Beam Spin Asymmetries for Positively Charged Kaons

David Riser, University of Connecticut
in collaboration with Kyungseon Joo and Nick Markov

This study measures the beam spin asymmetry for positively charged kaons in semi-inclusive deeply inelastic scattering over four SIDIS kinematic variables. The unpolarized cross section is,

$$\frac{d\sigma}{dx_B\, dQ^2\, dz\, d\phi_h\, dp_{h\perp}^2} = K(x,y,Q^2)\Big\{F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\,\varepsilon(1+\varepsilon)}\cos\phi_h F_{UU}^{\cos\phi_h} + \varepsilon\cos(2\phi_h)F_{UU}^{\cos 2\phi_h} + \lambda_e\sqrt{2\,\varepsilon(1-\varepsilon)}\sin\phi_h F_{LU}^{\sin\phi_h}\Big\}$$

$$BSA = \frac{d\sigma^+ - d\sigma^-}{d\sigma^+ + d\sigma^-} = \frac{A_{LU}^{\sin\phi}\sin\phi}{1 + A_{UU}^{\cos\phi}\cos\phi + A_{UU}^{\cos(2\phi)}\cos(2\phi)}$$

The beam spin asymmetry is sensitive to the sine moment, which is pure twist-3.

$$F_{LU}^{\sin\phi} = \frac{2M}{Q}\mathcal{C}\left(-\frac{\hat{\mathbf{h}}\cdot\mathbf{k_T}}{M_h}\left(xeH_1^{\perp} + \frac{M_h}{M}f_1\frac{\tilde{G}^{\perp}}{z}\right) + \frac{\hat{\mathbf{h}}\cdot\mathbf{p_T}}{M}\left(xg^{\perp}D_1 + \frac{M_h}{M}h_1^{\perp}\frac{\tilde{E}}{z}\right)\right)$$

twist-3 pdf

Collins FF

unpolarized dist. function

twist-3 FF

twist-3 t-odd dist. function

Boer-Mulders

twist-3 FF

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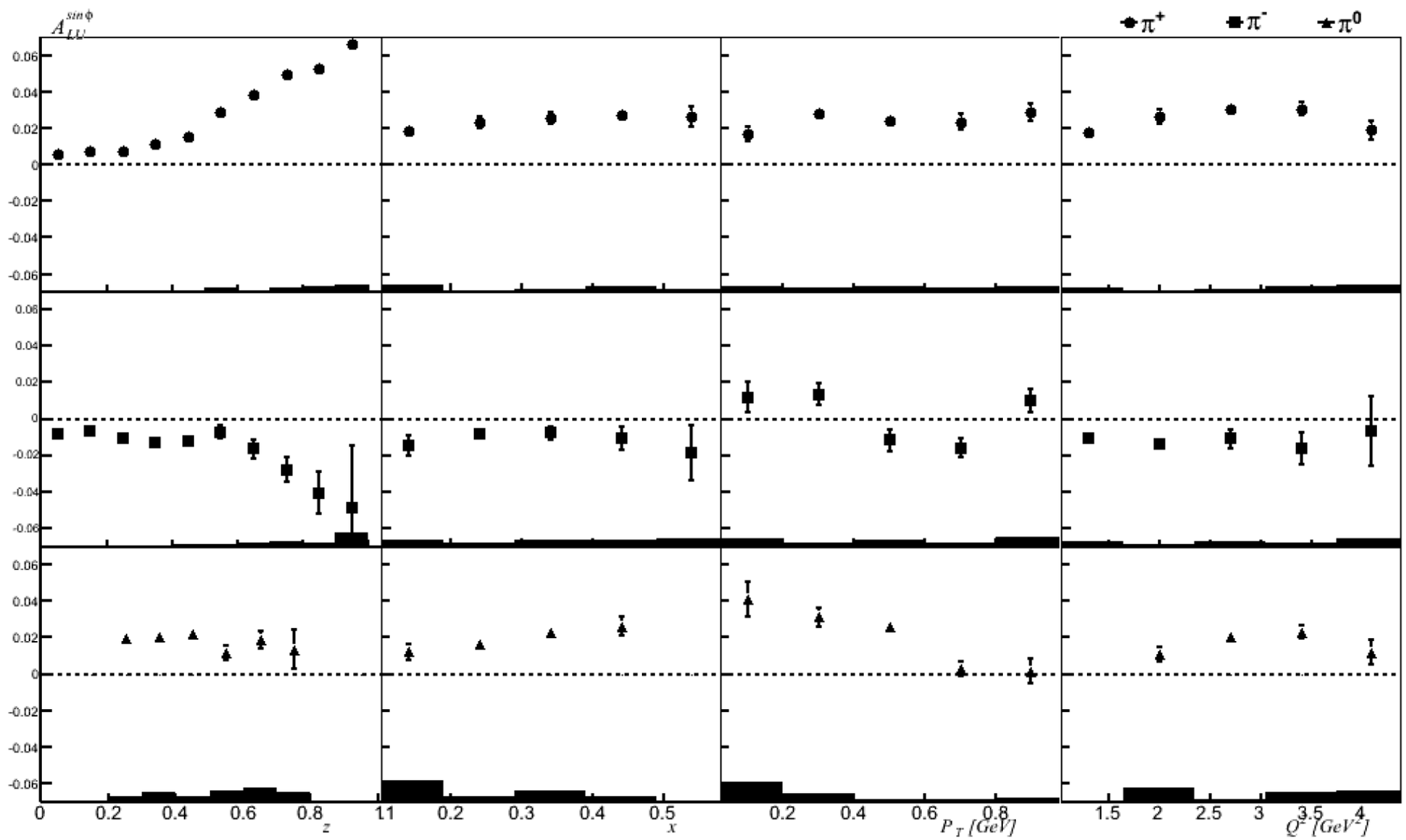
Previous CLAS measurements demonstrate that for pions, the SIDIS beam spin asymmetry is not consistent with zero.



Gohn et. al, Beam Spin Asymmetries from Semi-Inclusive Pion Electroproduction.

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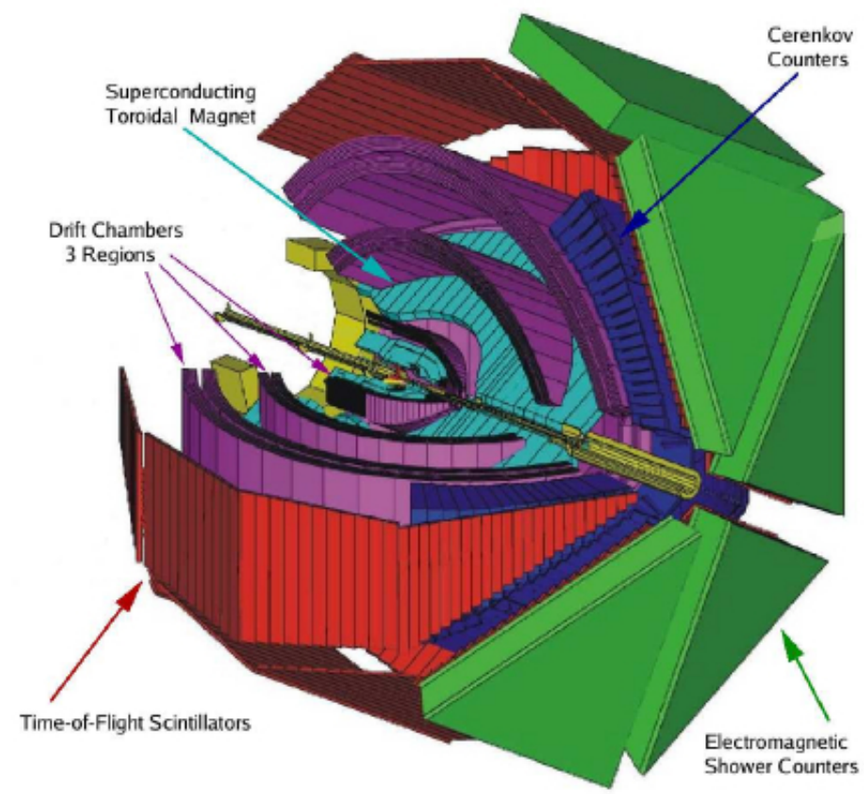
Experimental Considerations - How do we actually measure this?

$$BSA_i = \frac{1}{P_e}\frac{N_i^+ - N_i^-}{N_i^+ + N_i^-}$$

This measurement is performed at Jefferson Laboratory In Hall B by CLAS.

Run period: E1-F

- Beam energy 5.5 GeV
- Torus field run at 60% (2250 A)
- Negatively charged particles - inbending
- Over 1B event triggers
- LH_2 target, 5 cm length



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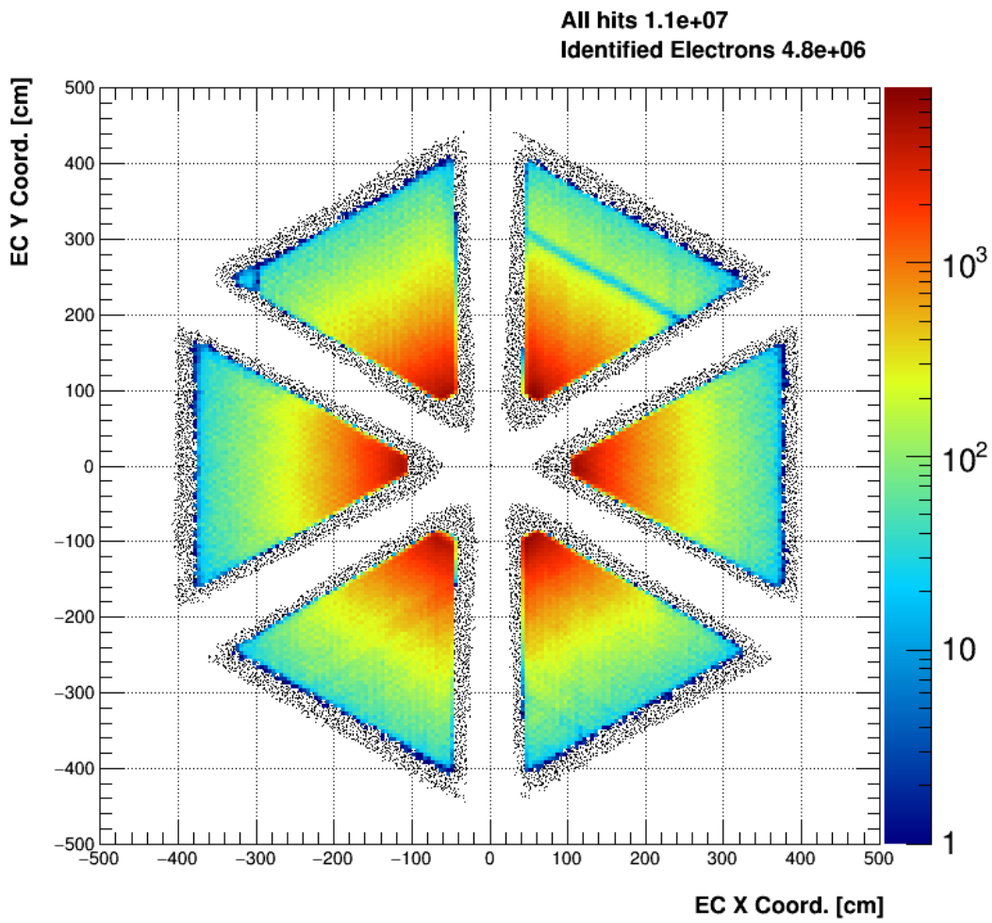

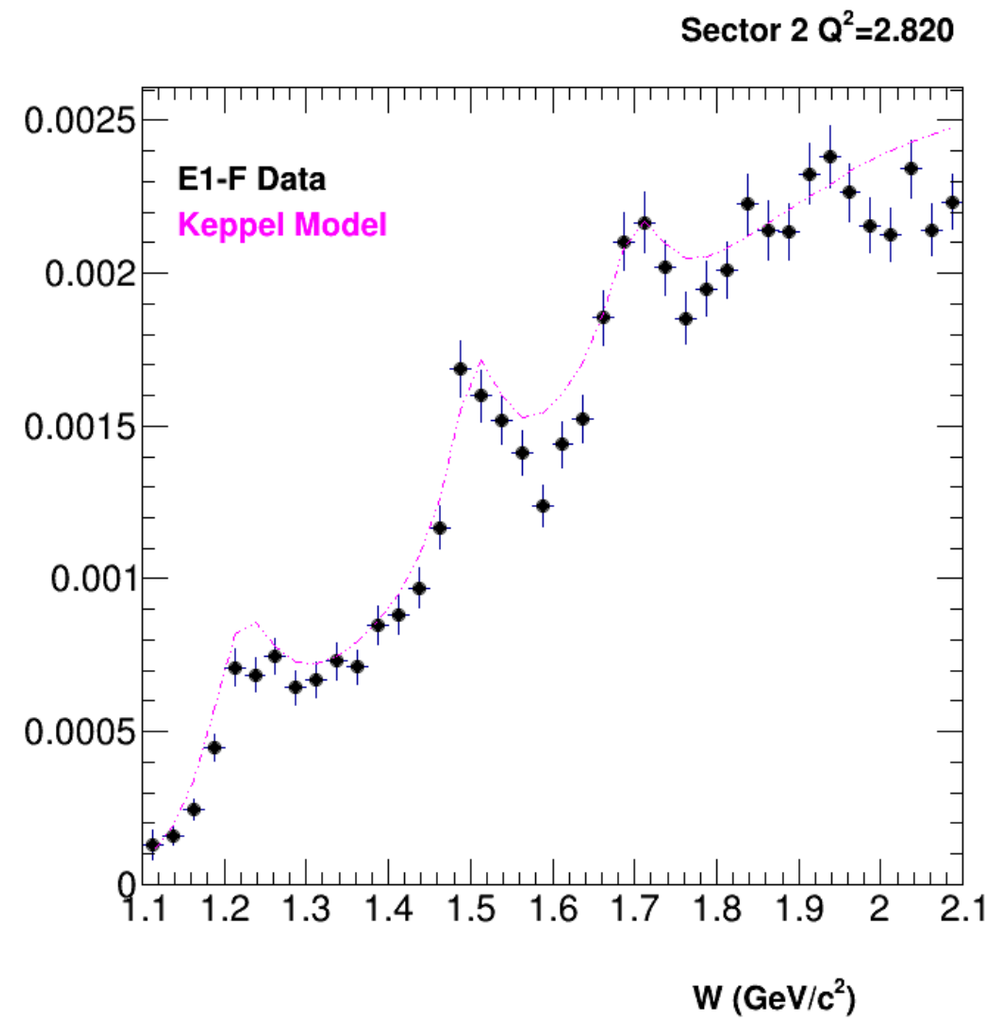

A brief overview of electron identification.

- Sampling fraction cut (momentum dependent)
- Geometrical fiducial cuts (DC, EC, CC)
- Cherenkov PMT matching cuts (theta, phi)

- EC energy deposition cut
- Z-vertex cut
- kinematic corrections done after ID.

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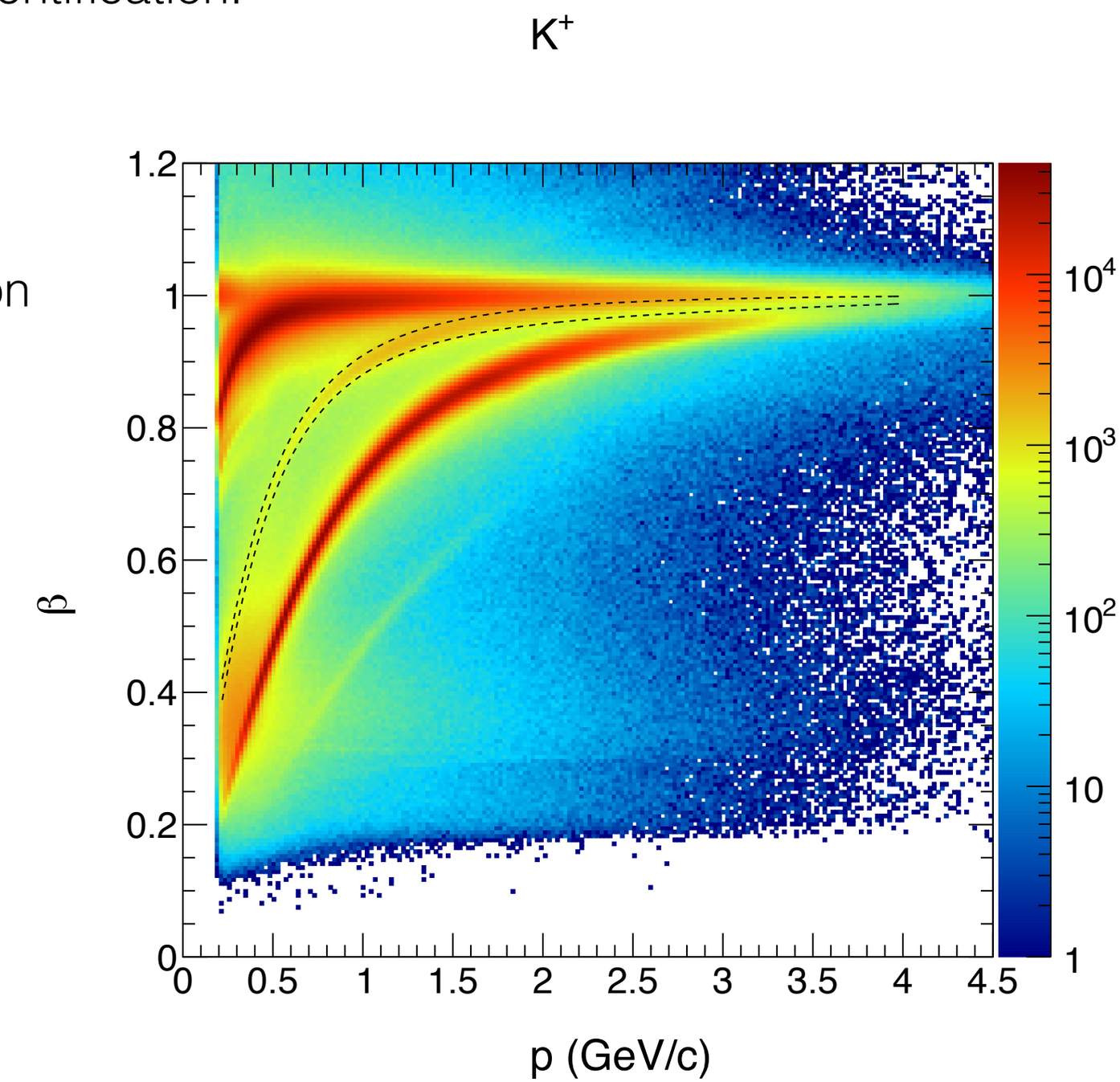
A brief overview of kaon identification.

- Drift chamber region 1 fiducial cut
- Electron vertex difference cut
- Likelihood ratio maximization condition
- Confidence level cut

$$\frac{\mathcal{L}_h}{\mathcal{L}_\pi + \mathcal{L}_K + \mathcal{L}_p}$$

Choose hadron which maximizes this ratio and then use confidence to control quality

$$\alpha = 1 - \int_{\mu-\beta_{obs}}^{\mu+\beta_{obs}} P(\beta; p, h) d\beta$$



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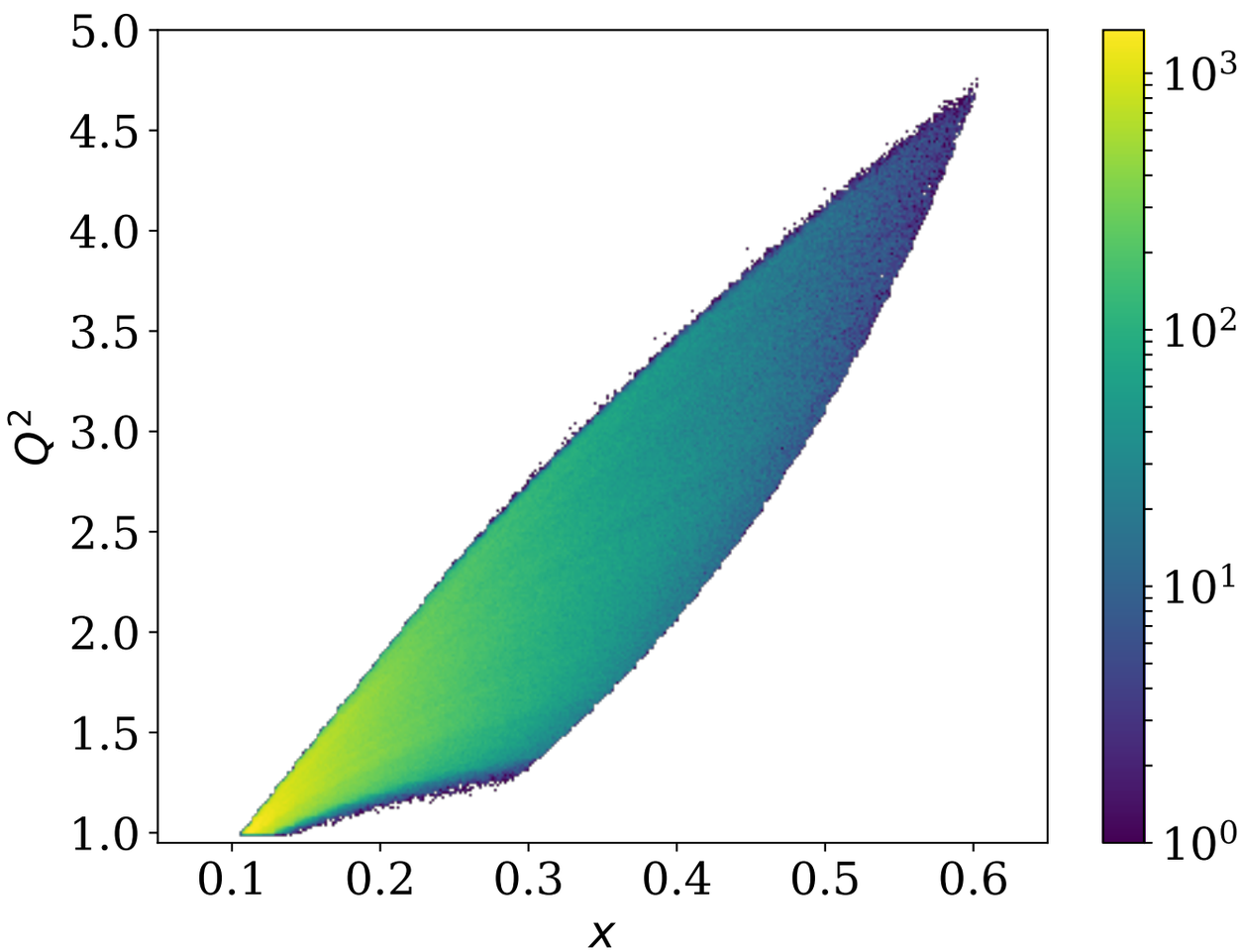
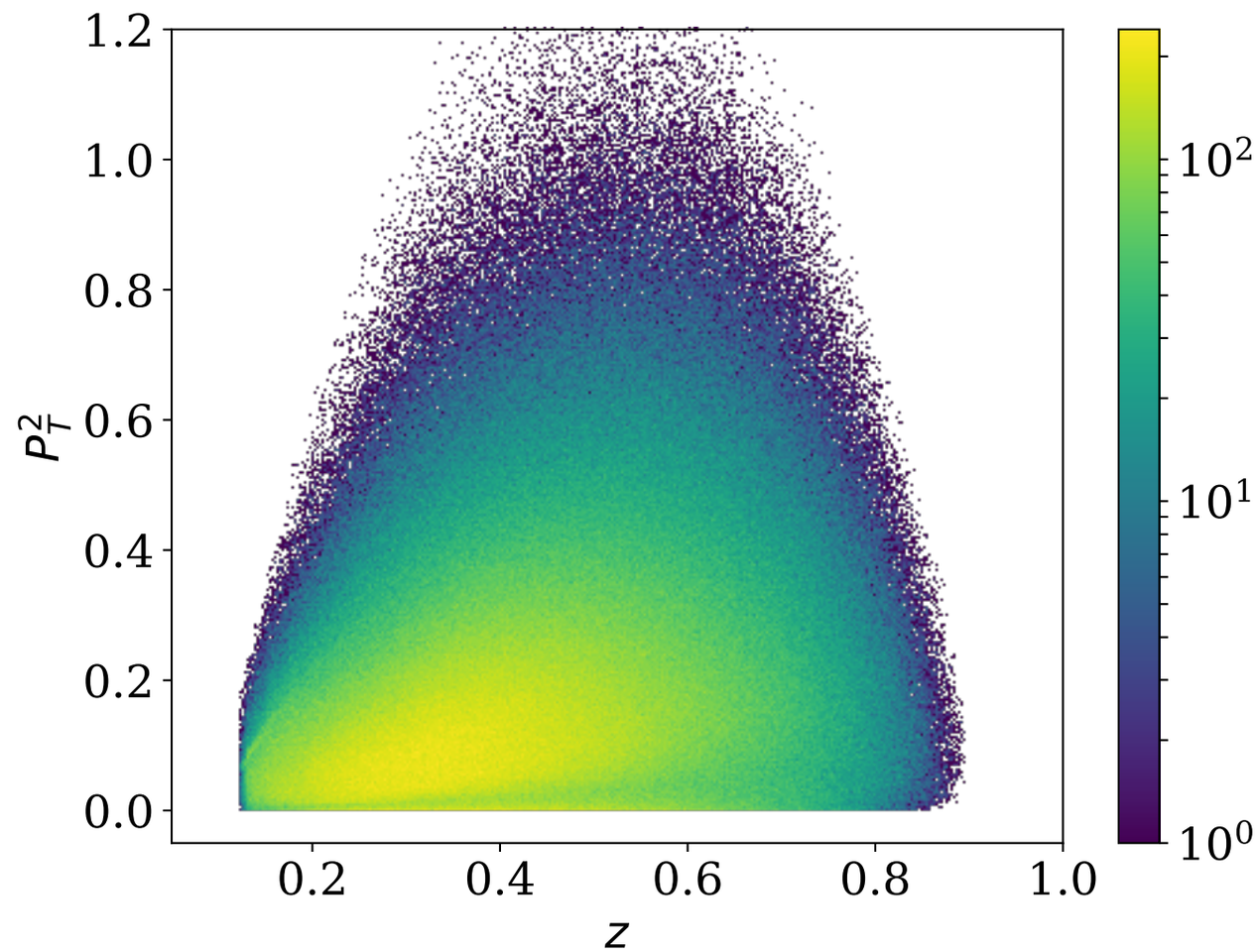
Kinematics of SIDIS Kaons





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Simple binning for 4 axes of interest
The z-range is restricted in non-z axes (0.25, 0.75).

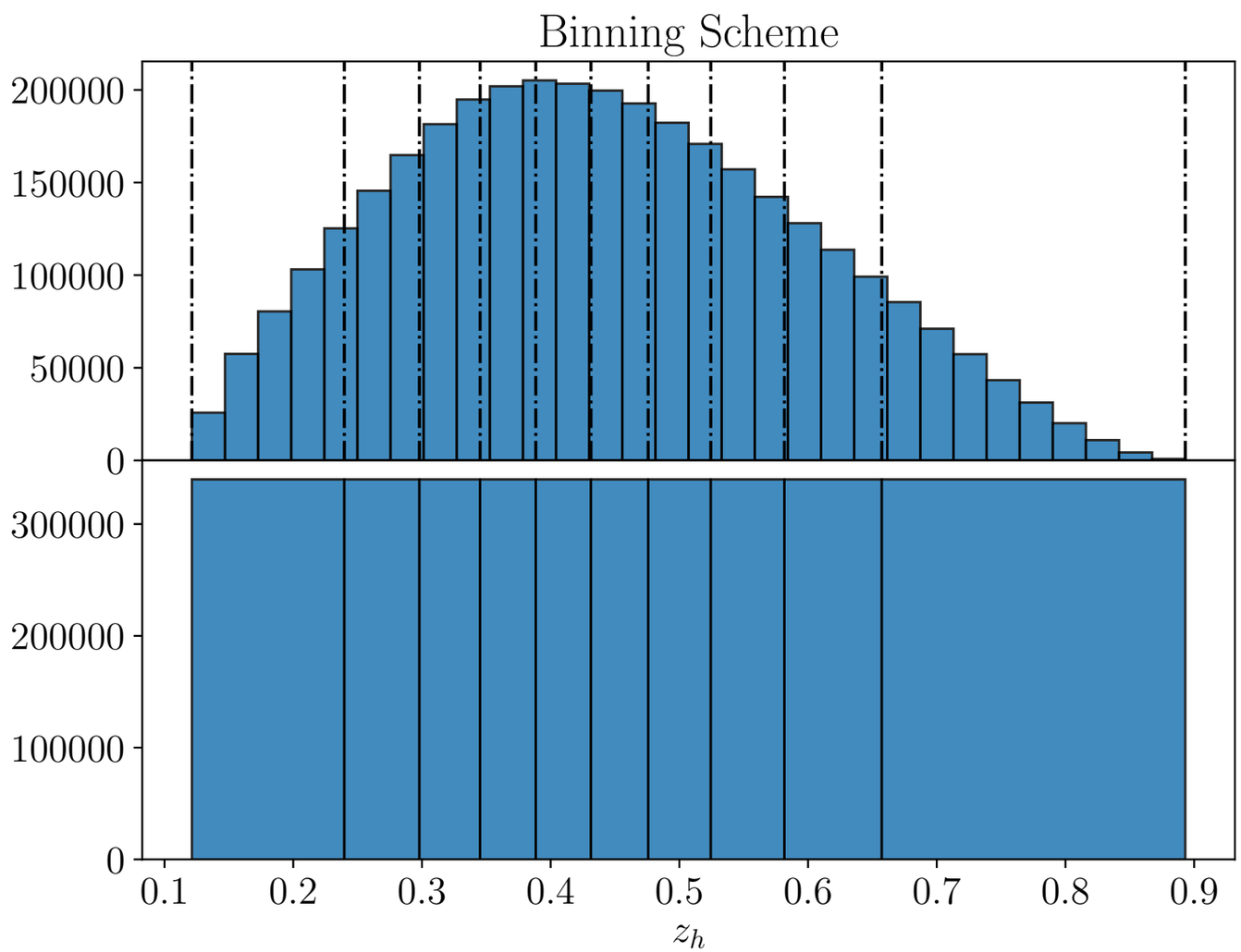

Figure: The distribution of z is shown for 30 evenly sized bins, overlaid are the 11 bin edges used to define the 10 analysis bins. In the lower figure, the counts for each of the 10 (unevenly sized) analysis bins is shown.

$$Q^2 > 1.0\ GeV^2/c^2$$

$$W > 2.0\ GeV/c^2$$

$$M_X > 1.25\ GeV/c^2$$

12 bins in phi
10 bins in other axes

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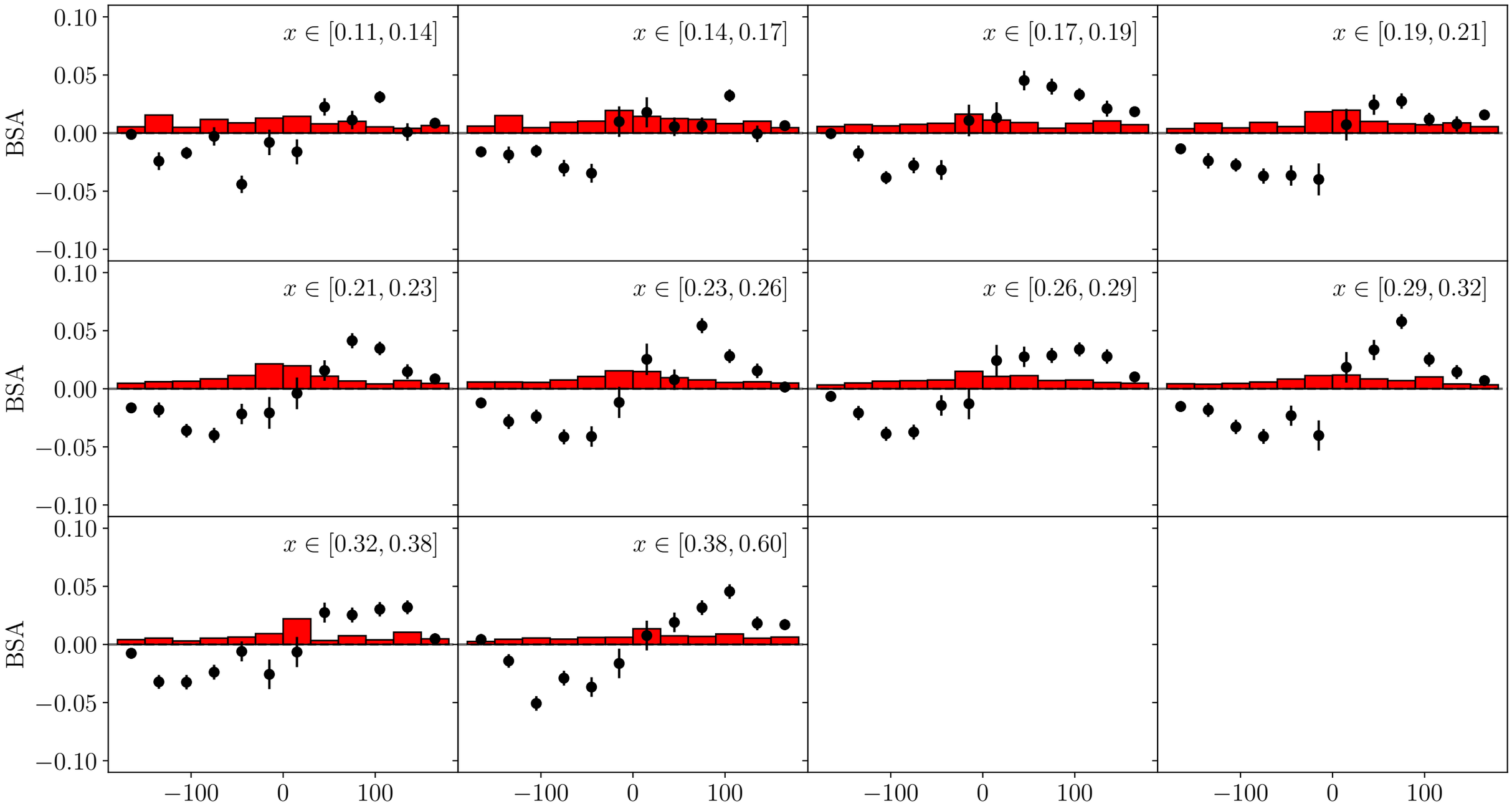
Beam spin asymmetry results with systematic uncertainties.. To be explained next



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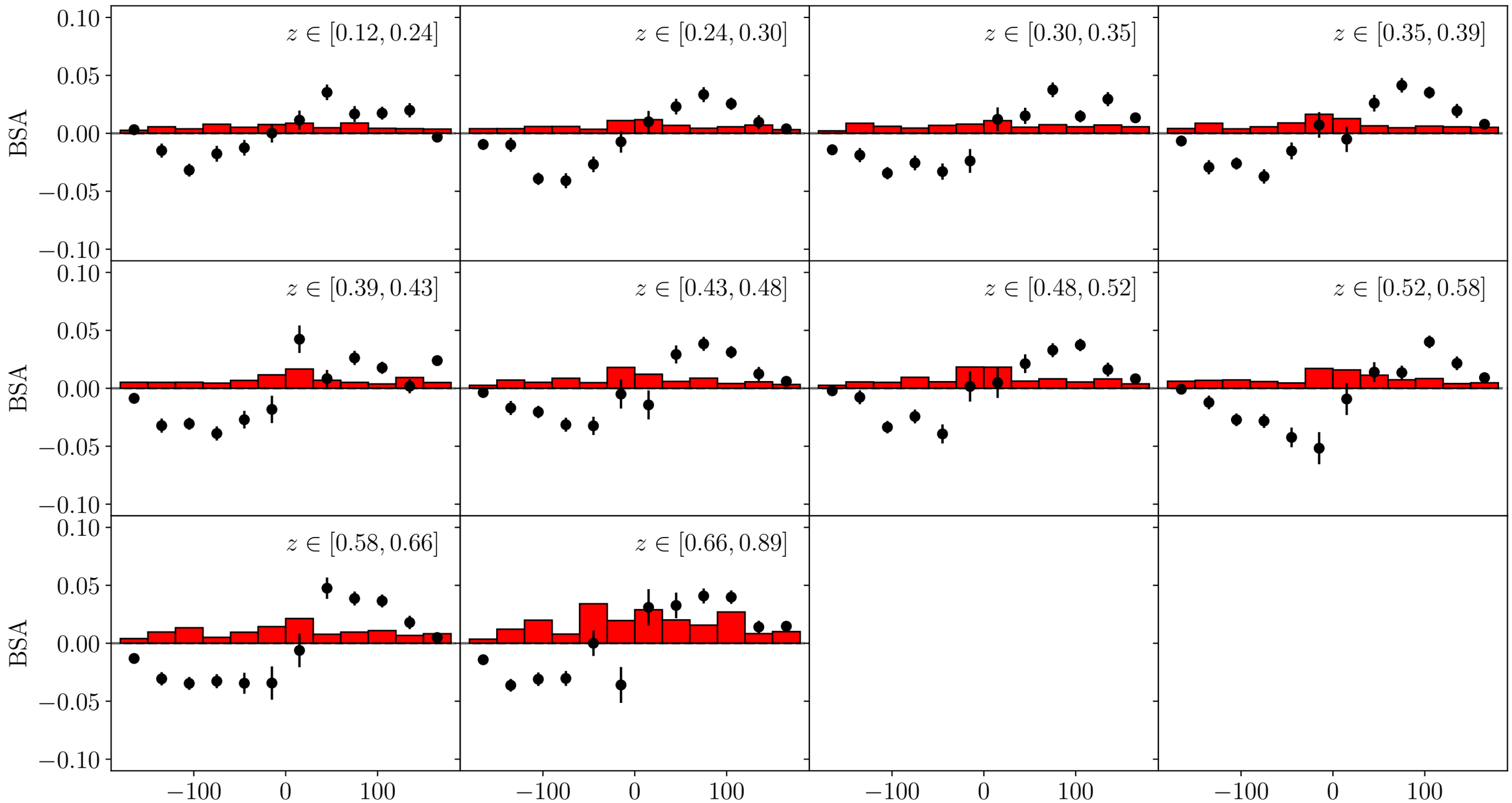
Beam spin asymmetry results with systematic uncertainties.. To be explained next



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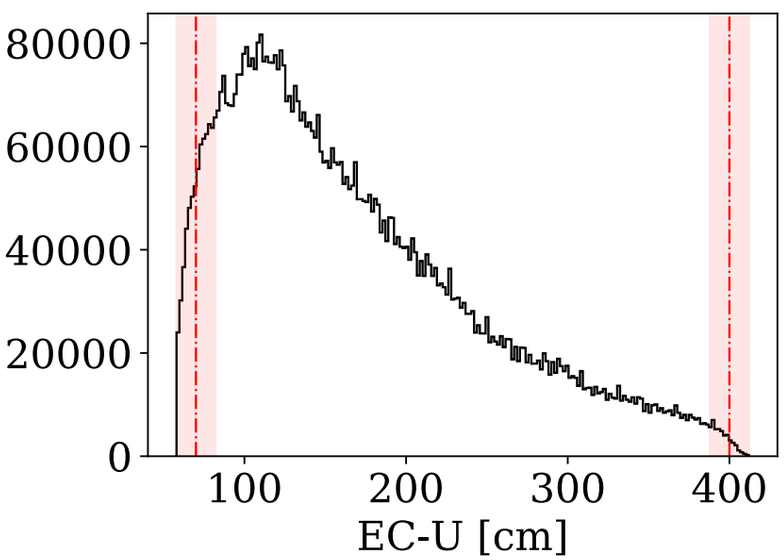
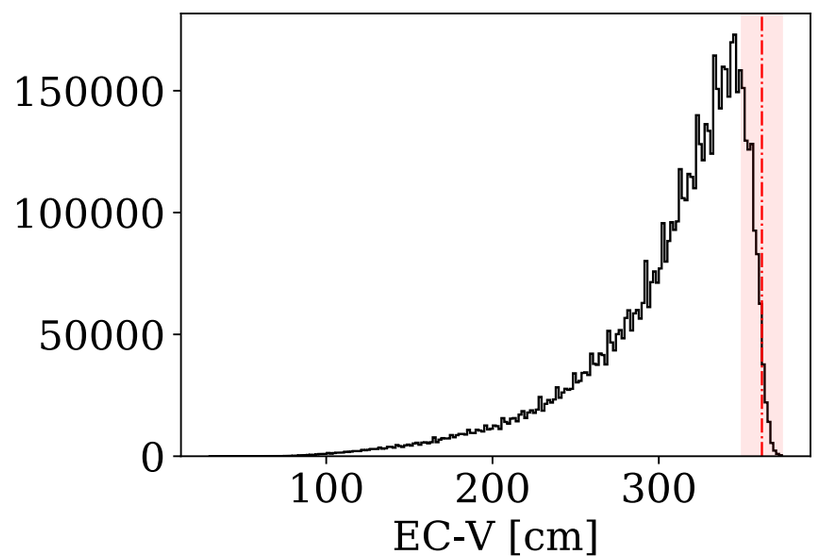
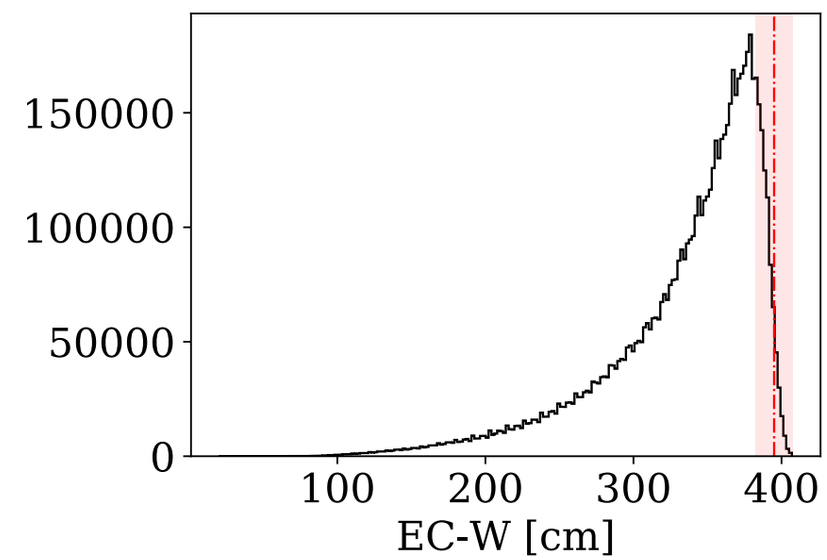
Systematic uncertainties from EC fiducial cuts







Use standard error propagation formula, but numerically obtain the dependence.

$$(\delta\mathcal{O})^2 = \sum_{i=1}^{N}\sum_{j=1}^{N}\frac{\partial\mathcal{O}}{\partial\theta_i}\frac{\partial\mathcal{O}}{\partial\theta_j}\rho_{ij}\delta\theta_i\delta\theta_j$$

Approximate the dependence using finite difference

$$(\delta\mathcal{O})^2 = \sum_{i=1}^{N}(\mathcal{O}(\theta_i + \delta\theta_i/2) - \mathcal{O}(\theta_i - \delta\theta_i/2))^2$$

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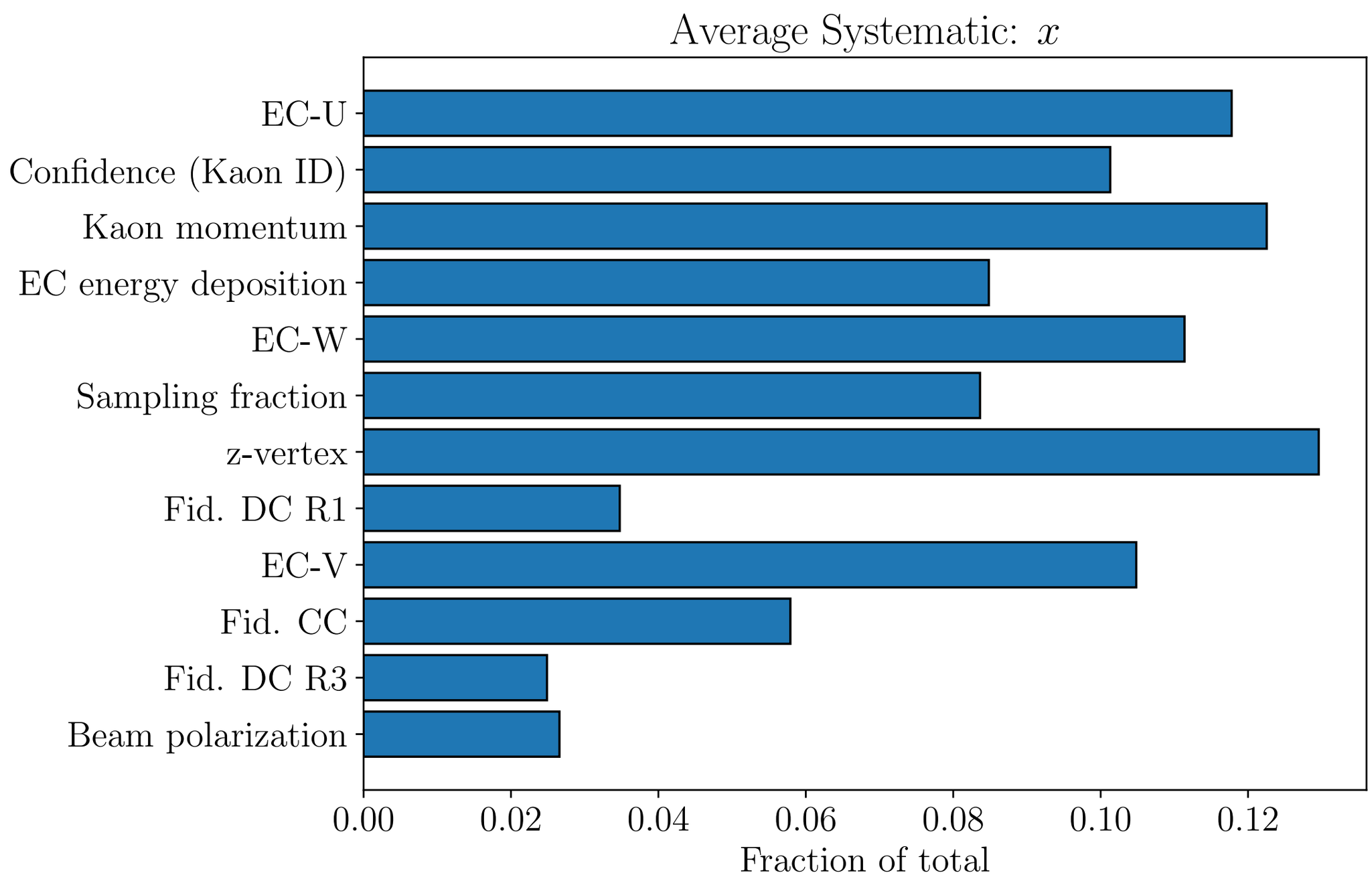

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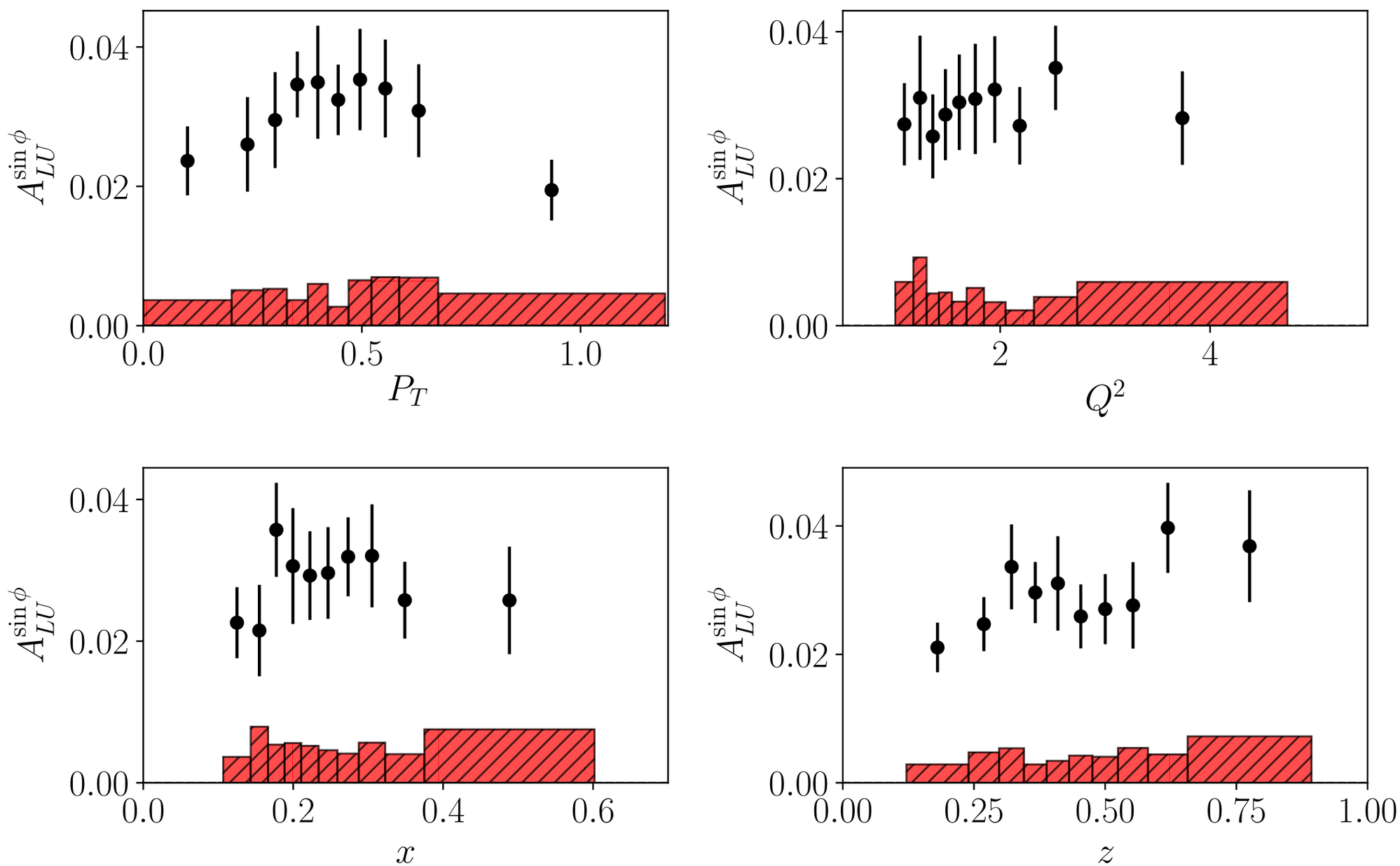

After fitting the beam spin asymmetry the sine coefficient can be extracted as a function of the kinematic variables. Systematic errors are calculated again in the same way previously described.

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Points of conclusion

- For the first time, we have measured integrated BSA for positive kaons in SIDIS.
- Our results for positively charged kaon BSA measurements in SIDIS demonstrates that twist three TMD functions are non-zero at JLab 6 GeV kinematics.
- A theoretical study is being prepared, and an analysis note is in review.

Thanks to the following people for helping with this analysis:

Kyungseon Joo, Harut Avakian, Nick Markov, Andrey Kim, Nobuo Sato,
Nathan Harrison, Kemal Tezgin, Frank Cao, and Brandon Clary

For various parts of the analysis I thank previous workers:
Wes Gohn, Marco Mirazita, Nathan Harrison

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Extra Slides

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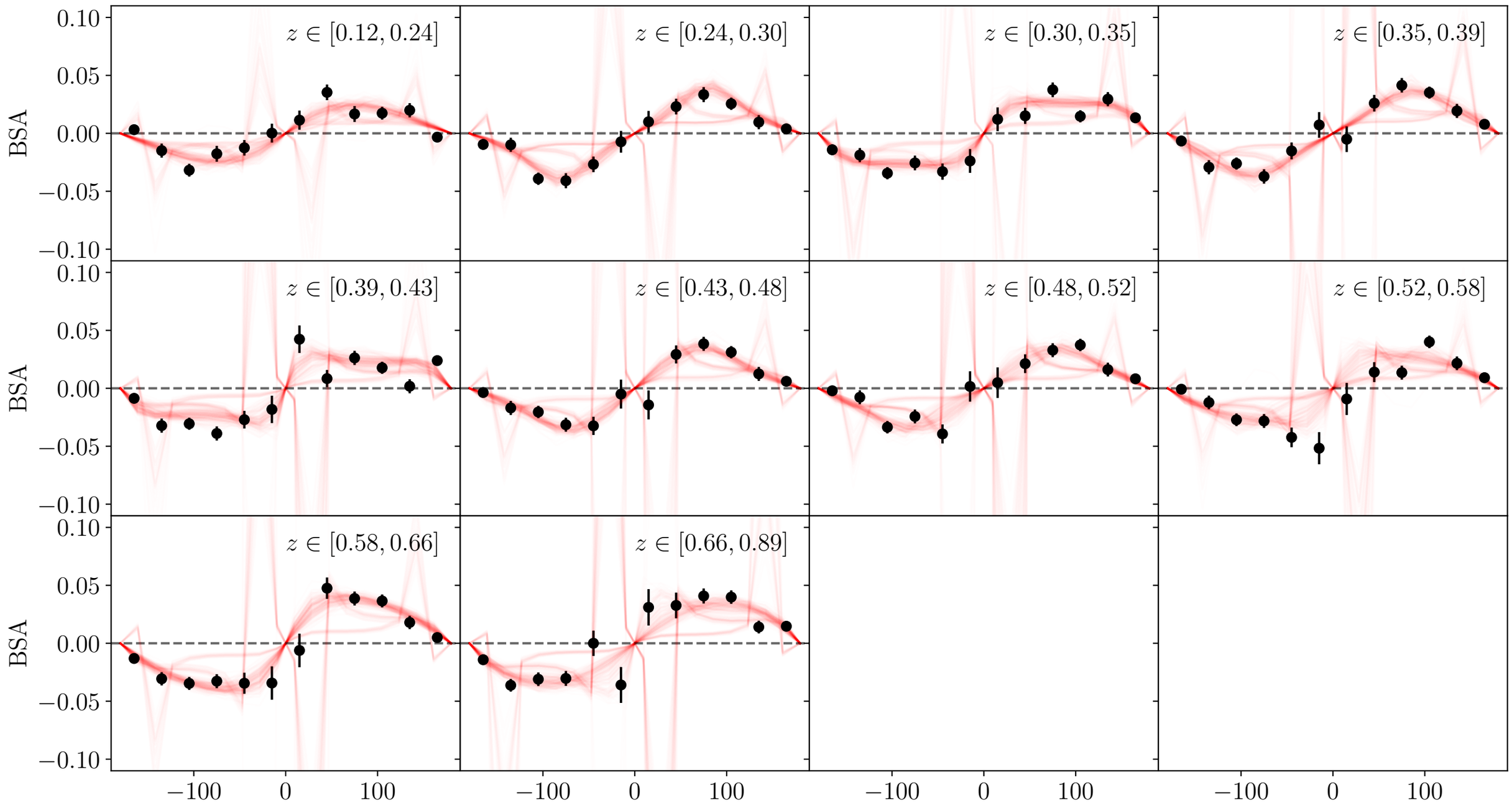

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Recall what we are measuring

$$BSA = \frac{d\sigma^+ - d\sigma^-}{d\sigma^+ + d\sigma^-} = \frac{A_{LU}^{\sin\phi}\sin\phi}{1 + A_{UU}^{\cos\phi}\cos\phi + A_{UU}^{\cos(2\phi)}\cos(2\phi)}$$

We minimize the total chi-2 (with respect to the parameters a) for each kinematic bin by gradient descent

$$\chi^2 = \sum_{i=1}^{n_\phi} \frac{(A_{obs}(\phi_i)) - A_{pred}(\phi_i, \vec{a}))^2}{\sigma_{stat}^2}$$

One would be very happy to extract all 3 moments, in some cases it may be possible.

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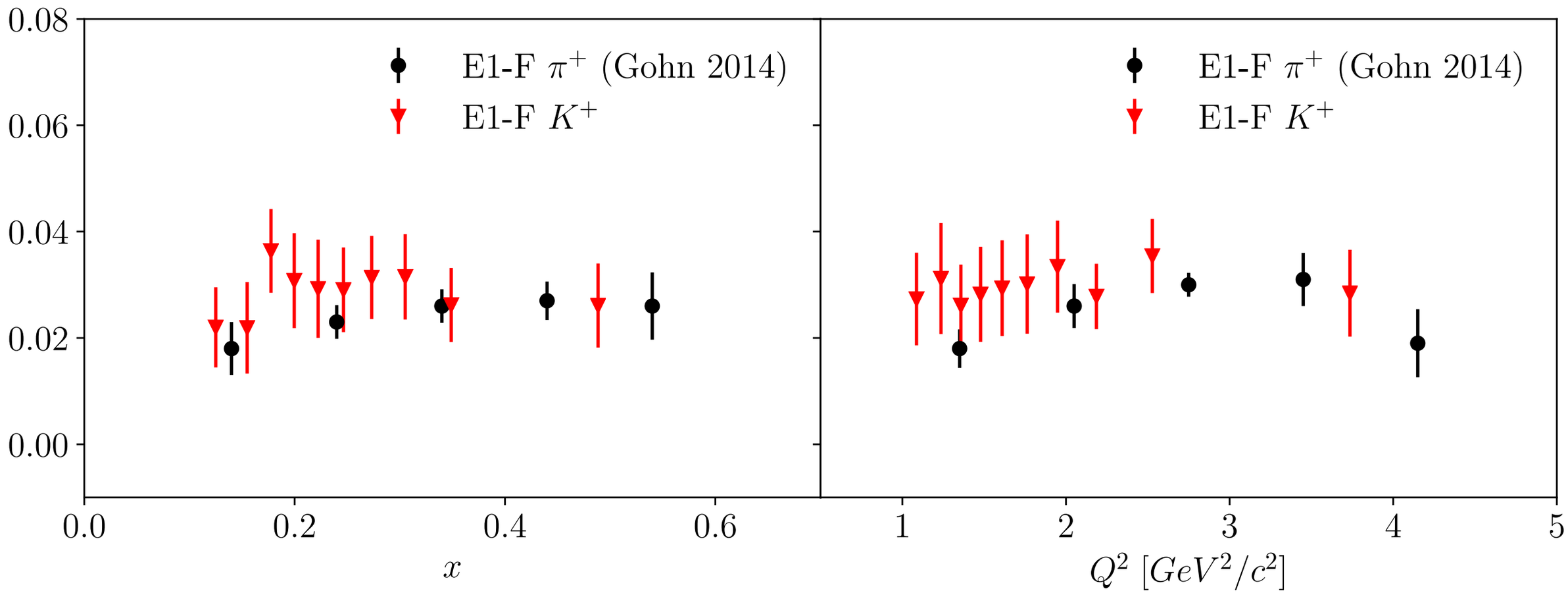

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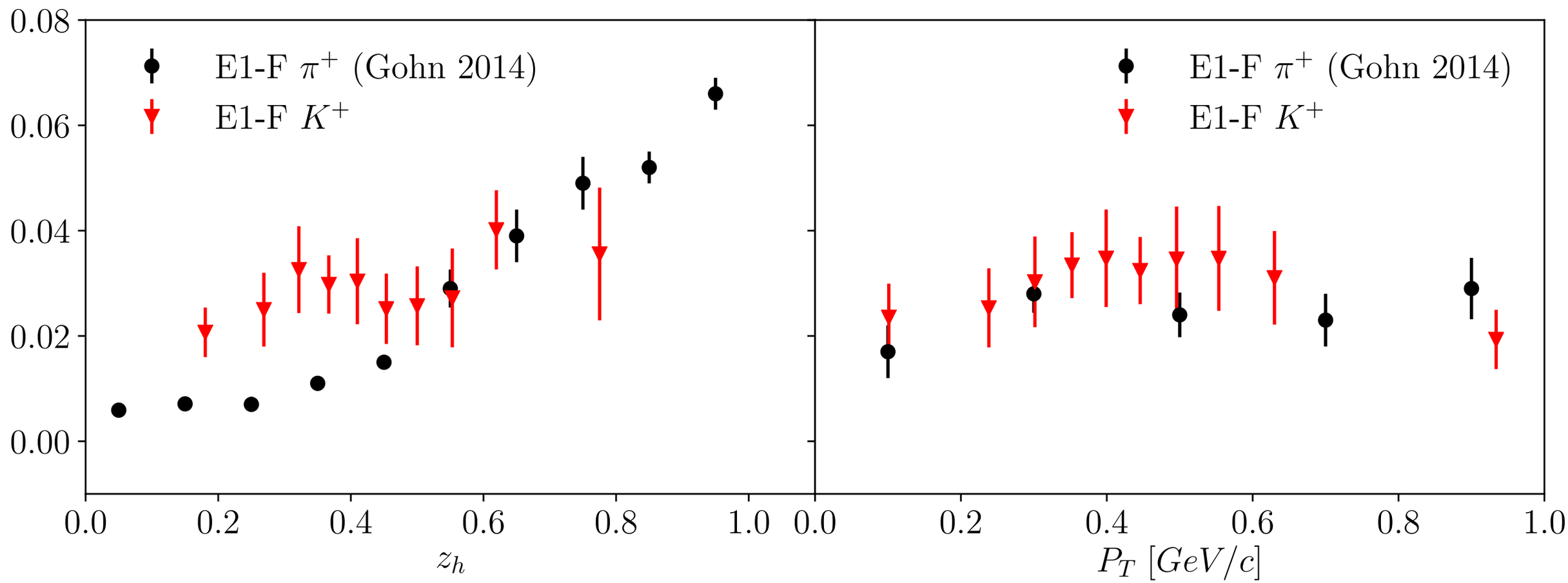

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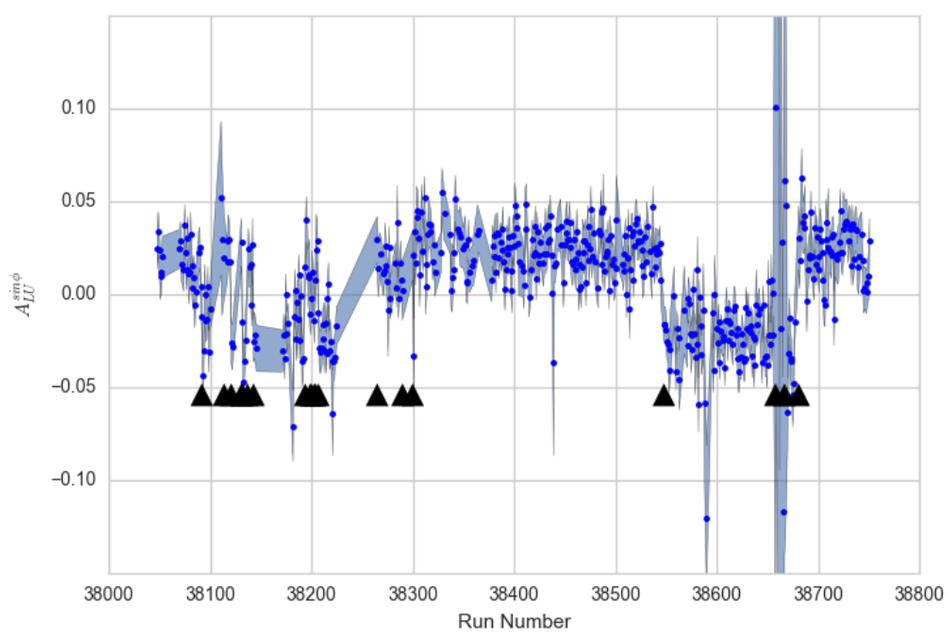
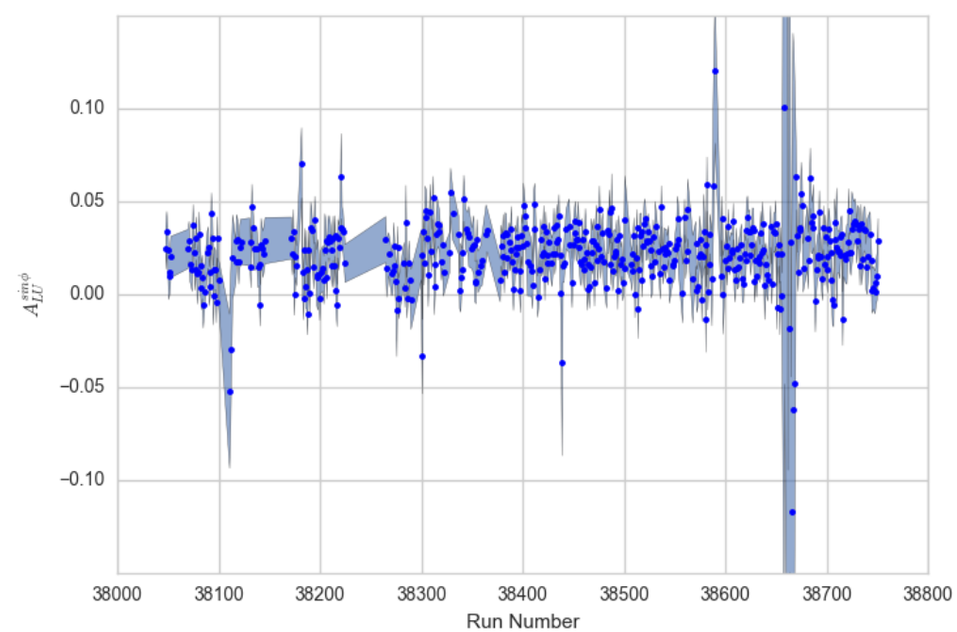
Measurement of the beam spin asymmetry is done experimentally by recording events with different electron helicity states and counting the ratio below. Helicity flipping occurs at high enough frequency that acceptance effects are expected to cancel.

$$A_{LU}^{\sin\phi} = \frac{1}{P_e}\frac{N^+ - N^-}{N^+ + N^-}$$

The **average beam polarization** was determined to be (75 +/- 3) %, and the wave-plate position was determined as a function of run number by analyzing the sine phi moment for positive pions.





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Treatment of systematic uncertainties

Analysis depends on some set of parameters, cut values, calibration values, etc.

$$\vec{\theta} = (\theta_i, \theta_2, ..., \theta_N)$$

The values of these parameters impact the outcome of the measurement of your observable. The standard formula for error propagation is,

$$(\delta\mathcal{O})^2 = \sum_{i=1}^{N}\sum_{j=1}^{N} \frac{\partial\mathcal{O}}{\partial\theta_i}\frac{\partial\mathcal{O}}{\partial\theta_j}\rho_{ij}\delta\theta_i\delta\theta_j$$

However it is not analytically possible to find in most cases the relationship between the parameter and the observable.

$$\frac{\partial(BSA)}{\partial(ECU\ Cut\ Value)} = ?$$

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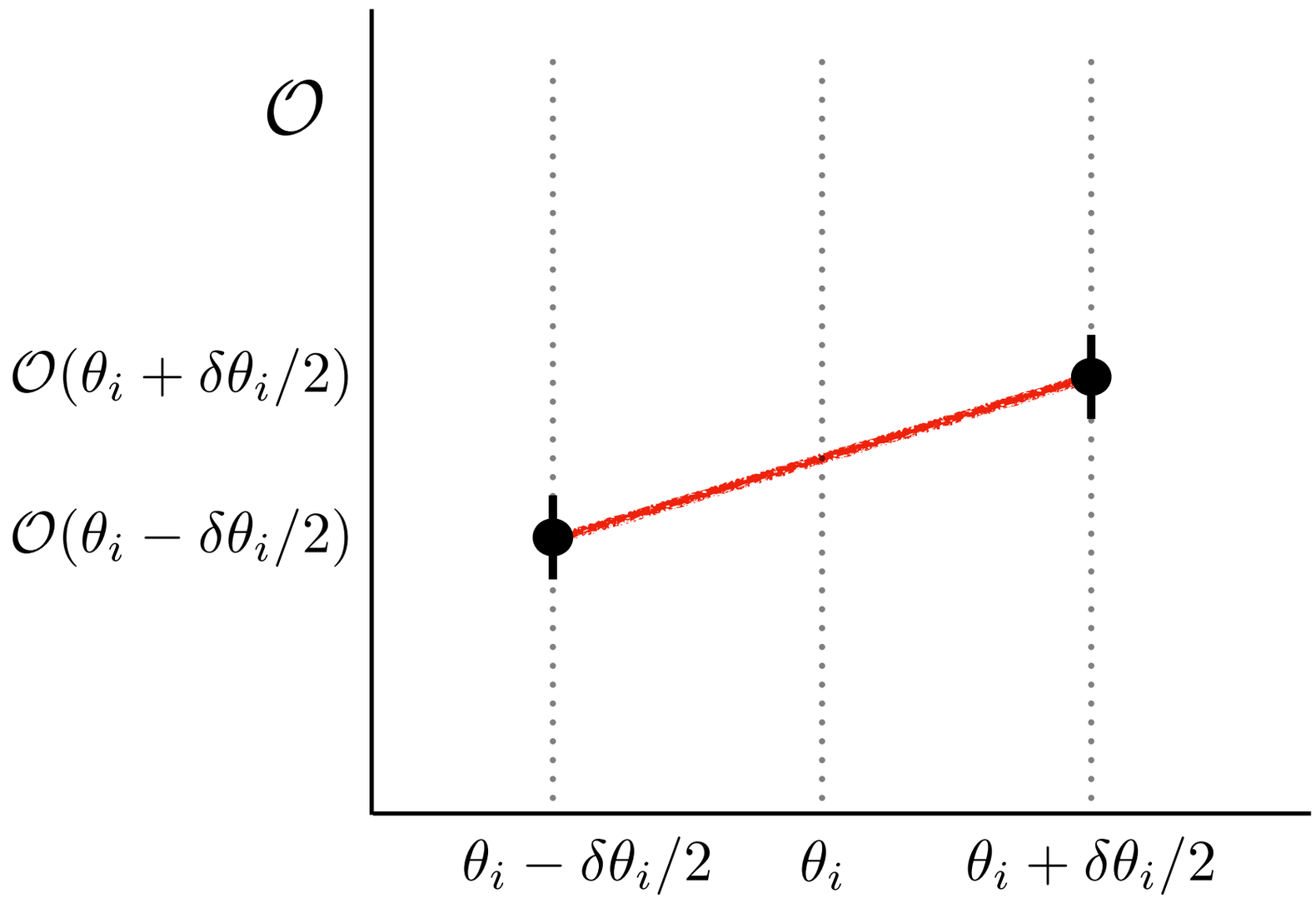
Numerically find the derivative around the nominal parameter value

$$\frac{\partial \mathcal{O}}{\partial \theta_i} \approx \frac{\mathcal{O}(\theta_i + \delta\theta_i/2) - \mathcal{O}(\theta_i - \delta\theta_i/2)}{\delta\theta_i}$$



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$$\frac{\partial \mathcal{O}}{\partial \theta_i}\frac{\partial \mathcal{O}}{\partial \theta_j}\rho_{ij}\delta\theta_i\delta\theta_j \approx (\mathcal{O}(\theta_i + \delta\theta_i/2) - \mathcal{O}(\theta_i - \delta\theta_i/2))$$
$$\times(\mathcal{O}(\theta_j + \delta\theta_j/2) - \mathcal{O}(\theta_j - \delta\theta_j/2))\rho_{ij}$$

In the case that none of the parameters are correlated, $\rho_{ij} = \delta_{ij}$

$$(\delta\mathcal{O})^2 = \sum_{i=1}^{N}(\mathcal{O}(\theta_i + \delta\theta_i/2) - \mathcal{O}(\theta_i - \delta\theta_i/2))^2$$

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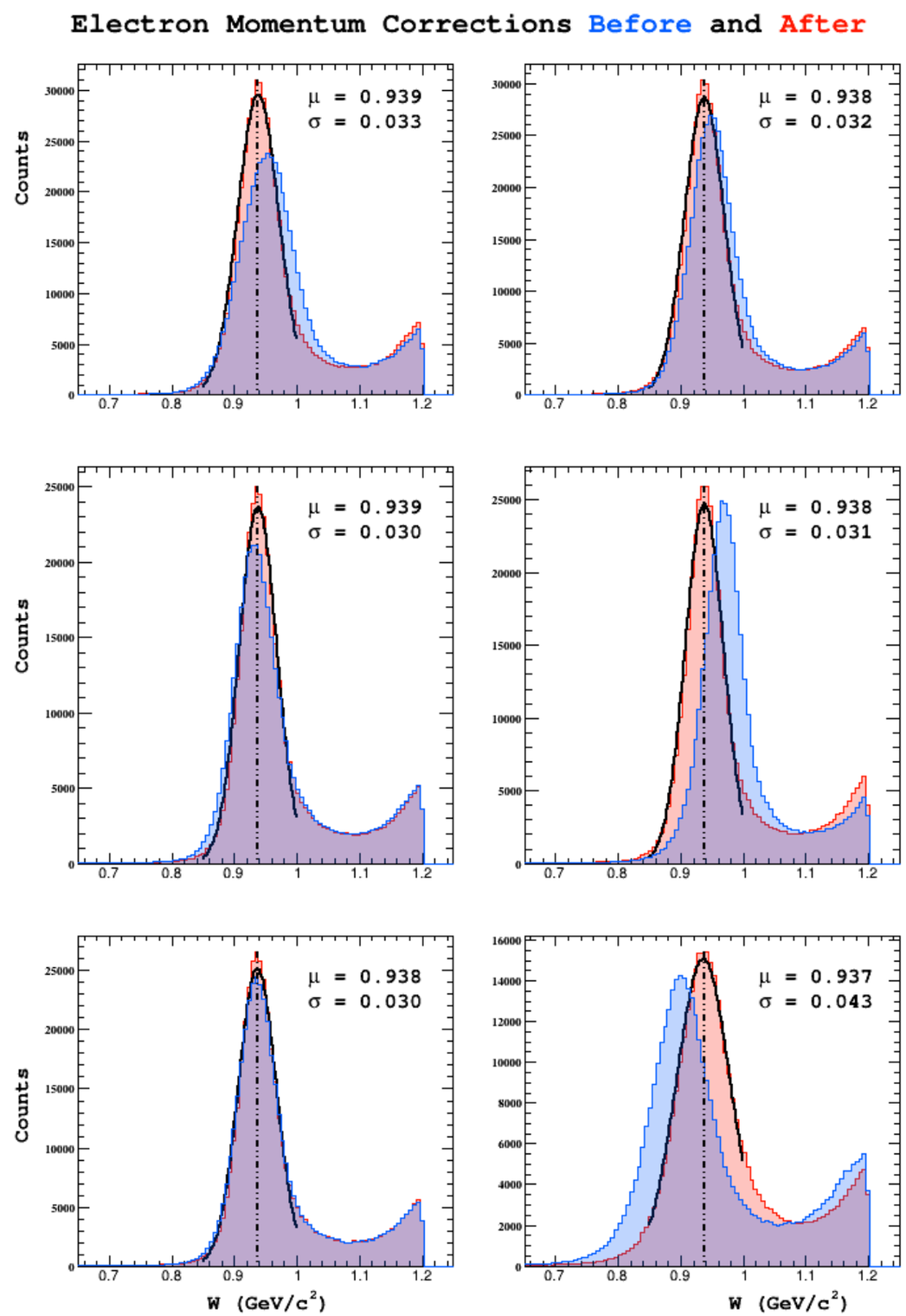

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$$C[\omega f D] = x \sum_a e_a^2 \int d^2\vec{p}_\perp d^2\vec{k}_\perp \delta^{(2)}\left(\vec{p}_\perp - \vec{k}_\perp - \vec{P}_{h\perp}/z\right) \omega(\vec{p}_\perp, \vec{k}_\perp) f^a(x, p_\perp^2) D^a(z, k_\perp^2)$$

Structure functions are generically written as convolutions of TMD PDFs and TMD Fragmentation Functions (TMD FFs), which encode information on the final state hadron.

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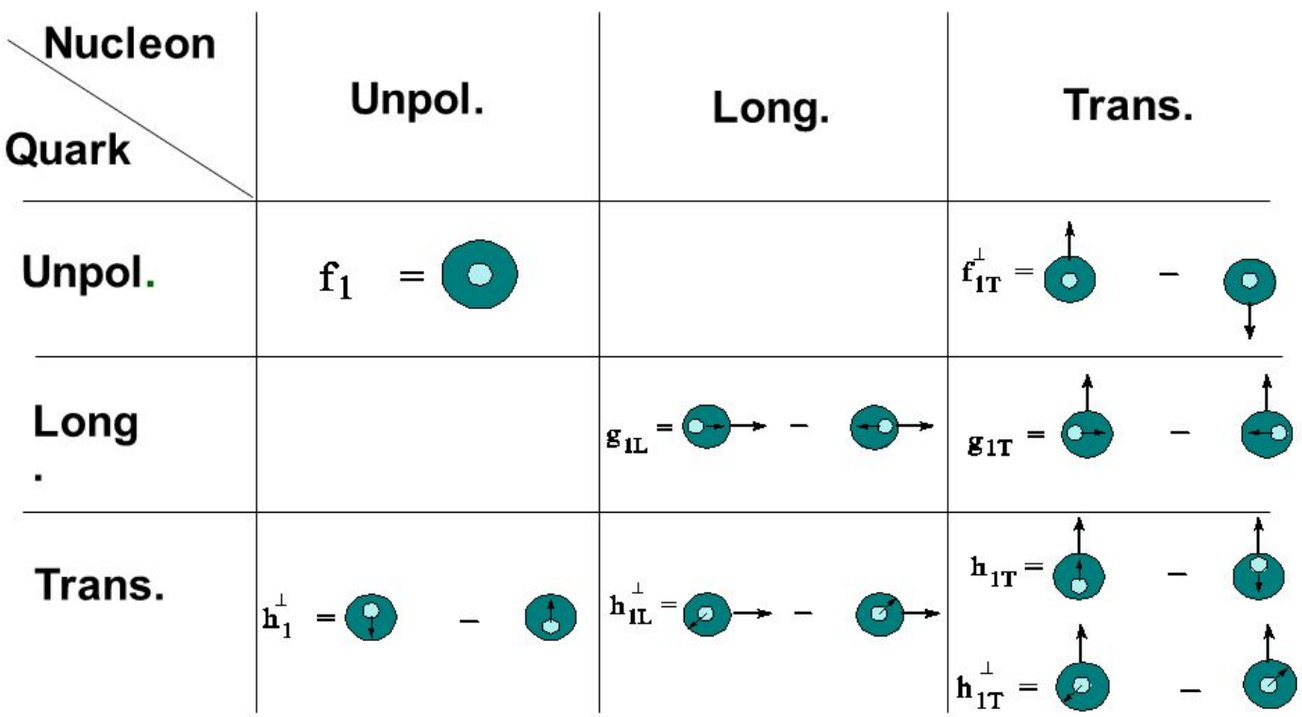
What are the quarks doing inside of the proton? How do they distribute themselves (in space and in momenta)?

"Leading-Twist" *TMD* Quark Distributions



Above: Eight leading order TMD PDFs exist, and each describes a different combination of quark/ nucleon spin.

The momentum structure of the proton can be described in terms of **transverse momentum dependent parton distribution functions** (**TMD PDF**s).

$$f(x, p_\perp^2)$$

x longitudinal momentum fraction of struck quark

$p_\perp^2$ Momentum in plane transverse to the hard momentum transfer

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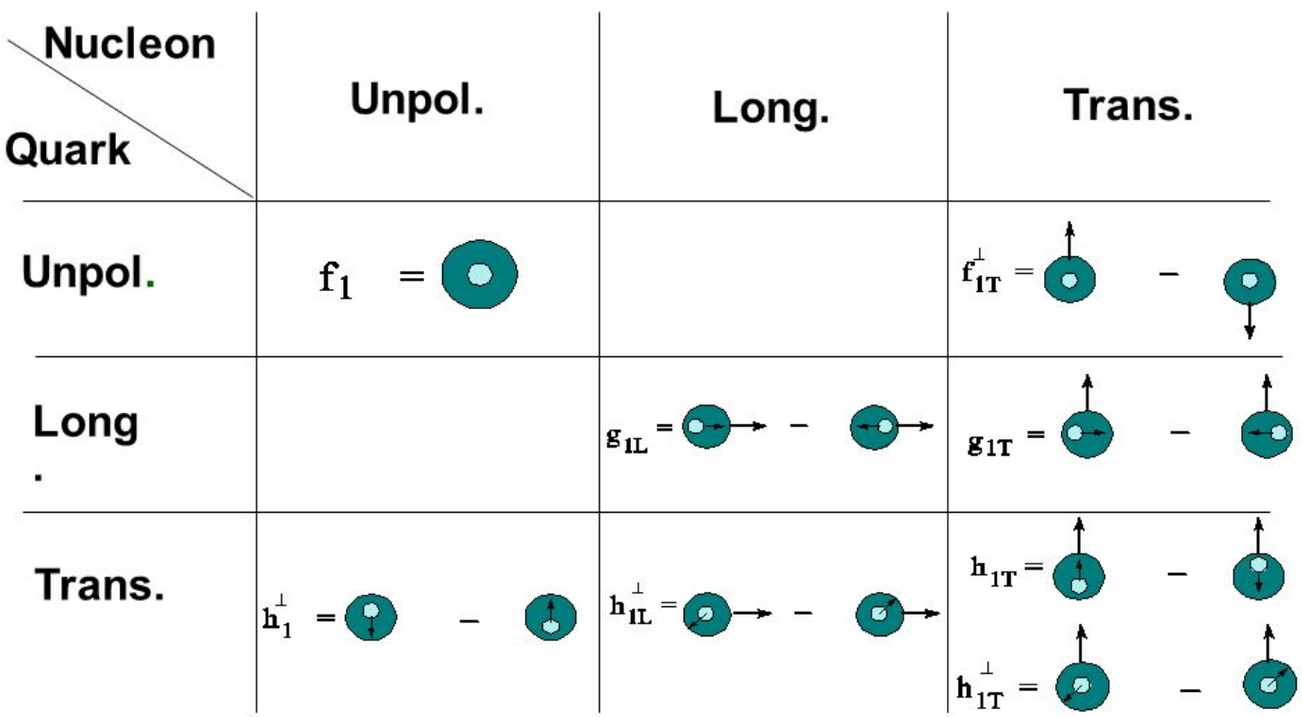
"Leading-Twist" *TMD* Quark Distributions



Many different experiments are being conducted to measure observables that can be used to extract different functions.

f_1 The unpolarized function, shows up in unpolarized SIDIS cross section.

$f_{1T}^{\perp}$ The Sivers function, shows up in single spin target asymmetries.

$h_1^{\perp}$ The Boer-Mulders, shows up in cosine modulations of unpolarized cross section, as well as beam spin asymmetries.

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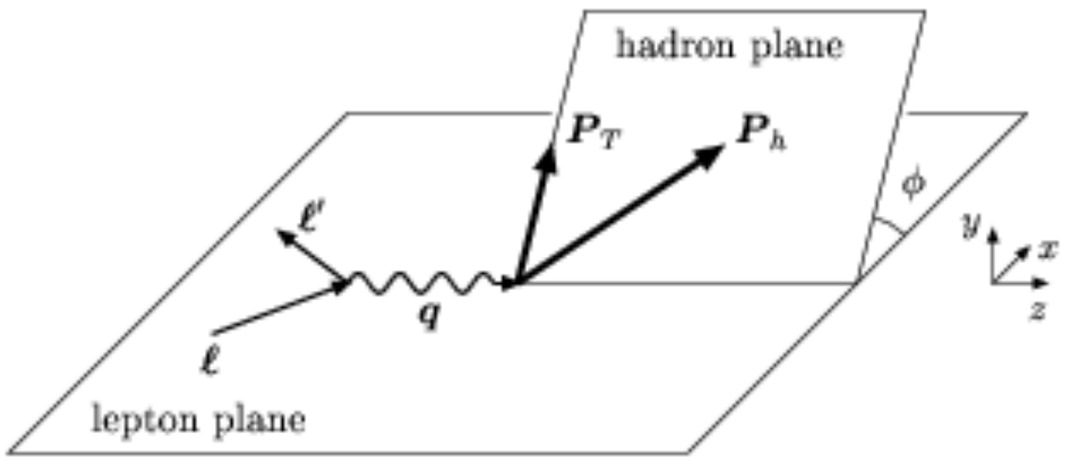
Quarks are charged and interact electromagnetically, physicists can use QED to probe the system which is bound by QCD.



Semi-Inclusive Deeply Inelastic Scattering (SIDIS) of electrons off of protons or neutrons is one example of a process described by QED that can be used to measure observables sensitive to TMDs.

$$\lambda_\gamma \ll r_p$$

Assuming one photon exchange the SIDIS cross section can be expressed in terms of model independent structure functions (these contain the TMDs)

$$\frac{d\sigma}{dx_B\, dQ^2\, dz\, d\phi_h\, dp_{h\perp}^2} = K(x,y,Q^2)\Big\{F_{UU,T} + \varepsilon F_{UU,L}$$
$$+\sqrt{2\,\varepsilon(1+\varepsilon)}\cos\phi_h F_{UU}^{\cos\phi_h} + \varepsilon\cos(2\phi_h)F_{UU}^{\cos 2\phi_h} + \lambda_e\sqrt{2\,\varepsilon(1-\varepsilon)}\sin\phi_h F_{LU}^{\sin\phi_h}\Big\}$$

(without polarized target)

Mulders, Tangerman (1995) Complete tree-level result for polarized deep-inelastic lepto-production.

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Beam Spin Asymmetry (BSA) measurements are a good tool for extracting “moments”.

$$BSA = \frac{d\sigma^+ - d\sigma^-}{d\sigma^+ + d\sigma^-} = \frac{A_{LU}^{\sin\phi}\sin\phi}{1 + A_{UU}^{\cos\phi}\cos\phi + A_{UU}^{\cos(2\phi)}\cos(2\phi)}$$

$$F_{LU}^{\sin\phi} = \frac{2M}{Q}\mathcal{C}\left(-\frac{\hat{\mathbf{h}}\cdot\mathbf{k_T}}{M_h}\left(xeH_1^\perp + \frac{M_h}{M}f_1\frac{\tilde{G}^\perp}{z}\right) + \frac{\hat{\mathbf{h}}\cdot\mathbf{p_T}}{M}\left(xg^\perp D_1 + \frac{M_h}{M}h_1^\perp\frac{\tilde{E}}{z}\right)\right)$$

twist-3 pdf

Collins FF

unpolarized dist. function

twist-3 FF

twist-3 t-odd dist. function

Boer-Mulders

twist-3 FF

This observable is particularly interesting because each of the four terms has a twist three piece, implying that if higher order TMD functions are not important the beam spin asymmetry should be zero (this statement depends on the kinematics over which the beam spin asymmetry is measured).

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