

# Exclusive $\eta$ Electroproduction Beam Spin Asymmetry Measurements using CLAS12 at Jefferson Lab

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# Unique Opportunity of $\eta$ N Final States

- **Key Idea:**  $\eta$ N final states provide a cleaner probe of nucleon resonances compared to  $\pi$ N final states
- $\eta$  is an isospin singlet ( $I = 0$ )
- “Isospin filter”:  $\eta$ N final states access only  $I = 1/2$  nucleon resonances
- Simplifies the analysis by reducing the number of contributing resonances
- Enables cleaner extraction of resonance properties

Particle	$J^P$	Overall	$N\gamma$	$N\pi$	$N\eta$
$N(1440)$	$1/2^+$	****	****	****	
$N(1520)$	$3/2^-$	****	****	****	****
$N(1535)$	$1/2^-$	****	****	****	****
$N(1650)$	$1/2^-$	****	****	****	****
$N(1675)$	$5/2^-$	****	****	****	*
$N(1680)$	$5/2^+$	****	****	****	*
$N(1700)$	$3/2^-$	***	**	***	*
$N(1710)$	$1/2^+$	****	****	****	****
$N(1720)$	$3/2^+$	****	****	****	*
$N(1860)$	$5/2^+$	**	*	**	*
$N(1875)$	$3/2^-$	***	**	**	*
$N(1880)$	$1/2^+$	***	**	*	*
$N(1895)$	$1/2^-$	****	****	*	****

Particle	$J^P$	Fraction $\Gamma_i/\Gamma$ for Decay Modes	
		$N\pi$	$N\eta$
$N(1440)$	$1/2^+$	55-75 %	<1 %
$N(1520)$	$3/2^-$	55-65 %	0.07-0.09 %
$N(1535)$	$1/2^-$	32-52 %	30-55 %
$N(1650)$	$1/2^-$	50-70 %	15-35 %
$N(1675)$	$5/2^-$	38-42 %	<1 %
$N(1680)$	$5/2^+$	60-70 %	<1 %
$N(1700)$	$3/2^-$	7-17 %	1-2 %
$N(1710)$	$1/2^+$	5-20 %	10-50 %
$N(1720)$	$3/2^+$	8-14 %	1-5 %
$N(1875)$	$3/2^-$	3-11 %	3-16 %
$N(1880)$	$1/2^+$	3-31 %	1-55 %
$N(1895)$	$1/2^-$	2-18 %	15-45 %
$N(1900)$	$3/2^+$	1-20 %	2-14 %
$N(2060)$	$5/2^-$	7-12 %	2-38 %
$N(2100)$	$1/2^+$	8-32 %	5-45 %
$N(2120)$	$3/2^-$	5-15 %	1-5 %
$N(2190)$	$7/2^-$	10-20 %	1-5 %
$N(2220)$	$9/2^-$	15-30 %	N/A

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Existence is certain.

Existence is very likely.

Evidence of existence is fair.

Evidence of existence is poor.

# Objective: Measuring Beam Spin Asymmetry (BSA/ $A_{LU}$ ) in $\eta$ Electroproduction

- **Key Idea:** First ever measurement of the beam spin asymmetry (BSA) in exclusive  $\eta$  electroproduction in a previously unexplored kinematic region.
- Unexplored kinematic region:  $1.6 \leq W \leq 2.2$  GeV
- Longitudinally polarized electron beam on unpolarized stationary proton target
- Complements existing cross section and polarization observable measurements

Beam Spin Asymmetry  $A_{LU}$   
(BSA):

$$A_{LU} = \frac{1}{P_b} \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-}$$

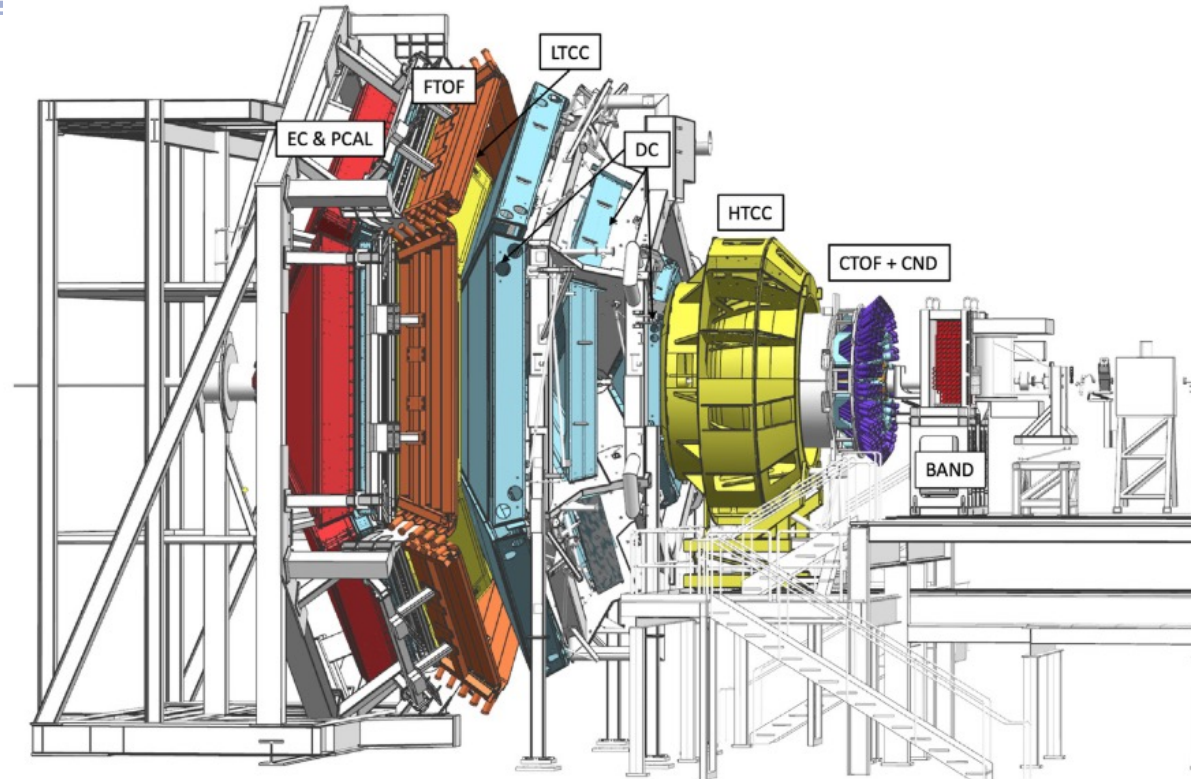
$$= \frac{1}{P_b} \frac{N^+ - N^-}{N^+ + N^-}$$

Sin  $\phi^*$  Moment:

$$A_{LU} \approx \boxed{A_{LU}^{\sin \phi^*}} \sin \phi^*$$

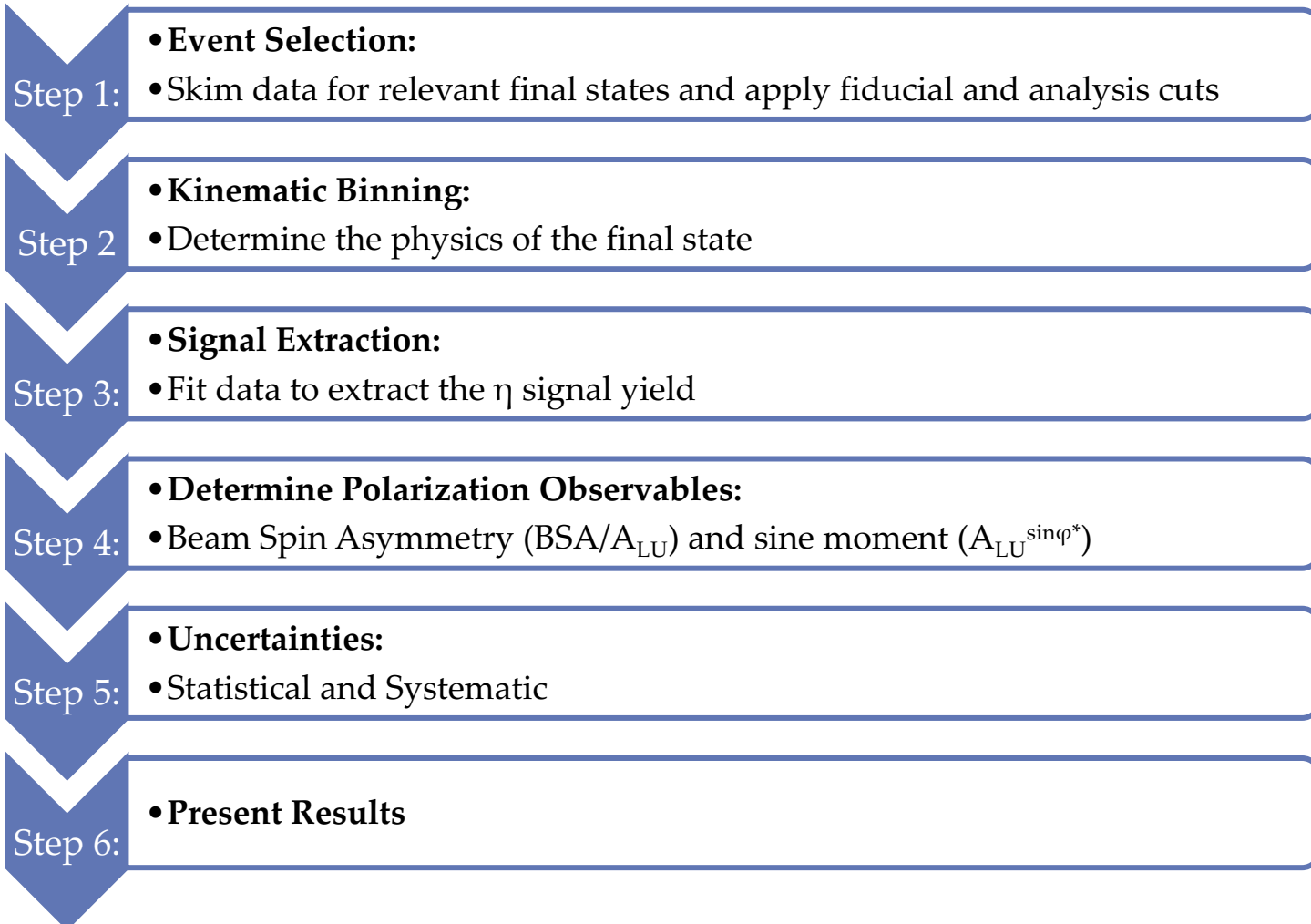
$N^\pm = \eta$  signal yield for ( $\pm 1$ ) helicity  
 $P_b =$  beam polarization (0.8517)

# CEBAF and CLAS12 at Jefferson Lab



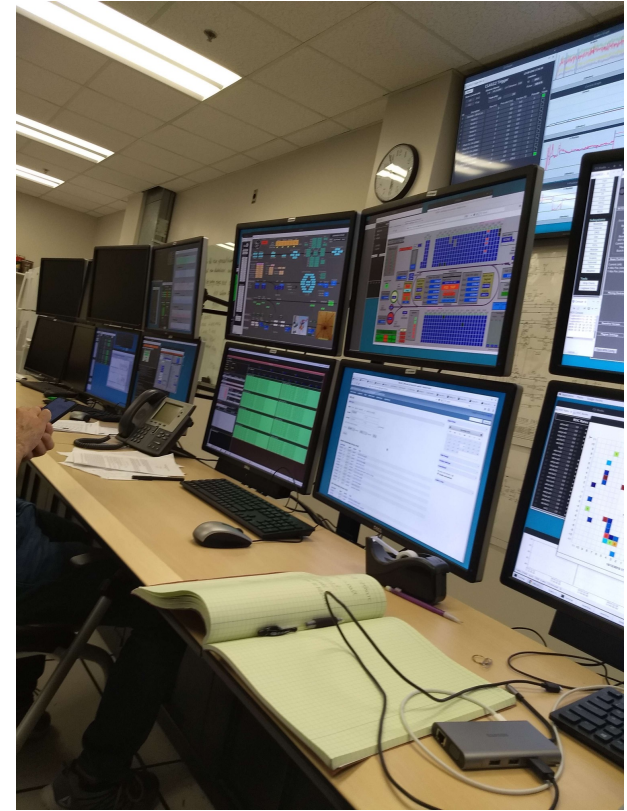
- **Key Idea:** The 12 GeV upgrade of the Continuous Electron Beam Accelerator Facility (CEBAF) and the CLAS12 spectrometer enable high-precision studies of nucleon structure and resonances.
- CEBAF delivers high-energy, longitudinally polarized electron beams
  - Up to 11 GeV to Hall B after 5 passes
  - Beam polarization is measured using the Møller polarimeter in Hall B

- **Key Idea:** A systematic approach to extract the beam spin asymmetry (BSA or  $A_{LU}$ ) and the  $\sin \varphi^*$  moment of the asymmetry ( $A_{LU}^{\sin \varphi^*}$ ) from the data.



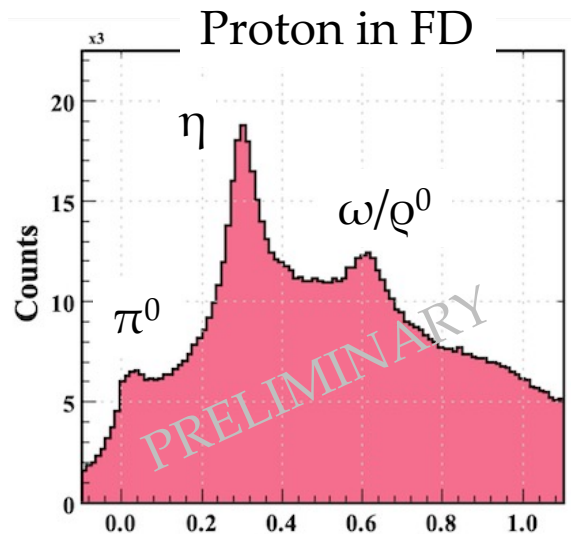


- **Key Idea:** This work utilizes a subset of the RG-K dataset
- Data collected from Nov. 28 to Dec. 20, 2018 as a short "opportunistic" run
  - ~10% of the approved RG-K beam time
- Beam energy: 6.5 GeV
- Longitudinally polarized electron beam ( $P_b \geq 85\%$ ) on unpolarized liquid hydrogen ( $\text{LH}_2$ ) target
- High luminosity:  $10^{35} \text{ cm}^{-2} \text{ s}^{-1}$
- Total events collected: 7.8 billion

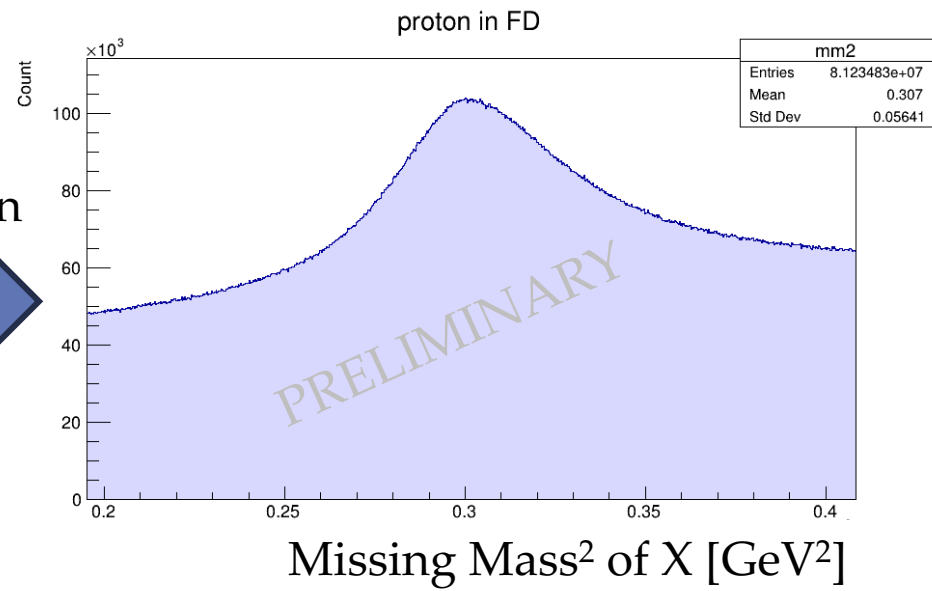


# Event Selection and $\eta$ Identification

- **Key Idea:**  $\eta$  mesons are identified using the missing mass technique in the  $ep \rightarrow e'p'X$  reaction.
- Detect scattered electron and proton in the Forward Detector
- Reconstruct the missing mass squared ( $MM^2$ ) of the undetected particle X
- $\eta$  signal appears as a peak around  $MM^2 = 0.3 \text{ GeV}^2$
- Apply analysis cuts:
  - $W < 2 \text{ GeV}$  (nucleon resonance region)
  - $0.15 \text{ GeV}^2 < MM^2 < 0.45 \text{ GeV}^2$  ( $\eta$  peak region)
- Implement standard RGK fiducial cuts and cuts developed for analysis

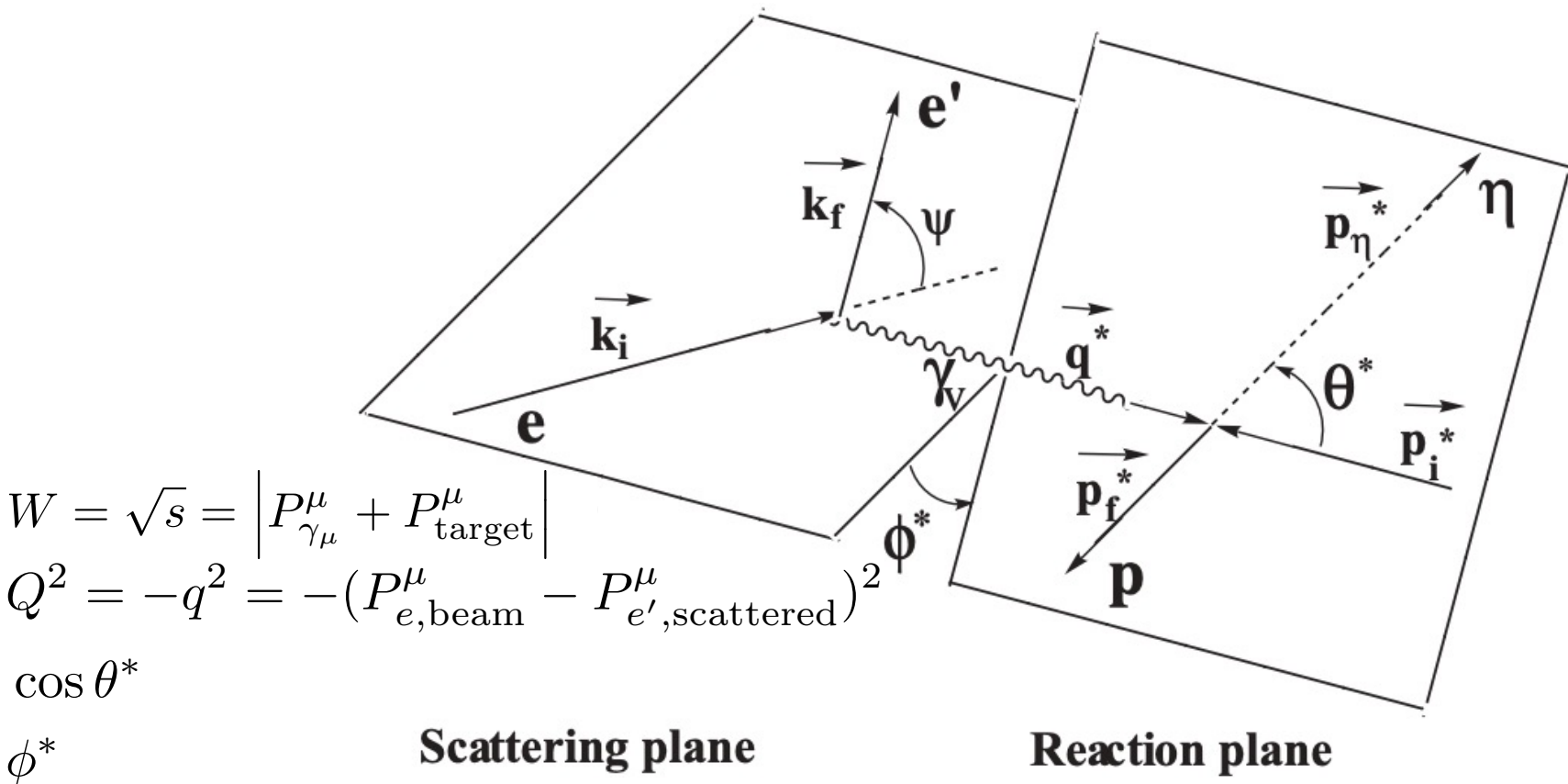


Event Selection



# $\eta$ Electroproduction Kinematics

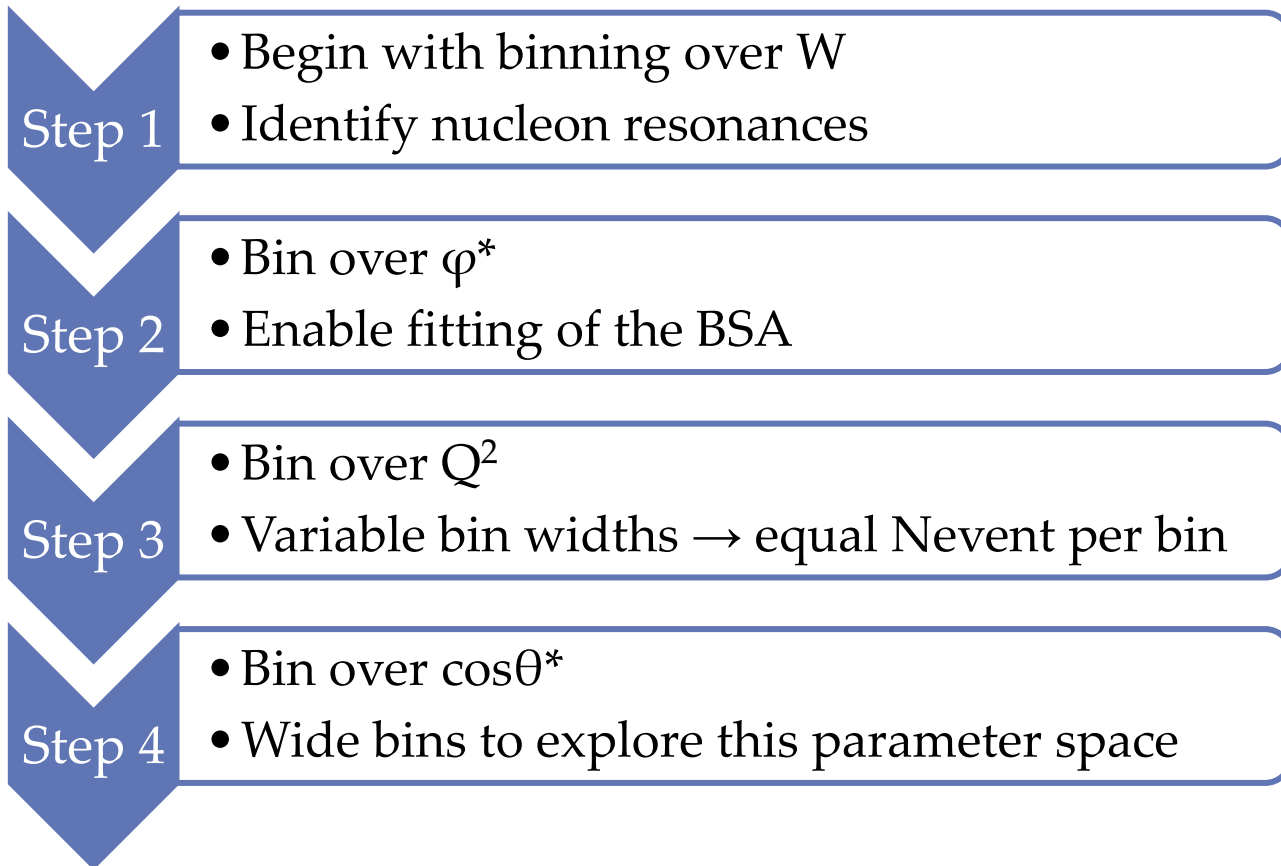
- **Key Idea:** The  $\eta$  electroproduction reaction is studied in the center-of-mass frame, with key kinematic variables  $W$ ,  $Q^2$ ,  $\cos(\theta^*)$ , and  $\phi^*$ .
- Reaction:  $ep \rightarrow e'p'\eta$
- Center-of-mass frame: resonance is at rest





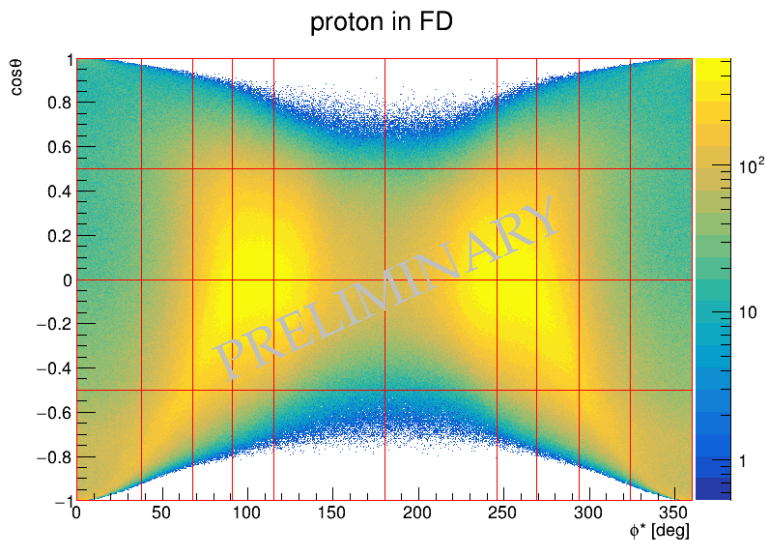
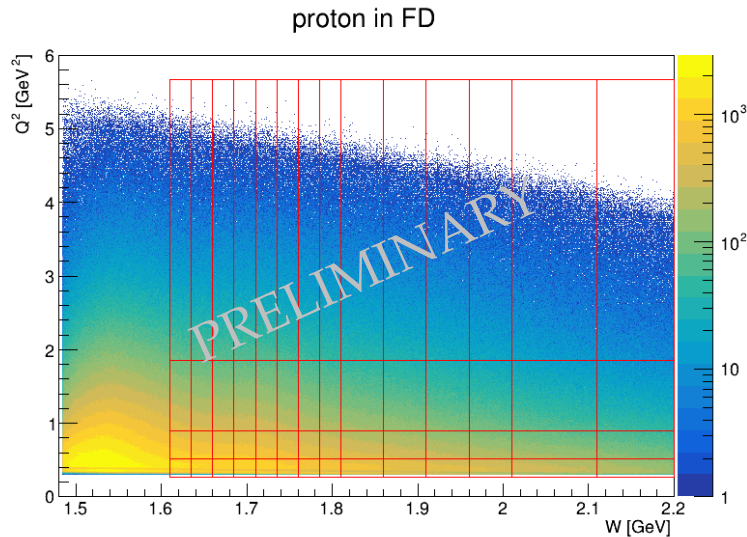
# Kinematic Binning: Stepwise Methodology

- **Key Idea:** A strategic, adaptive approach to binning is employed to balance kinematic resolution and statistical power.



# Kinematic Binning: Phase Space Coverage

- Key Idea:** The multi-dimensional kinematic phase space is partitioned into discrete bins for detailed analysis.

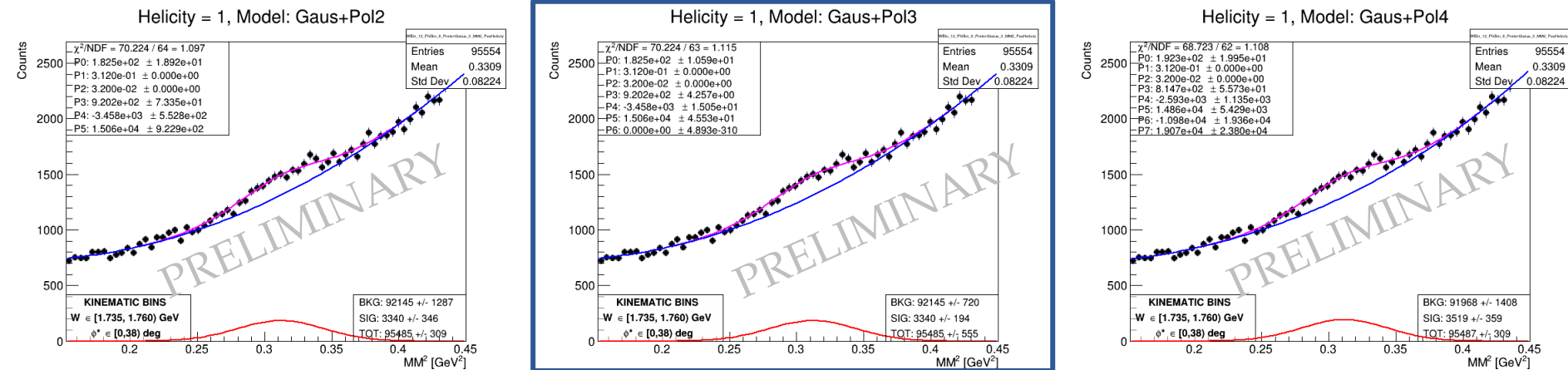


W [GeV]	$\phi^*$ [deg]	$Q^2$ [GeV <sup>2</sup> ]	$\cos(\theta^*)$
1.610 to 1.635	0 to 38	0.300 to 0.521	-1.0 to -0.5
1.635 to 1.660	38 to 68	0.521 to 0.896	-0.5 to 0.0
1.660 to 1.685	68 to 91	0.896 to 1.850	0.0 to 0.5
1.685 to 1.710	91 to 115	1.850 to 5.671	0.5 to 1.0
1.710 to 1.735	115 to 180		
1.735 to 1.760	180 to 246		
1.760 to 1.785	246 to 269		
1.785 to 1.810	269 to 294		
1.810 to 1.860	294 to 324		
1.860 to 1.910	324 to 360		
1.910 to 1.960			
1.960 to 2.010			
2.010 to 2.110			
2.110 to 2.210			

# Signal Extraction and Background Fit

- Key Idea: Extracting the  $\eta$  signal yield requires fitting the missing mass squared distribution with a combination of signal and background fits.

pol3 as "benchmark"

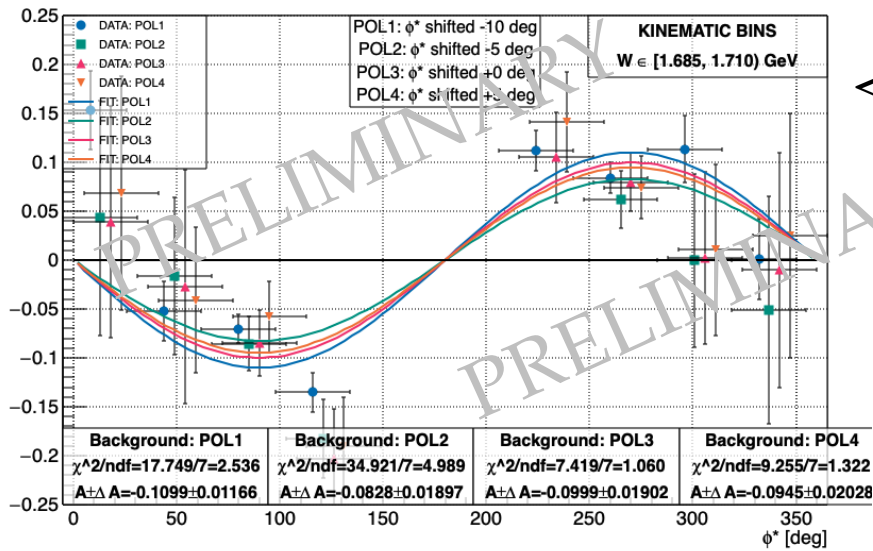


- Signal: Fitted using a Gaussian function
- Background: Fitted using polynomial functions of various orders (pol2, pol3, pol4)
- pol3 chosen as the "benchmark" fits, balancing bias and variance
- Systematic uncertainty analysis is preliminary
  - Dominant source considered is the yield extraction procedure, estimated by comparing different background fits (pol2, pol3, pol4)

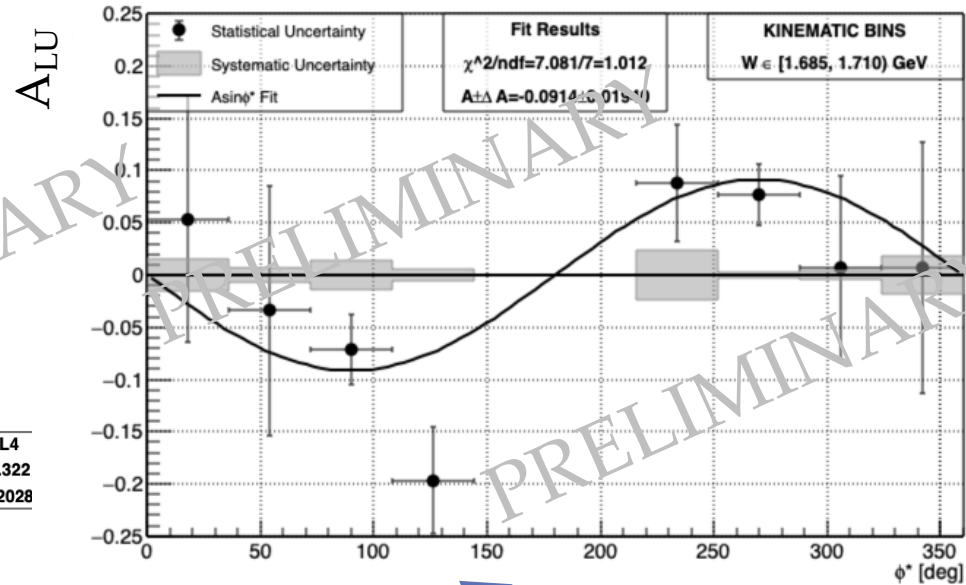
# Representative Fit to Beam Spin Asymmetry

- **Key Idea:** The BSA is extracted by fitting the asymmetry as a function of  $\phi^*$  with a sine function.
- Data binned over  $W$  and  $\phi^*$ , integrated over  $Q^2$  and  $\cos\theta^*$

BSA Calculated from  $\eta$  SIGNAL vs  $\phi^*$



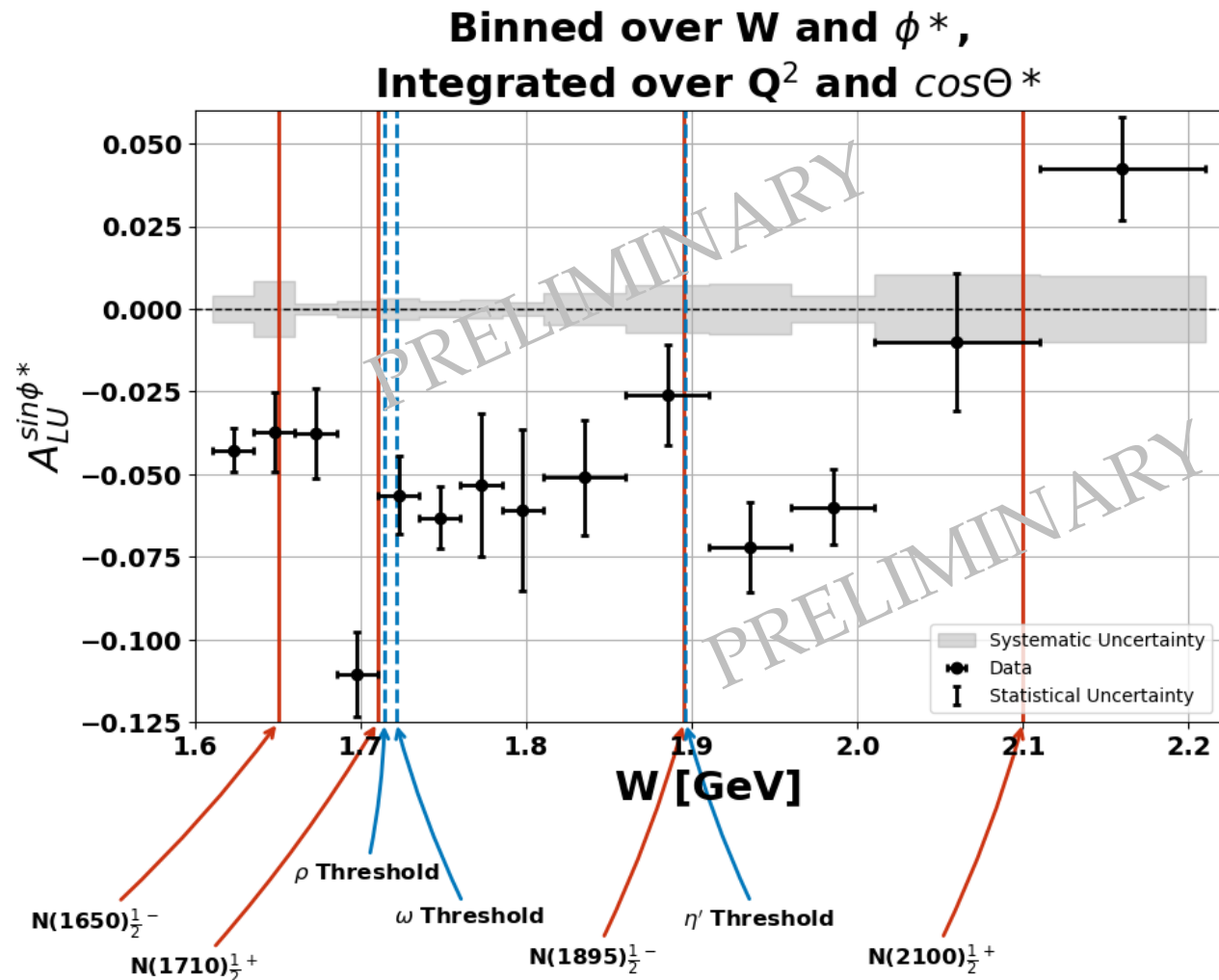
BSA Calculated from  $\eta$  SIGNAL vs  $\phi^*$



$$A_{LU} = \frac{1}{P_b} \frac{N^+ - N^-}{N^+ + N^-} \quad A_{LU} \approx A_{LU}^{\sin \phi^*} \sin \phi^*$$

# Sine Moment of the Beam Spin Asymmetry ( $A_{LU}^{\sin\phi^*}$ )

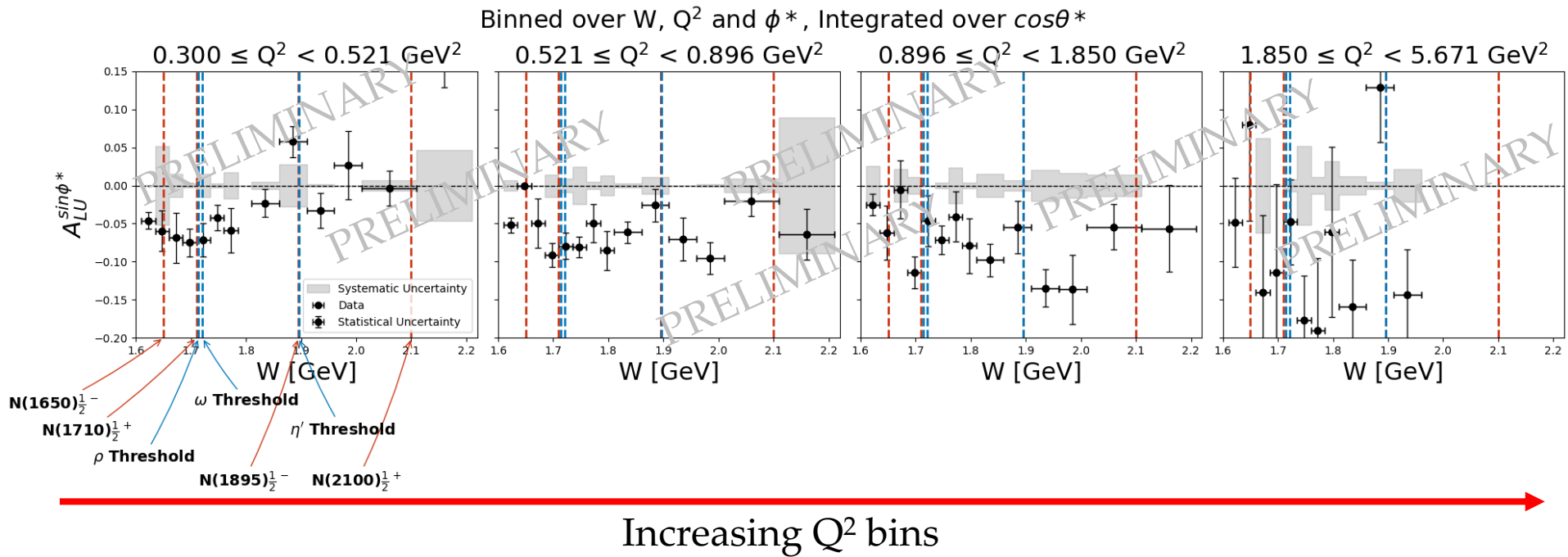
- **Key Idea:** The sine moment of the asymmetry,  $A_{LU}^{\sin\phi^*}$ , is extracted to study the dependence on the center-of-mass energy  $W$ .
- Data binned over  $W$  and  $\phi^*$ , integrated over  $Q^2$  and  $\cos\theta^*$
- Error bars represent statistical uncertainties
- Grey histograms around zero line indicate systematic uncertainties
- Selected nucleon resonances
- Selected meson production thresholds





# $Q^2$ Dependence of the Sine Moment ( $A_{LU}^{\sin\phi^*}$ )

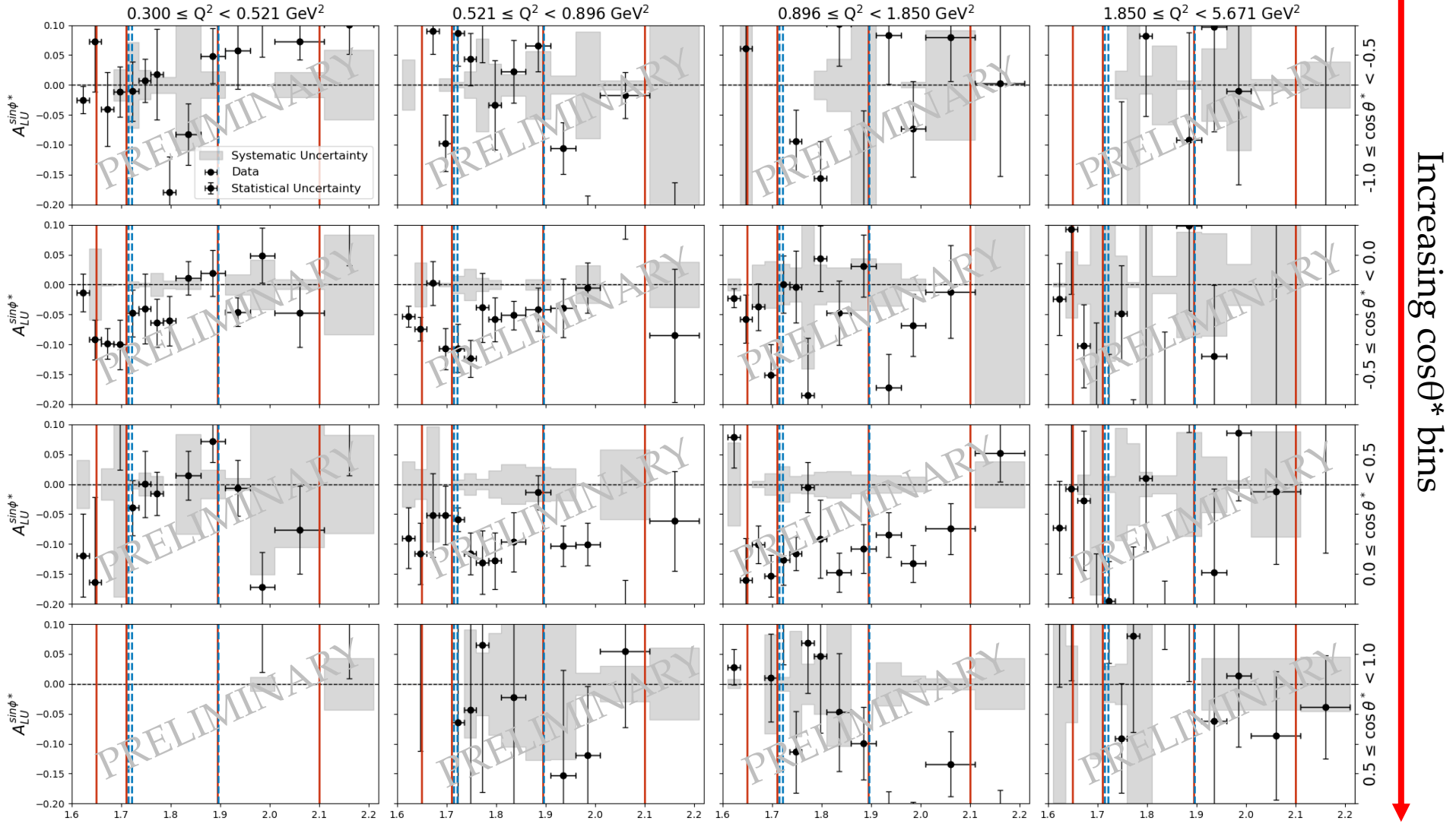
- Key Idea:** Binning the data over  $Q^2$  allows for investigating the dependence of  $A_{LU}^{\sin\phi^*}$  on the four-momentum transfer squared.



# Full Kinematic Dependence of the Sine Moment

Increasing  $Q^2$  bins

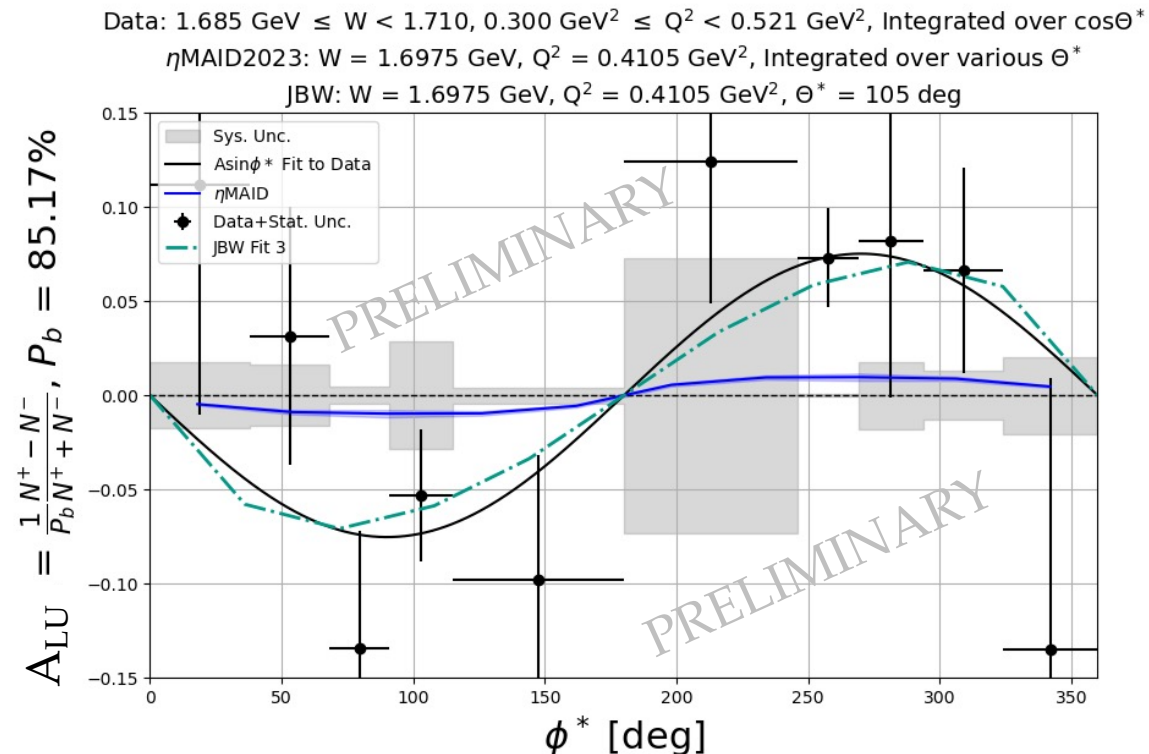
Binned over  $W$ ,  $Q^2$ ,  $\cos\theta^*$ , and  $\phi^*$



**Key Idea:** A comprehensive study of the sine moment's dependence on the kinematic phase space.

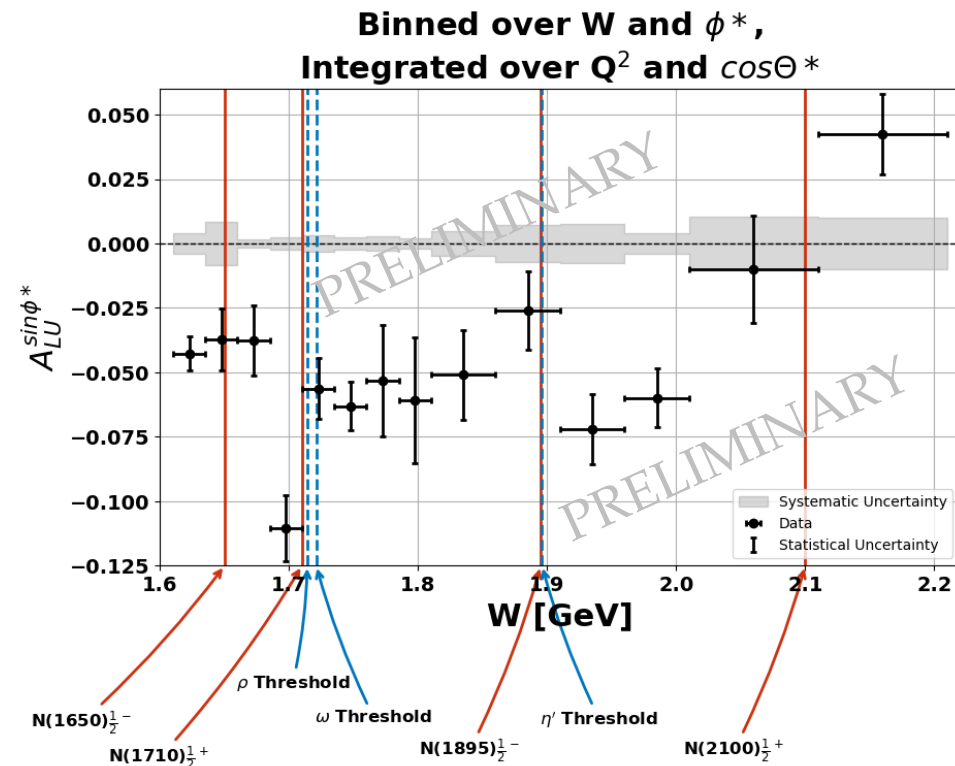
# Comparison with Theoretical Models: An Illustrative Example

- **Key Idea:** The beam spin asymmetry data has the potential to constrain and improve theoretical models of  $\eta$  electroproduction.
- Data binned over  $W$ ,  $\varphi^*$ , and  $Q^2$  and integrated over  $\cos\theta^*$
- Jülich-Bonn-Washington (JBW)
- EtaMAID
- Illustrative example of the potential for this data to constrain and improve theoretical models
- Limitations in the models (small  $N_\eta$  datasets, lack of polarization observables) prevent definitive conclusions at this stage



# Summary of Key Findings and Impact

- **Key Idea:** The beam spin asymmetry measurements in  $\eta$  electroproduction offer valuable data for theoretical models and could provide new insights into nucleon resonances.
- Key Findings:
  - Consistently negative  $A_{LU}^{\sin\phi^*}$  values across the  $W$  range
  - Dip-like structure near  $N(1710)$
  - Cusp-like behavior near  $N(1895)$
- Impact:
  - Expands kinematic reach in  $\eta$  electroproduction BSA measurements
  - Bridges the gap between well-studied  $S_{11}(1535)$  and higher mass states
  - Provides new data to evaluate and constrain theoretical models



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# Any Questions?

