Exclusive Coherent Electroproduction of the Neutral Pion Off Helium-4 and The Case for Kinematic Fitting

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University of Connecticut

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When embedded in the nucleus,

- What about proton changes?
- What remains the same?

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Nuclear targets offer two distinct channels:

- Coherent (Nucleus stays intact)
- Incoherent (Nucleon breaks off and traverses nuclear medium)

Enter the CLAS EG6 Experiment

Start with the simplest dense stable nucleus: $^4\mathrm{He}$.

Measure the BSA for exclusive processes to get at nuclear and modified nucleonic FFs and GPDs.

Channel	Process		BSA
Coherent	DVCS:	$\left(e\ ^4\mathrm{He}, e\ ^4\mathrm{He}\ \gamma\right)$	Published[1]
	DVMP:	$\boxed{\left(e\ ^4\mathrm{He}, e\ ^4\mathrm{He}\ \pi^0\right)}$	This talk
		$\left(e\ ^4\mathrm{He}, e\ ^4\mathrm{He}\ \eta\right)$	Stats. too low
Incoherent	DVCS :	$^4\mathrm{He}\,(e, e\ p\ \gamma)\,X$	Under review
	DVMP:	$^4\mathrm{He}\left(e, e\ p\ \pi^0\right)X$	Work in prog.[2]
		$^4\mathrm{He}\,(e, e\ p\ \eta)\,X$	Work in prog.[2]

[1] M. Hattawy Phys. Rev. Lett. 119, 202004 (Nov. 2017)

[2] Perfectly suited for future ALERT detector

Formalism

Generally, the BSA can be expressed in terms of the squared-transition amplitude $\langle|\mathcal{M}_\pm|^2\rangle$:

$$BSA = \frac{\langle|\mathcal{M}_+|^2\rangle - \langle|\mathcal{M}_-|^2\rangle}{\langle|\mathcal{M}_+|^2\rangle + \langle|\mathcal{M}_-|^2\rangle};$$

$$\left\langle|\mathcal{M}_\pm|^2\right\rangle = \left(\frac{e^2}{q^2}\right)^2 \mathcal{L}_\pm^{\mu\nu}\mathcal{H}_{\mu\nu};$$

$$\mathcal{H}_{\mu\nu} := J_\mu^\dagger J_\nu$$

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C. R. Ji's formulation[a] for 0^{-+} meson electroproduction off 0^{++} target

$$\left(e\ {}^4\mathrm{He} \to e\ {}^4\mathrm{He}\ \pi^0\right)$$

$$\begin{aligned} J_\mu &= F_{PS}\epsilon^{\mu\nu\alpha\beta}q_\nu\bar{P}_\alpha\Delta_\beta \\ \Rightarrow \mathcal{H}_{\mu\nu} &= |F_{PS}|^2\,\epsilon_{\mu\alpha\beta\gamma}\epsilon_{\nu\alpha'\beta'\gamma'}q^{\alpha'}\bar{P}^{\beta'}\Delta^{\gamma'} \\ &= \mathcal{H}_{\nu\mu} \end{aligned}$$

$$\Rightarrow \boldsymbol{BSA \equiv 0}$$

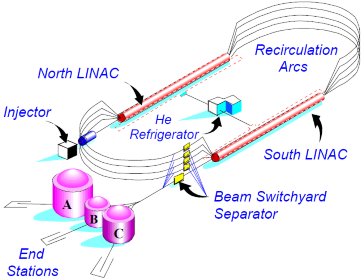
[a] Ji et al., arXiv:1806.01379 (June 2018)

Experiment

CEBAF @ JLab delivers long. polarized 6 GeV electrons to CLAS which detects the scattered electrons:

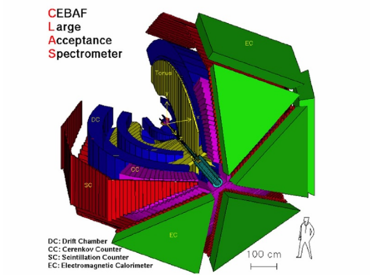
Energy	:	6 GeV
Luminosity	:	10^{34} cm^2s^{-1}
Long. Beam Polarization	:	85%

CEBAF



Delivers e

CLAS



Detects e'

$p_{\text{thres}} > 250$ MeV$/c$

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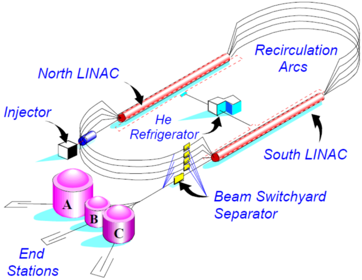

Delivers e

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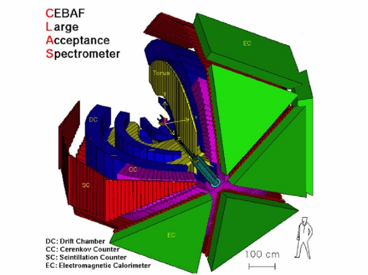


Detects e'

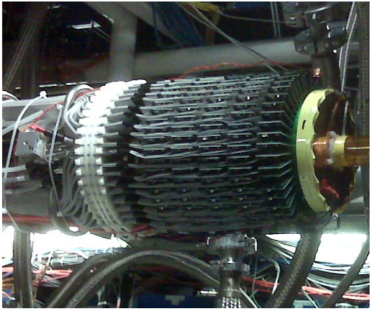
$p_{\text{thres}} > 250$ MeV$/c$

$p_{^4\mathrm{He}} \approx 100$ MeV$/c$

Experiment

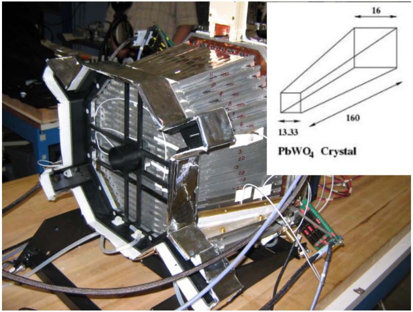
The Jefferson Lab's CLAS EG6 experiment is characterized by its helium gas target, solenoid magnet, and the addition of two detectors:

Radial Time Projection Chamber (RTPC)



Detects $^4\mathrm{He}'$

Inner Calorimeter (IC)



Detects γ

$\theta_\gamma \in (8^\circ, 45^\circ) \bigcup (4^\circ, 15^\circ)$

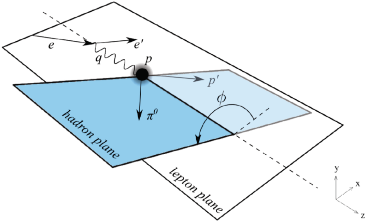
Measuring BSA of π^0 DVMP

We measured the fully exclusive coherent reaction:

$$e\ {}^4\mathrm{He} \rightarrow e\ {}^4\mathrm{He}\ \pi^0 \rightarrow e\ {}^4\mathrm{He}\ \gamma\ \gamma$$

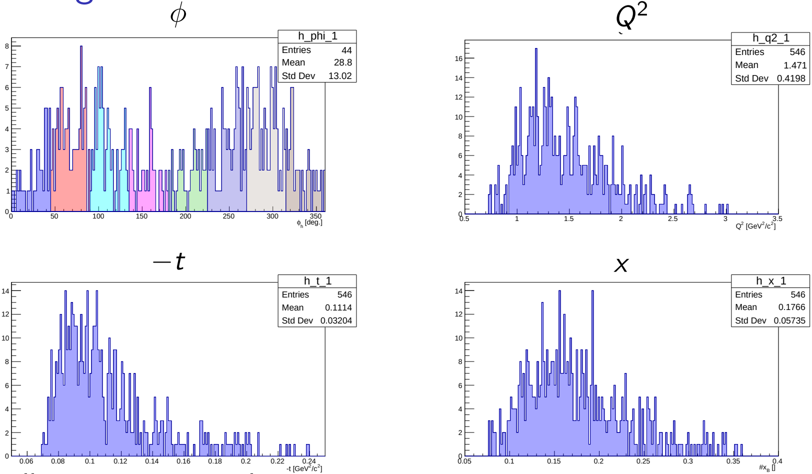
Measure the beam-spin asymmetry (BSA):

$$BSA(\phi) = \left(\frac{1}{P_B}\right)\frac{N^+(\phi) - N^-(\phi)}{N^+(\phi) + N^-(\phi)}$$



- Small cross-section $\rightarrow$ low statistics
- Relatively large background
- Clean event selection is important!
    - Exclusivity Variable Cuts
    - Kinematic Fitting

Measuring BSA of π^0 DVMP



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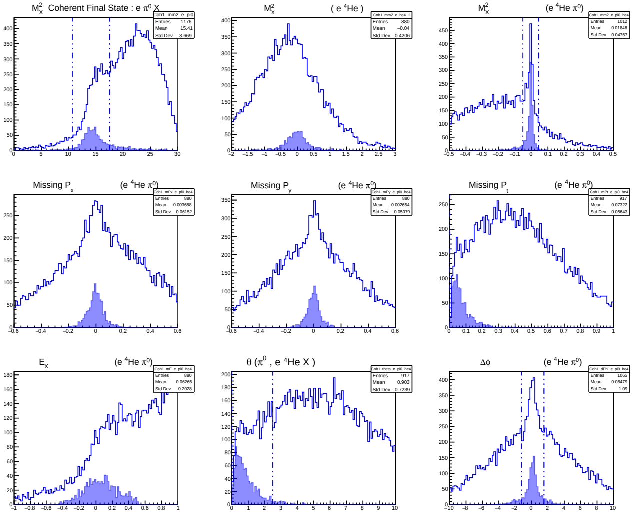
Measurir



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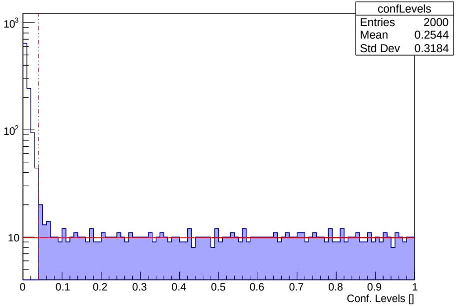
Kinematic Fitting in a Nutshell

Introduce and minimize $\mathcal{L}$, with Lagrange multipliers $\vec{\boldsymbol{\mu}}$:

$$\mathcal{L} = \left(\vec{\boldsymbol{\epsilon}}^{\nu}\right)^T C_{\eta}^{-1}\ \vec{\boldsymbol{\epsilon}}^{\nu} + 2\left(\vec{\boldsymbol{\mu}}^{\nu}\right)^T \left(A^{\nu}\vec{\boldsymbol{\xi}}^{\nu} + B^{\nu}\vec{\boldsymbol{\delta}}^{\nu} + \vec{\boldsymbol{c}}^{\nu}\right) \quad .$$

At the end of the day, there is **one** cut that selects your events:
The Confidence Level Cut (CLC)



(Toy data)

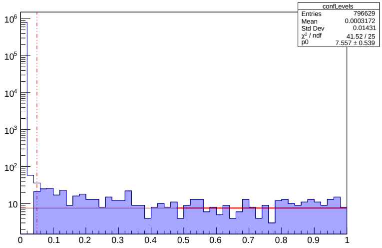
$5C$-Kinematic Fit on EG6: DVπ^0P

$$e\ {}^4\mathrm{He} \to e\ {}^4\mathrm{He}\ \pi^0$$

$$\pi^0 \to \gamma\ \gamma$$

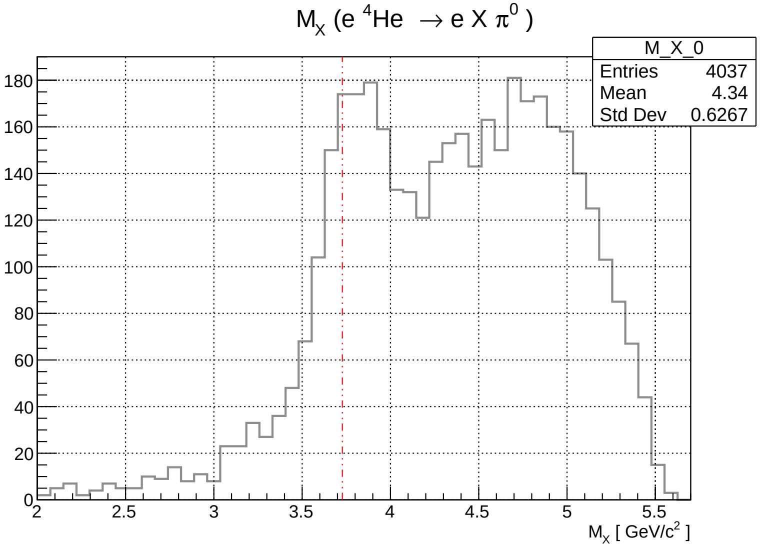
$$5C \Rightarrow \begin{cases} E_{init} - E_{fin} \equiv 0 \\ \vec{p}_{init} - \vec{p}_{fin} \equiv \vec{0} \\ M_{\pi^0} - \sqrt{(E_{\gamma_1} + E_{\gamma_2})^2 - \|\vec{p}_{\gamma_1} + \vec{p}_{\gamma_2}\|^2} \equiv 0 \end{cases}$$

Confidence Level Distribution



CLC = 5%

Kin. Fit Applied



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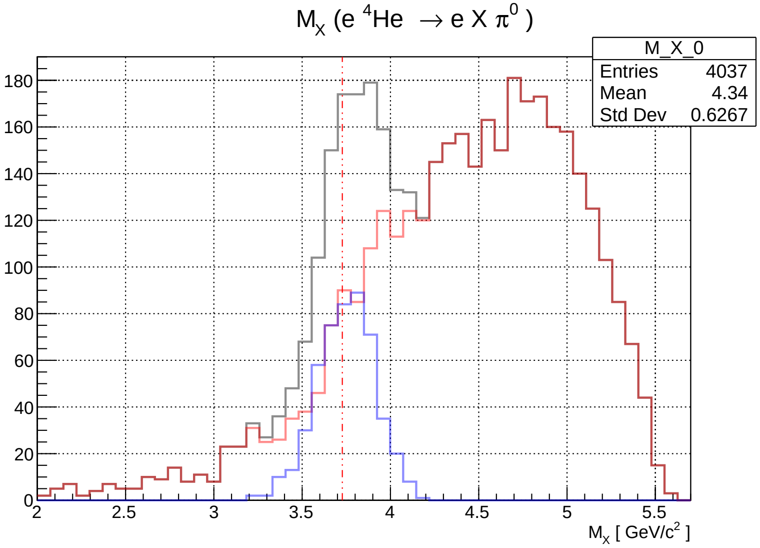
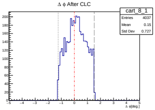


Red : Events failing CLC

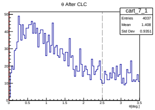
Blue : Events passing CLC

Sequential Exclusivity Cuts Applied

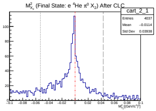
Coplanarity



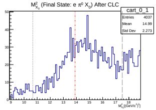
Cone Angle

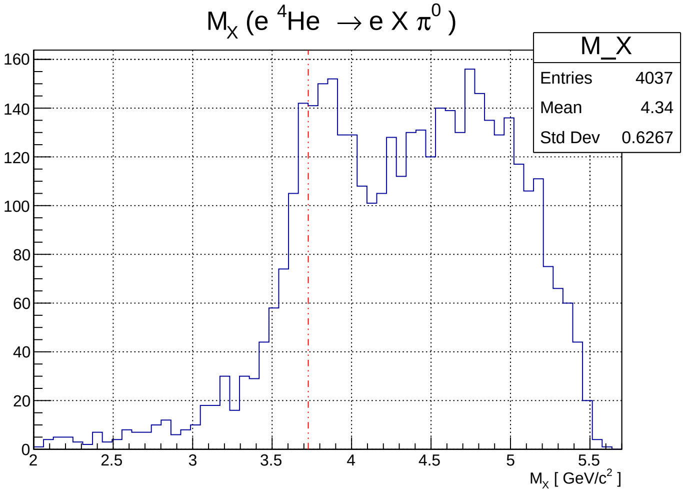


$M^2_{X_{\pi^0}}$



$M^2_{X_{^4\mathrm{He}}}$





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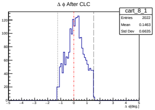

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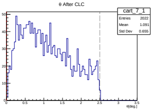

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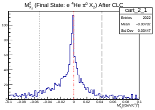

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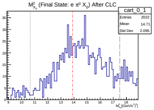

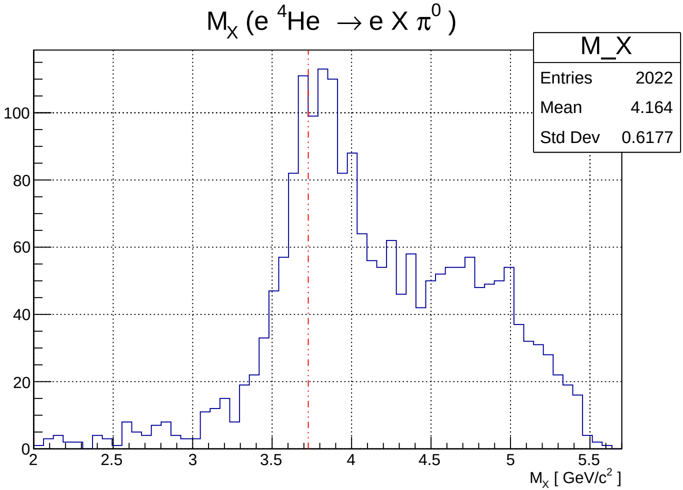

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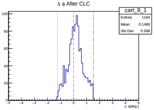

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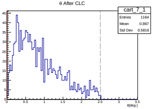

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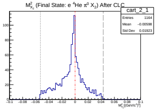

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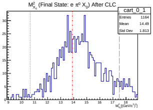

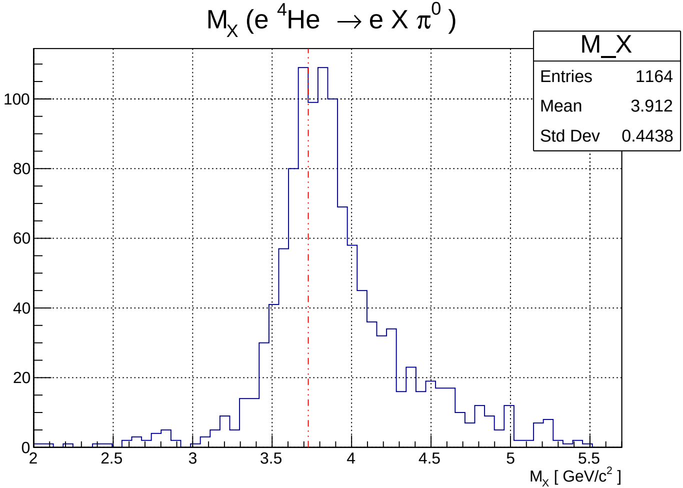

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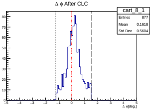

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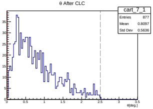

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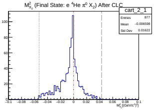

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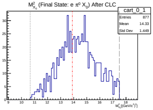
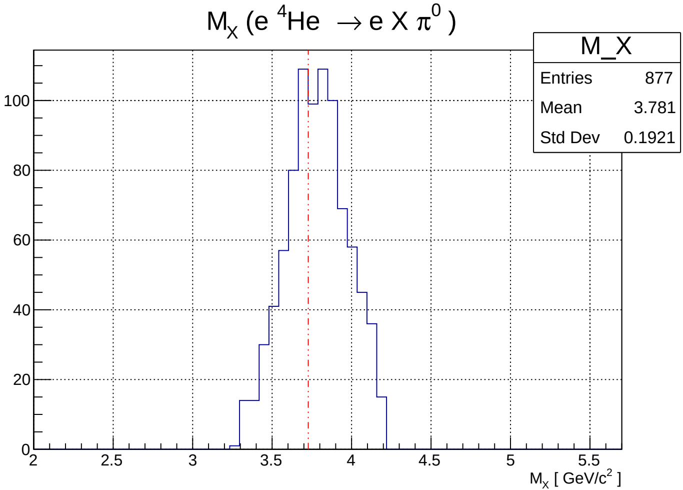
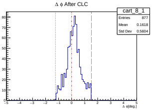




Sequential Exclusivity Cuts Applied

Coplanarity



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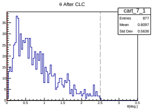

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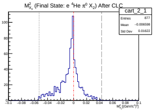

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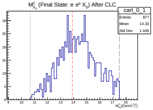
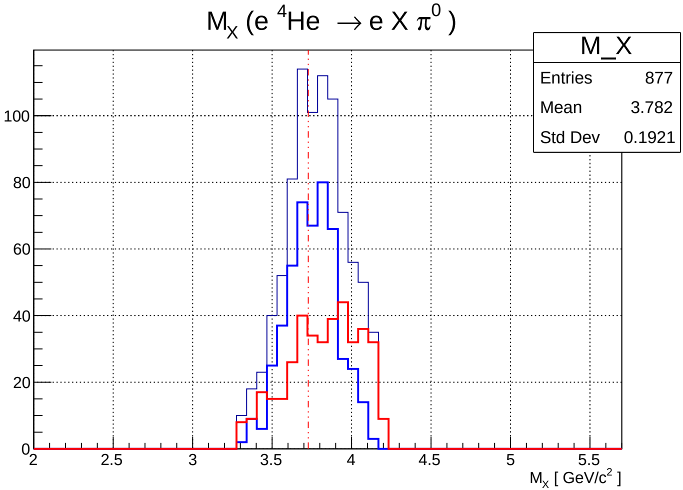




Red : Events failing CLC

Blue : Events passing CLC

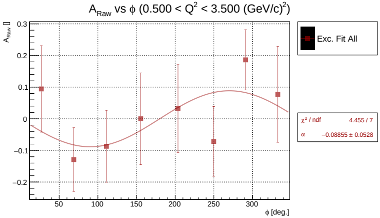
Beam-Spin Asymmetry Comparison

For

$$e\ {}^4\mathrm{He} \rightarrow e\ {}^4\mathrm{He}\ \pi^0 \quad , \tag{1}$$

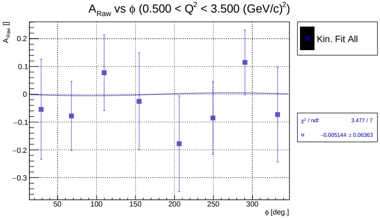
the BSA is obtained from two different event selection methods:

Exclusivity Cuts



BSA = -8.9±5.3 %
(800 events)

Kinematic Fit

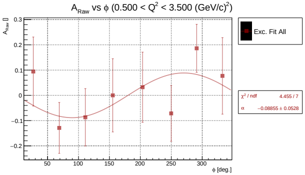


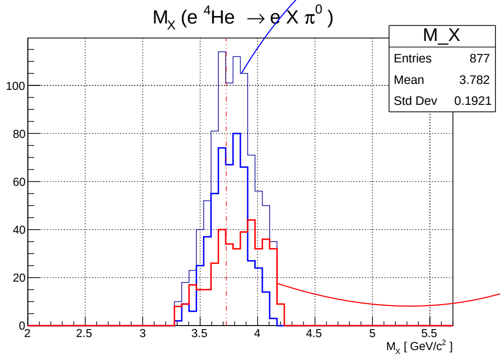
BSA = -0.5±6.3 %
(537 events)

Beam-Spin Asymmetry

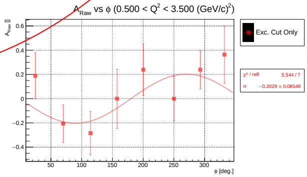
Beam-spin asymmetries for events passing exclusivity cuts *but* failing kin. fitting:

BSA = -8.9±5.3%





BSA = -20.3±8.5 %



Summary

- The BSA of coherent π^0 electroproduction off $^4\mathrm{He}$ is consistent with 0 (-0.5$\pm$6.4%)
  - Benchmark measurement for Ji's formulation
- Event selection plays a *crucial* role
- Exclusivity cuts require some cleverness
  - Intimate knowledge of the dataset and reaction needed to remove background and to clean the dataset
- Kin. fitting does not
  - It uses both detector resolutions and conservation law constraints to do a fantastic job in rejecting background
  - Some of these events cannot be rejected by any obvious series of cuts
- Kinematic fitting should be used in more analyses!

Outlook

- Extend kin. fitting to look into the incoherent channel
- Measure BSA for incoherent DVMP

Thank you!

. . .

Questions?

Backup Slides

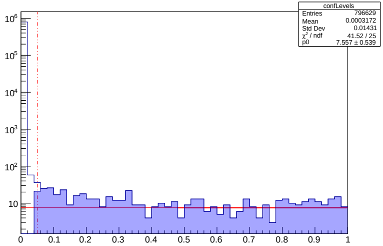
5C-Kinematic Fit on EG6: DVπ^0P

$$e\ {}^4\mathrm{He} \to e\ {}^4\mathrm{He}\ \pi^0$$

$$\pi^0 \to \gamma\ \gamma$$

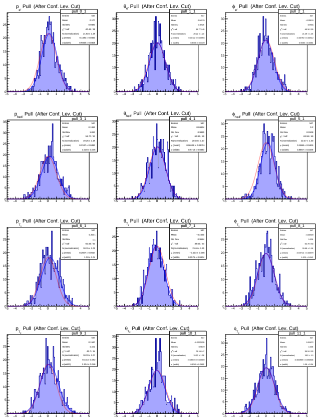
$$5C \Rightarrow \begin{cases} E_{init} - E_{fin} \equiv 0 \\ \vec{\boldsymbol{p}}_{init} - \vec{\boldsymbol{p}}_{fin} \equiv \vec{\boldsymbol{0}} \\ M_{\pi^0} - \sqrt{(E_{\gamma 1} + E_{\gamma 2})^2 - \|\vec{\boldsymbol{p}}_{\gamma 1} + \vec{\boldsymbol{p}}_{\gamma 2}\|^2} \equiv 0 \end{cases}$$

Confidence Level Distribution



CLC = 5%

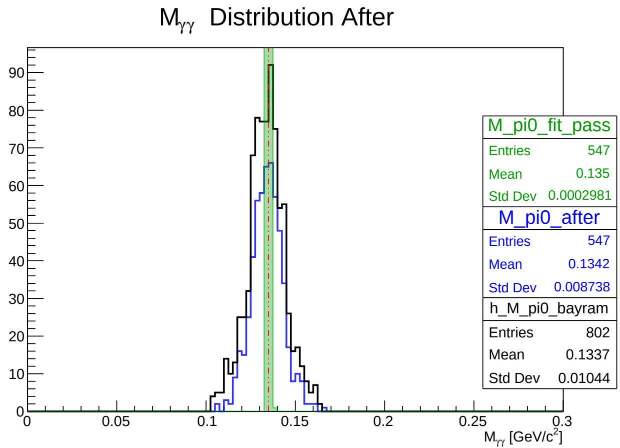
Pull Distributions



Invariant Mass Distribution for $\gamma\gamma$

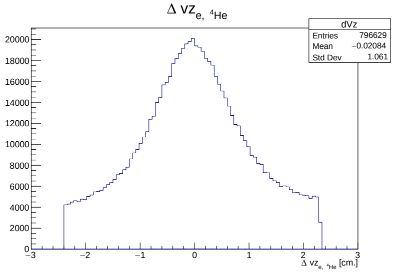
<u>Measured values from</u>:
Black: Exclusivity Cuts
Blue: Kinematic Fit

<u>Fitted values from</u>:
Green: Kinematic Fit

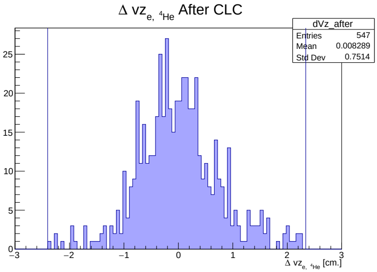


Sanity Check: Vertex Coincidence

Before CLC

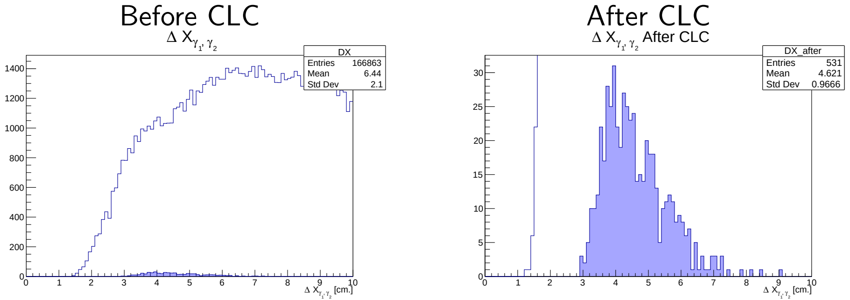


After CLC



Line Distribution: All Measured Events
Filled Distribution: Measured Events After CLC

Sanity Check: Photon Distance

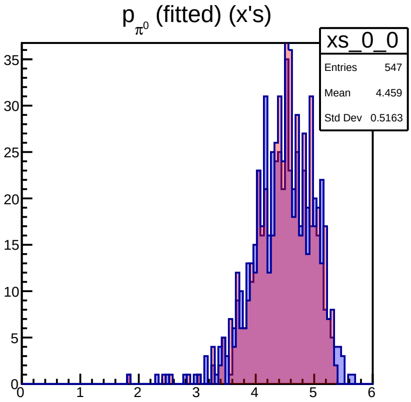


Line Distribution: All Measured Events
Filled Distribution: Measured Events After CLC

The $5C$-fit has no knowledge of the vertex coincidence between the helium in the RTPC and the electron in CLAS but produces a clean distribution of their distance.

B. Torayev's Cut : $\Delta X \in [3, 7]$ cm

Sanity Check: π^0 Momentum Distribution

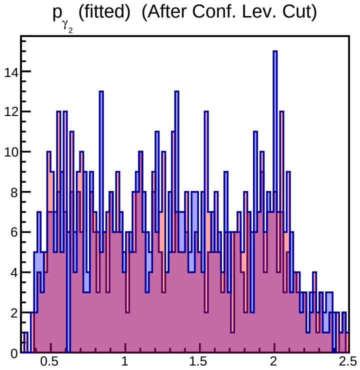


Red: Fitted After CLC
Blue: Measured After CLC

The $5C$-fit has no cut on the π^0 momentum but the distribution shows that the minimum momentum is around $3GeV/c$.

B. Torayev's Cut : $P_{\pi^0} > 3$ GeV$/c$

Sanity Check: γ_2 Momentum Distribution

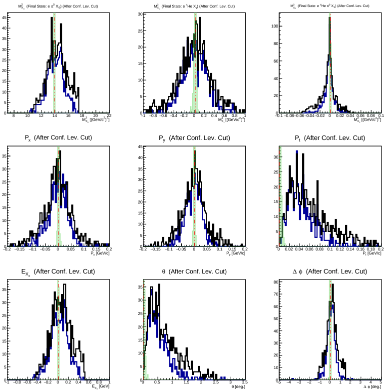


Red: Fitted After CLC
Blue: Measured After CLC

The $5C$-fit has no cut on the γ_2 but the distribution shows that the minimum momentum is around $0.3 GeV/c$.

B. Torayev's Cut : $P_{\gamma_2} > 0.4 GeV/c$

Sanity Check: Exclusivity Variable Distributions



Black: B. Torayev's Distributions
Blue: Measured After CLC
Green: Fitted After CLC

B. Torayev's Cuts:

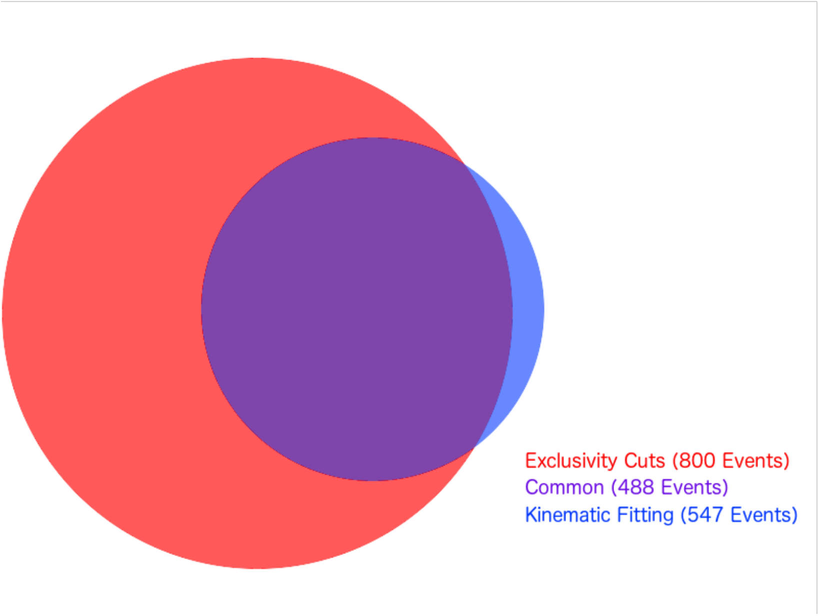
$$|M^2_{X_2} - 0.005| < 0.048\,\left(\text{GeV}/c^2\right)^2$$
$$|\Delta\phi - 0.16| < 0.138 \text{ deg.}$$

$$|\theta_{\pi^0,X_1} - 2.5| < 0.03 \text{ deg.}$$
$$|M^2_{X_0} - 14.079| < 0.03\,\left(\text{GeV}/c^2\right)^2$$

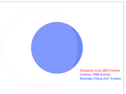
The $5C$-fit has no cuts on any of the exclusivity variables but they are essentially within the previous cuts.

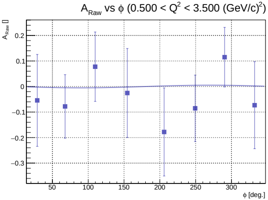
Datasets

Consider the Venn diagram of the datasets:

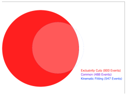


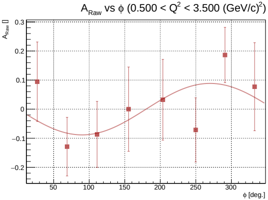
Beam Spin Asymmetries



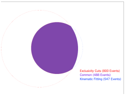


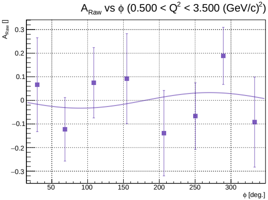
(537 events, BSA = -0.5±6.4%)





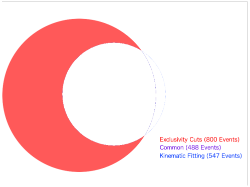
(800 events, BSA = -8.9±5.3%)

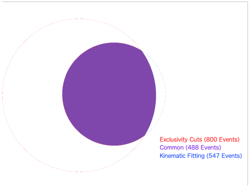


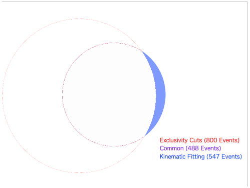


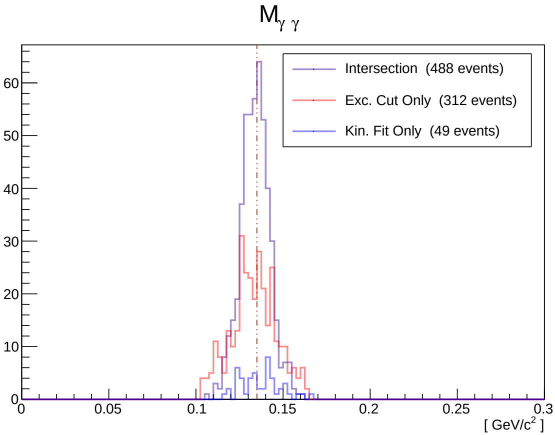
(488 events, BSA = -3.3±6.8%)

Invariant Mass Distributions

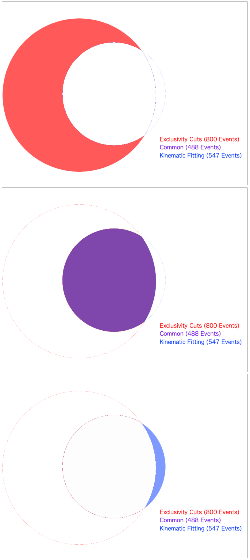


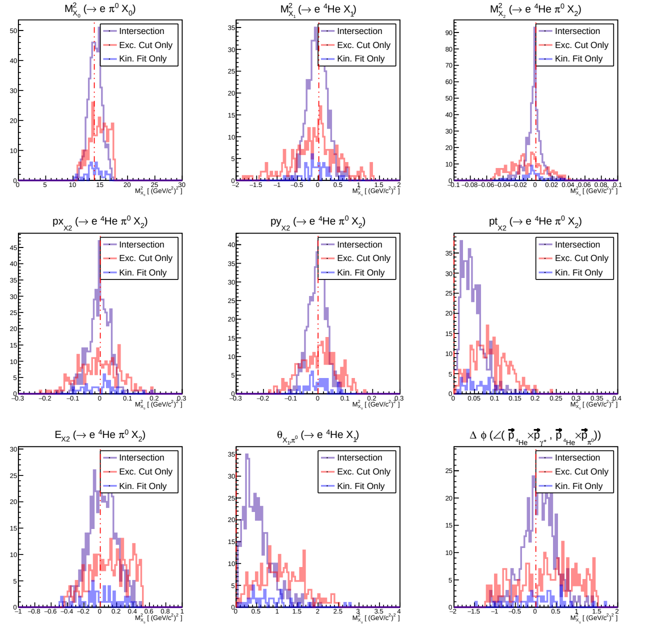






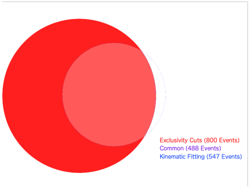
Exclusivity Variable Distributions



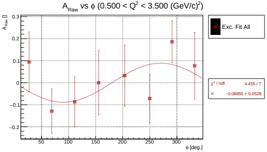


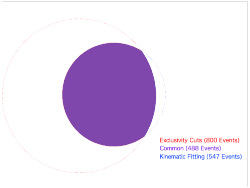
Beam Spin Asymmetries

Beam spin asymmetries summary:

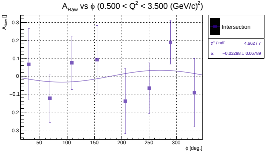


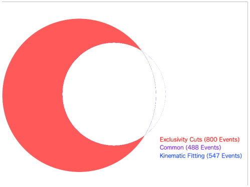
(800 events, BSA = -8.9±5.3%)



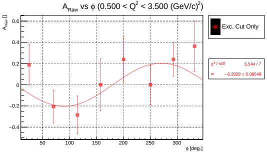


(488 events, BSA = -3.3±6.8%)





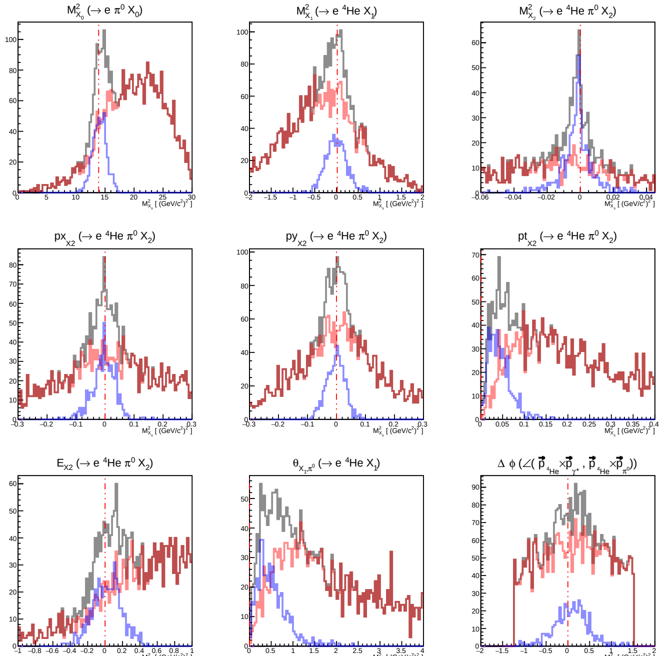
(312 events, BSA = -20.3±8.5%)



Failed Fit == Background?

$e\ {}^4\mathrm{He} \rightarrow e\ {}^4\mathrm{He}\ \pi^0$

All Exclusivity Variables



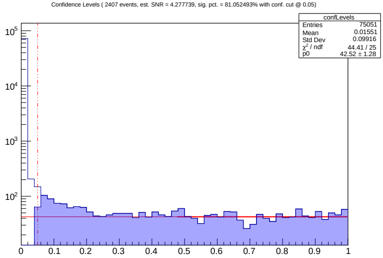
Kinematic Fit Applied to EG6: DVCS $4C$-fit Validation

$$e\ {}^4\mathrm{He} \to e\ {}^4\mathrm{He}\ \gamma$$

$$4C \Rightarrow \begin{cases} E_{init} - E_{fin} \equiv 0 \\ \vec{\boldsymbol{p}}_{init} - \vec{\boldsymbol{p}}_{fin} \equiv \vec{\boldsymbol{0}} \end{cases}$$

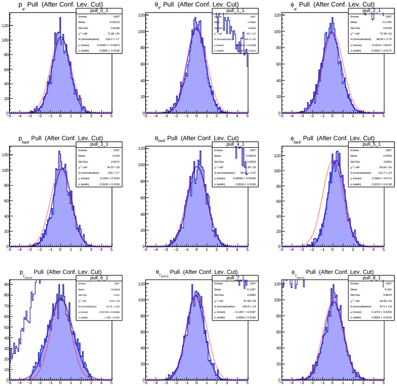
DVCS 4C-fit Outputs

Confidence Level Distribution

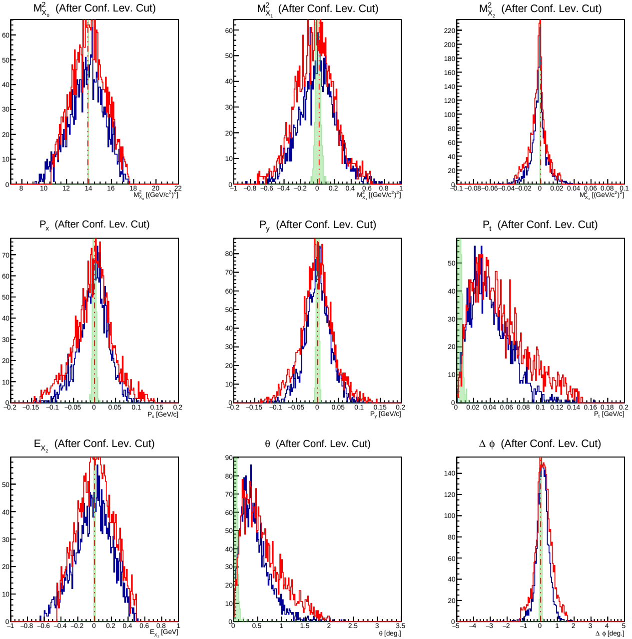


CLC = 5%

Pull Distributions



DVCS 4C-fit Exclusivity Variable Distributions

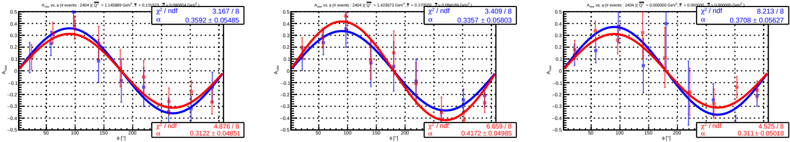


<u>Measured values from</u>:
Red: Exclusivity Cuts
Blue: Kinematic Fit

<u>Fitted values from</u>:
Green: Kinematic Fit

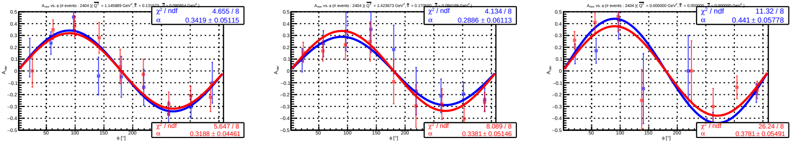
DVCS 4C-fit Beam-Spin Asymmetries

Bins in Q^2

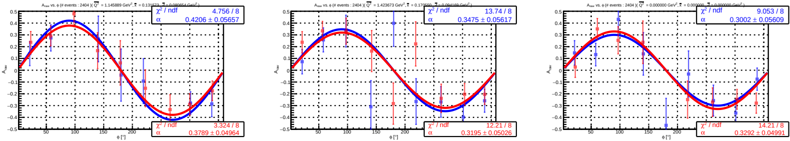


Bins in x

Measured values from:
Red: Exclusivity Cuts
Blue: Kinematic Fit



Bins in $-t$

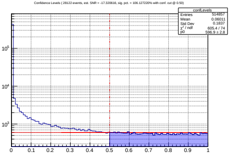


Power of Kin. Fit: E1-DVCS2 Dataset

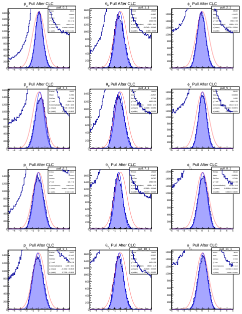
5C-Kinematic Fit on E1-DVCS2: DVπ^0P

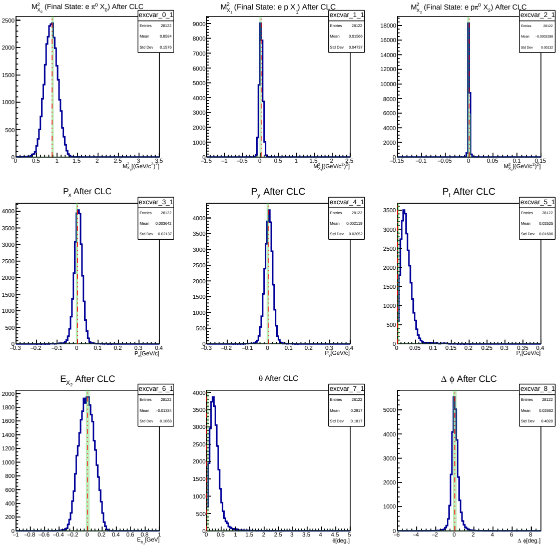
$$e\ p \rightarrow e\ p\ \pi^0 \quad , \quad \pi^0 \rightarrow \gamma\ \gamma$$

Confidence Level

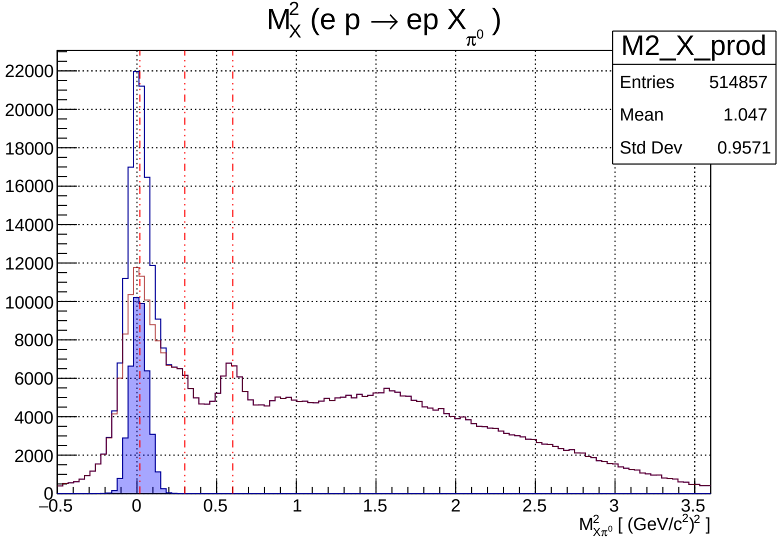


Pulls

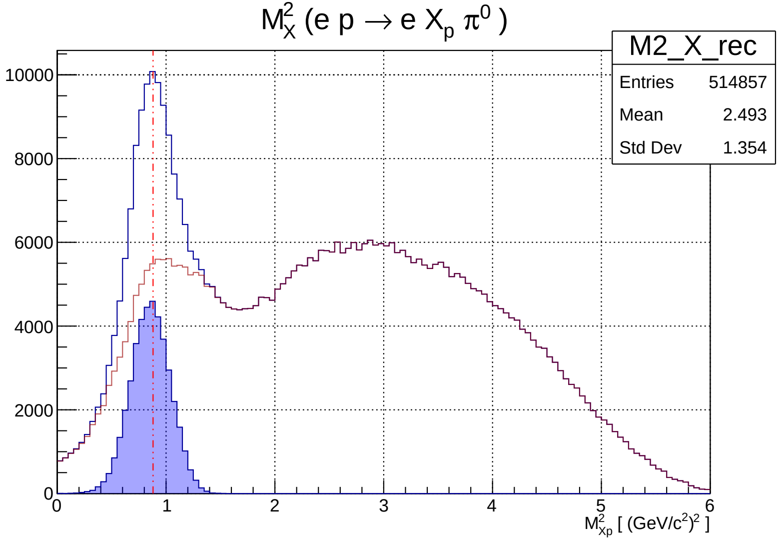




Motivation: Missing Mass^2 Distribution



Motivation: Missing Mass^2 Distribution



Kinematic Fit Applied to EG6: $4C$-fit on DVπ^0P

$e\ ^4\mathrm{He} \to e\ ^4\mathrm{He}\ \gamma\ \gamma$

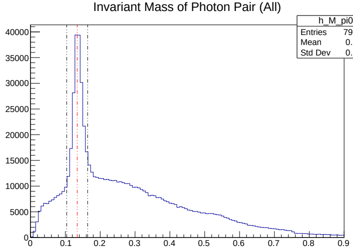
$$4C \Rightarrow \begin{cases} E_{init} - E_{fin} \equiv 0 \\ \vec{\boldsymbol{p}}_{init} - \vec{\boldsymbol{p}}_{fin} \equiv \vec{\mathbf{0}} \end{cases}$$

(No $\gamma\gamma$ invariant mass constraint!)

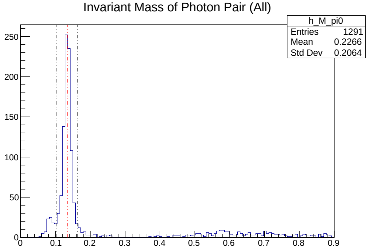
Motivation: Invariant Mass Dist.

Even with the detected *e* in CLAS and $^4\mathrm{He}$ in the RTPC, we still have to sift all combinations of photon pairs formed from both the IC and EC:

No Cuts



[3]Exc. Cuts



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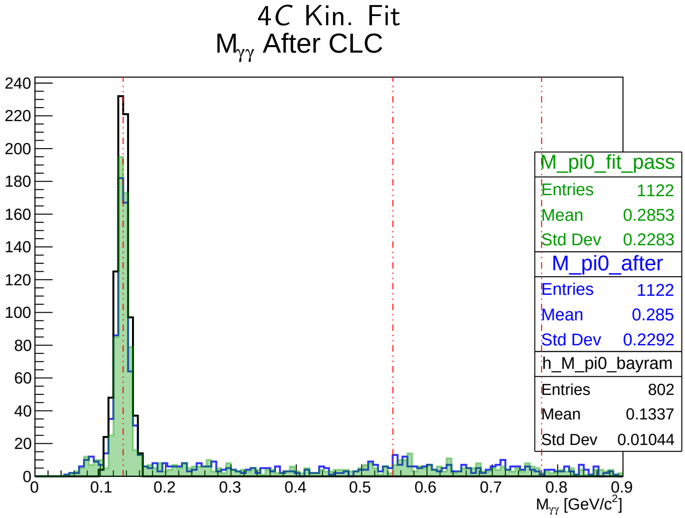
[1]For a fair comparison, additional π^0 cuts includes a photon distance cut ($|\Delta x_{\gamma\gamma} - 5\mathrm{cm}| < 2\mathrm{cm}$) and a momentum cut ($p_{\pi^0} > 3\mathrm{GeV/c}$).

Motivation: Invariant Mass Dist.



Even with the $4C$ kinematic fit, we see that the invariant mass distribution has a clear π^0-peak with very little background.

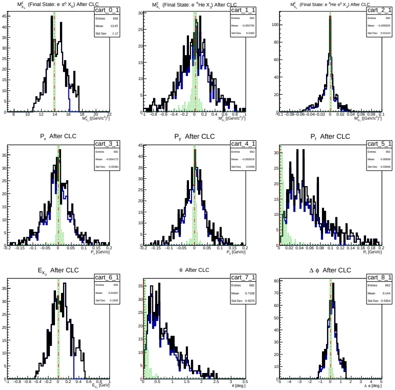
Note: Nowhere in the implementation is the nominal value of M_{π^0} used!

Robustness of Exc. Cuts (or lack thereof)

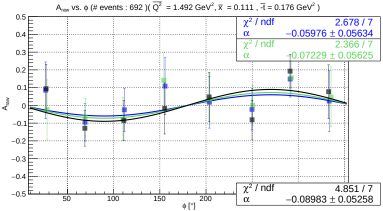
$e\ {}^4\mathrm{He} \rightarrow e\ {}^4\mathrm{He}\ \pi^0$

Adding One Exclusivity Cut: E Cut

Exclusivity Variable Distributions



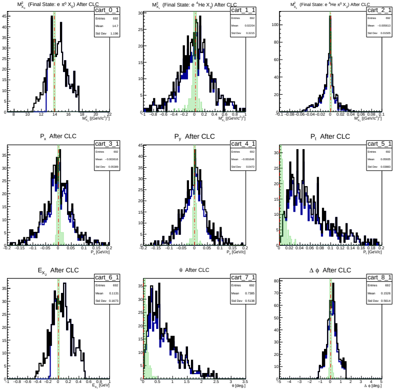
Beam Spin Asymmetry



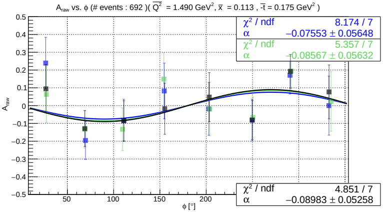
(692 events, BSA = -6.4±5.6%)

Adding One Exclusivity Cut: *E* Cut

Exclusivity Variable Distributions



Beam Spin Asymmetry

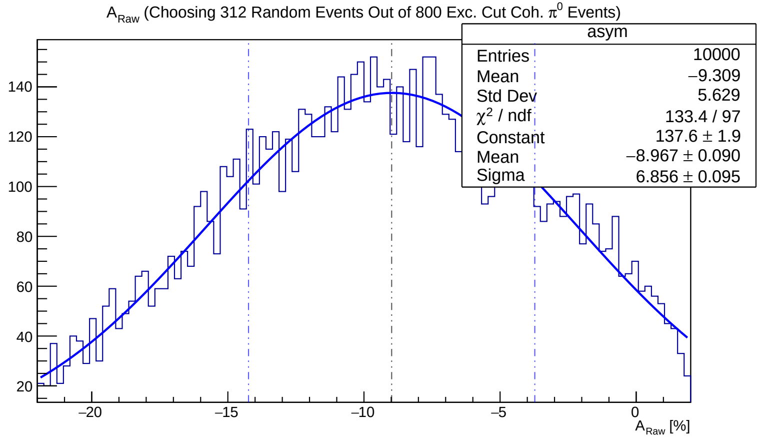


(692 events, BSA = -7.8±5.6%)

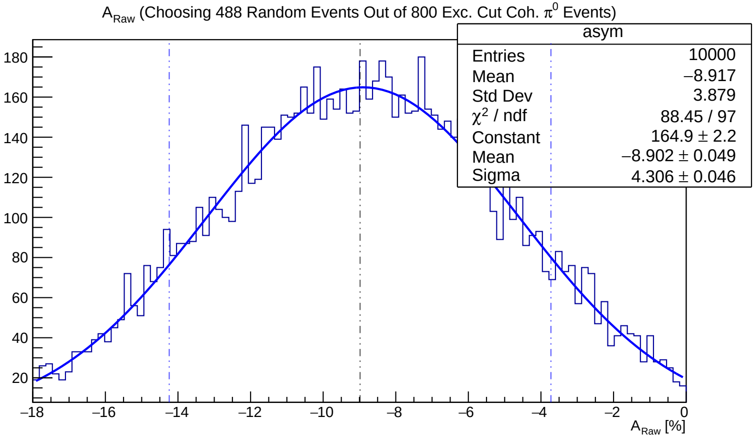
Sampling Subsets of Exc. Cuts

$e\ ^4\mathrm{He} \rightarrow e\ ^4\mathrm{He}\ \pi^0$

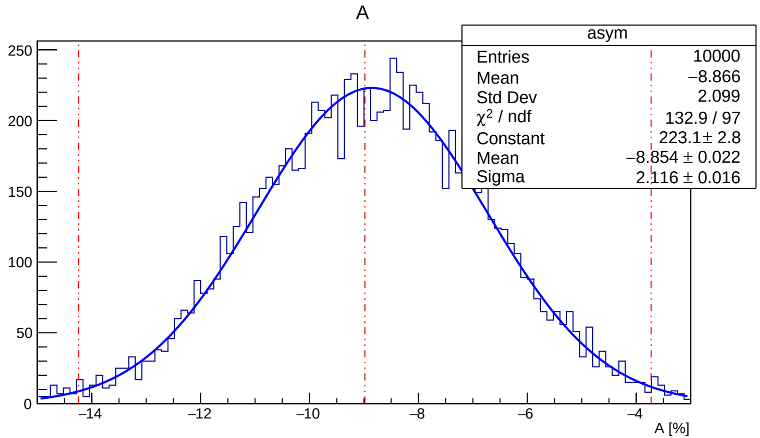
Likelihood of Selecting 312 out of 800 events having $A_{Raw} = -20.3\%$



Likelihood of Selecting 488 out of 800 events having $A_{Raw} = -3.3\%$



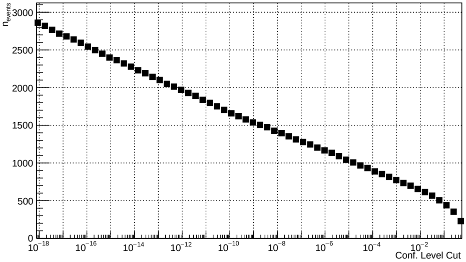
Likelihood of 692/800 events having 33% Less Asymmetry

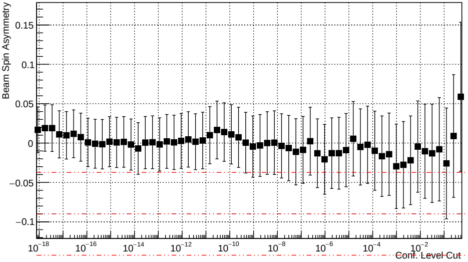


BSA and N_{events} vs. CLC

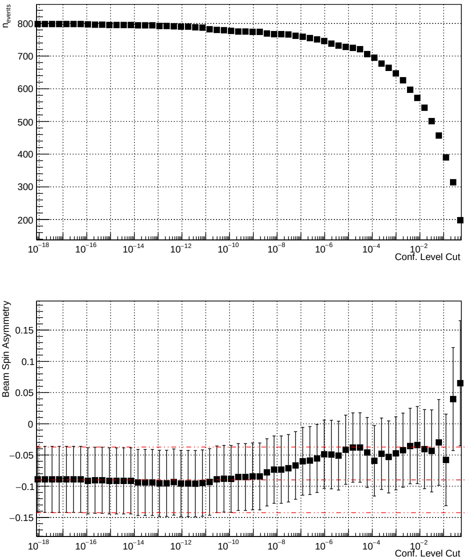
$e\ ^4\mathrm{He} \rightarrow e\ ^4\mathrm{He}\ \pi^0$

BSA vs. Conf. Level Cut: Full Dataset





BSA vs. Conf. Level Cut: Exclusivity Selected Events



RTPC: Particle Determination