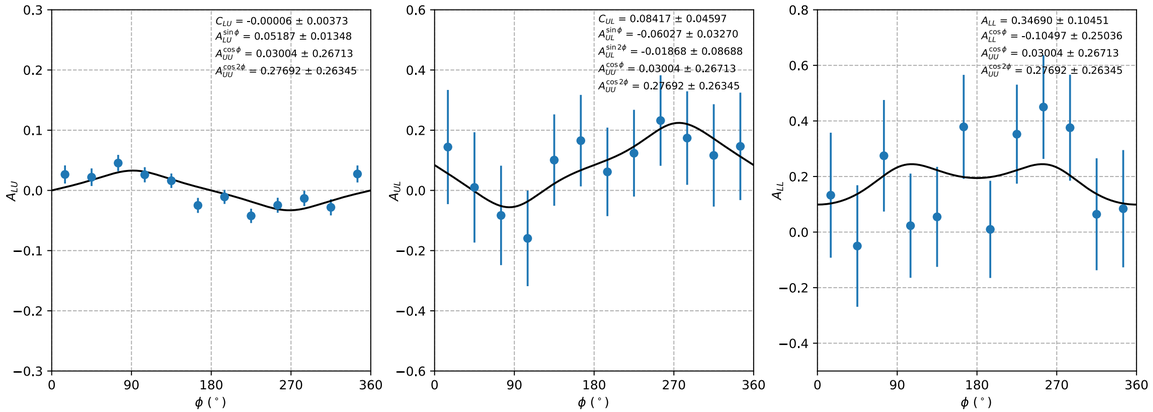
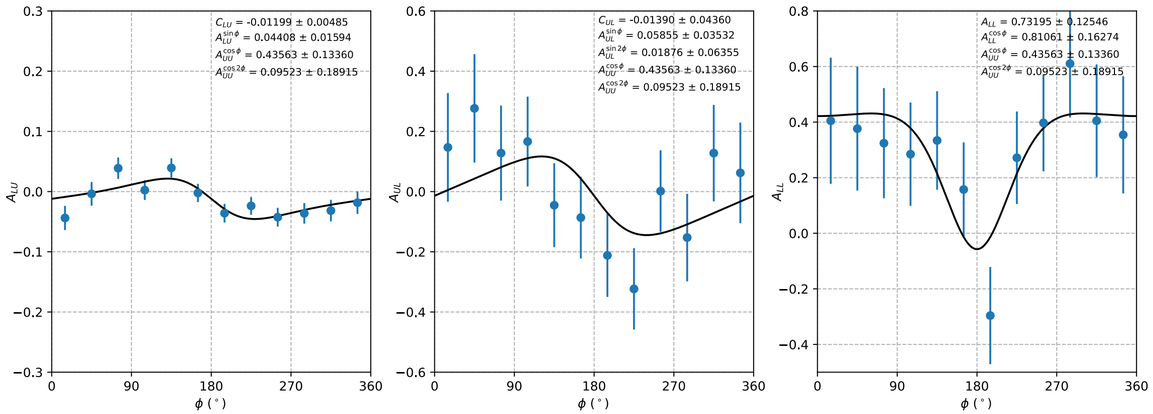
(Very) preliminary spin asymmetry set results across all run periods

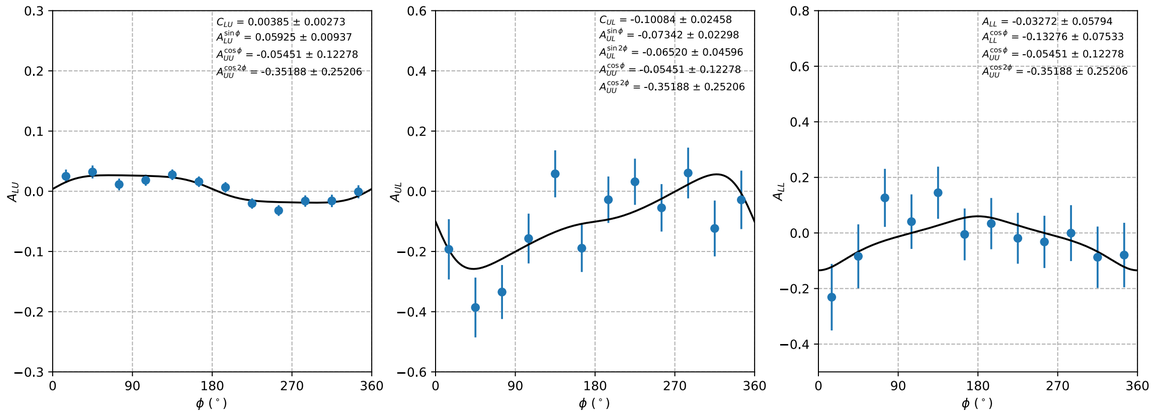
Summer 2022, $0.10 \leq x_B < 0.60$, $0.05\ \text{GeV}^2 \leq -t' < 1.25\ \text{GeV}^2$



Spring 2023, $0.10 \leq x_B < 0.60$, $0.05\ \text{GeV}^2 \leq -t' < 1.25\ \text{GeV}^2$



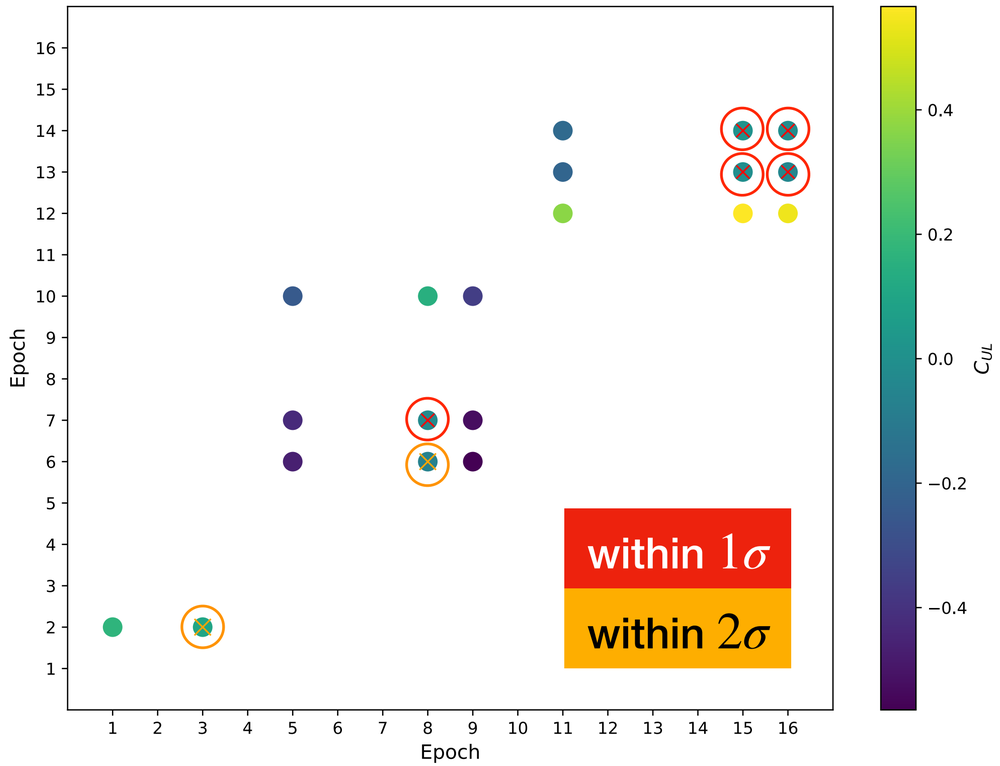
Fall 2022, $0.10 \leq x_B < 0.60$, $0.05\ \text{GeV}^2 \leq -t' < 1.25\ \text{GeV}^2$

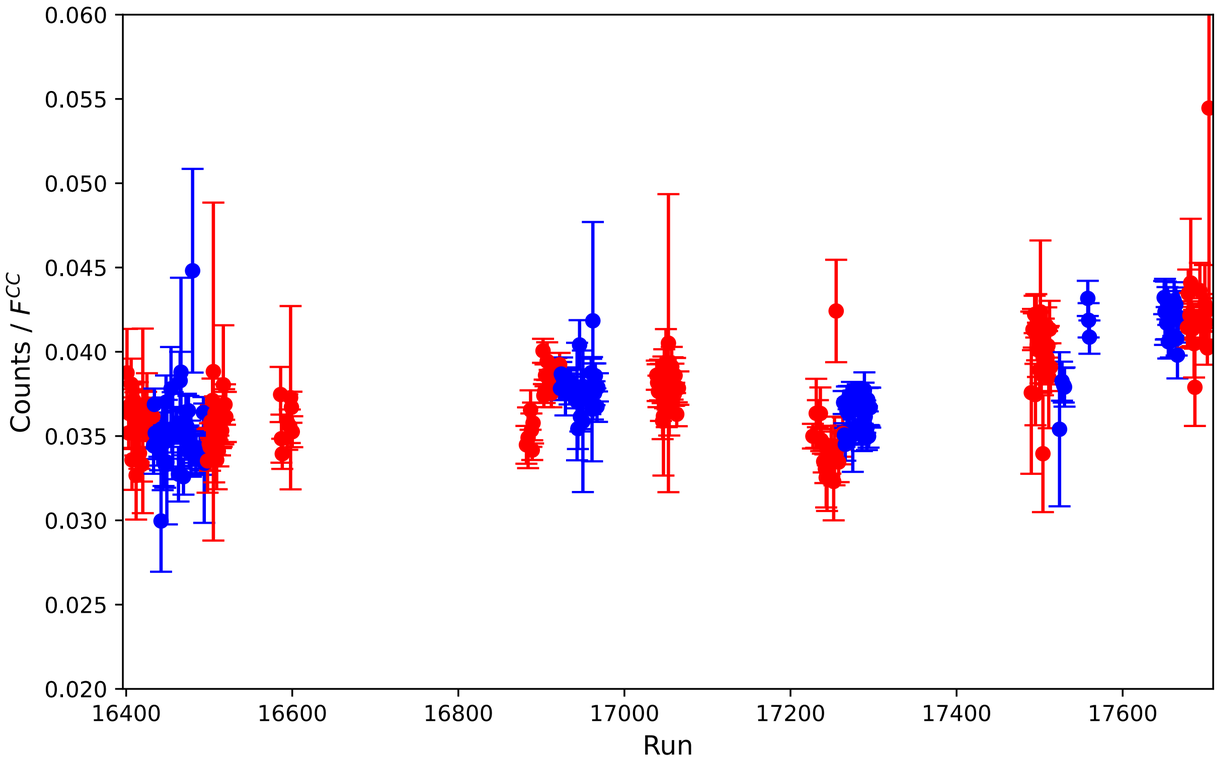


CEBAF Large Acceptance Spectrometer

Troubleshooting target spin asymmetry

C_{UL} consistency per epoch





Positive target polarization

Negative target polarization

Some examples of what we've been working on…