KAON SIDIS AT CLAS12

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Multi-dimensional spin asymmetries studies in Semi-Inclusive DIS processes with longitudinal polarized target.

Strangeness in hard processes 2025

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INTRODUCTION

This analysis would highlight the **impact** that the **RGC** campaign, from **CLAS12 (JLAB),** will produce in the **extraction** of **multi-dimensional longitudinal spin asymmetries**, so it will be used only the statistic of the **summer 2022** campaign with $\boldsymbol{NH_3}$ target (1/3 of the total data).

Why **Semi-Inclusive DIS**? in order to probe the **nucleon internal structure** with high resolution.

Polarized DIS gives access to the **1D (collinear) spin structure**, encoded in **Parton Distribution Functions (PDFs).**

Semi-Inclusive DIS opens the door to the **3D nucleon structure**, described by **Transverse Momentum Dependent distributions** (TMDs).

FIRST POLARIZED TARGET AT CLAS

RGC is the **first CLAS12 experiment** with a **longitudinally polarized target** ($\boldsymbol{NH_3}$ & $\boldsymbol{ND_3}$ target) at **JLab**, enabling direct access to **longitudinal spin asymmetries** measurement in uncovered multi-dimensional kinematic space.

We will consider **SIDIS** processes with a **single** K^+ in the final state in order to be sensible to **strangeness**, from collision among e^- (10.6 GeV) and a **transverse polarized fixed target** of $\boldsymbol{NH_3}$.

Spin asymmetries in **SIDIS** are **direct manifestations** of the underlying **PDFs** and **TMDs**. They appear as **polarization** (beam and/or target) **dependent modulations** in the diff. **cross-section**.

SIDIS CROSS-SECTION

$$\ell(l) + N(P) \to \ell(l') + h(P_h) + X,$$

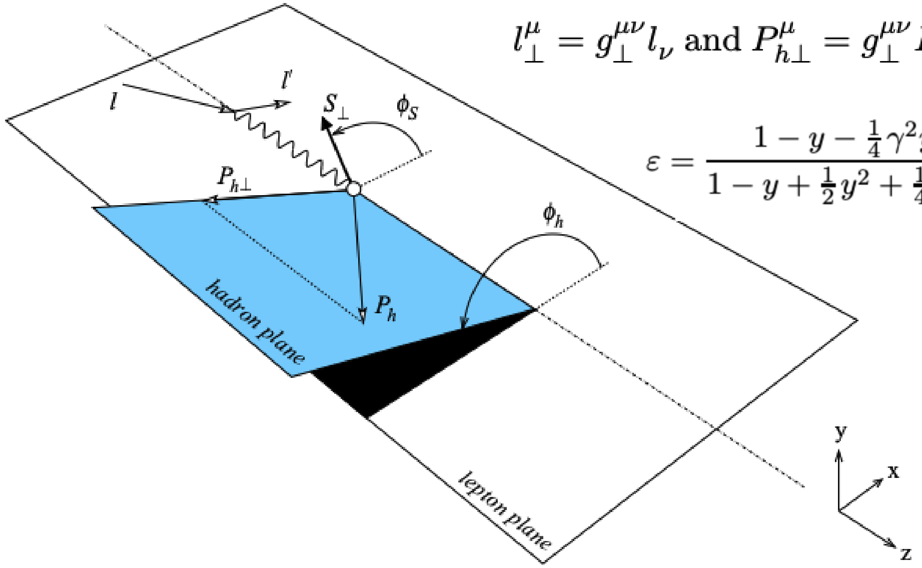
$$q = l - l'$$

$$Q^2 = -q^2$$

$$x = \frac{Q^2}{2\,P\cdot q}, \qquad y = \frac{P\cdot q}{P\cdot l}, \qquad z = \frac{P\cdot P_h}{P\cdot q}, \qquad \gamma = \frac{2Mx}{Q}.$$

$$l_\perp^\mu = g_\perp^{\mu\nu} l_\nu \text{ and } P_{h\perp}^\mu = g_\perp^{\mu\nu} P_{h\nu}$$

$$\varepsilon = \frac{1 - y - \frac{1}{4}\gamma^2 y^2}{1 - y + \frac{1}{2}y^2 + \frac{1}{4}\gamma^2 y^2},$$



$$\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} =$$
$$\frac{\alpha^2}{xyQ^2}\frac{y^2}{2\,(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Bigg\{F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{UU}^{\cos\phi_h}$$
$$+\,\varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h} + \lambda_e\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{LU}^{\sin\phi_h}$$
$$+\,S_\parallel\left[\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_h\,F_{UL}^{\sin\phi_h} + \varepsilon\sin(2\phi_h)\,F_{UL}^{\sin 2\phi_h}\right]$$
$$+\,S_\parallel\lambda_e\left[\sqrt{1-\varepsilon^2}\,F_{LL} + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_h\,F_{LL}^{\cos\phi_h}\right]$$
$$+\,|\boldsymbol{S}_\perp|\Bigg[\sin(\phi_h-\phi_S)\left(F_{UT,T}^{\sin(\phi_h-\phi_S)} + \varepsilon\,F_{UT,L}^{\sin(\phi_h-\phi_S)}\right)$$
$$+\,\varepsilon\,\sin(\phi_h+\phi_S)\,F_{UT}^{\sin(\phi_h+\phi_S)} + \varepsilon\,\sin(3\phi_h-\phi_S)\,F_{UT}^{\sin(3\phi_h-\phi_S)}$$
$$+\,\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_S\,F_{UT}^{\sin\phi_S} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin(2\phi_h-\phi_S)\,F_{UT}^{\sin(2\phi_h-\phi_S)}\Bigg]$$
$$+\,|\boldsymbol{S}_\perp|\lambda_e\Bigg[\sqrt{1-\varepsilon^2}\,\cos(\phi_h-\phi_S)\,F_{LT}^{\cos(\phi_h-\phi_S)} + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_S\,F_{LT}^{\cos\phi_S}$$
$$+\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos(2\phi_h-\phi_S)\,F_{LT}^{\cos(2\phi_h-\phi_S)}\Bigg]\Bigg\}, \qquad (2.7)$$

OUR MAIN FOCUS IS UL

Possible observables

SPIN ASYMMETRIES – FOCUS ON 'UL'

$A_{UL}^{\sin(2\phi_h)}$ is a **leading-twist** order azimuthal LSA.

- $h_{1L}^{\perp q}$ **(Worm-Gear TMD)**: Transversely polarized quarks in the longitudinally polarized nucleon.
- $H_{1L}^{\perp h}$ **Collins fragmentation function.**

Measure the formation of **quark** with **transverse spin** which then **fragment asymmetrically**. Not direct access to **transversity**, but still encloses transverse information.

$A_{UL}^{\sin(\phi_h)}$ is a **subleading-twist** order azimuthal LSA.

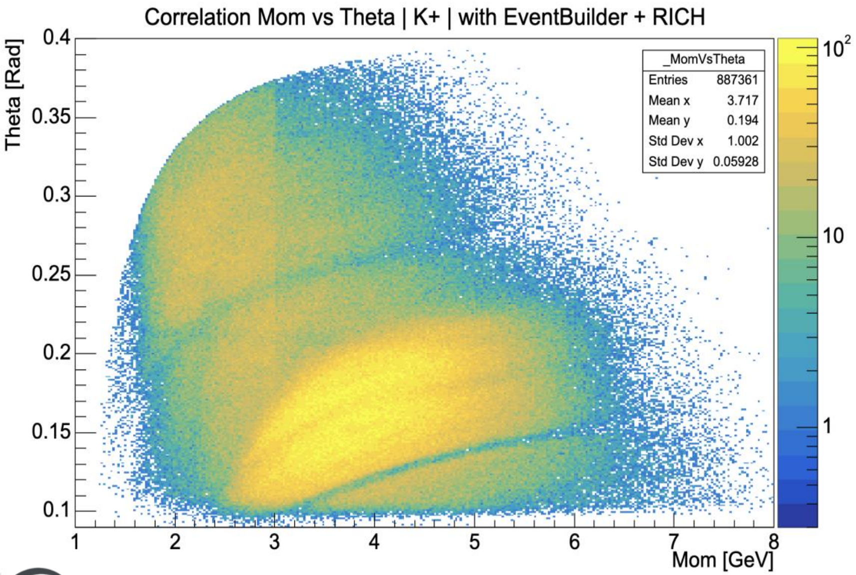
- Sensible to $f_L^{\perp}(x, k_T)$ and $h_L(x, k_T)$**:** longitudinal spin and quark transverse spin connection.

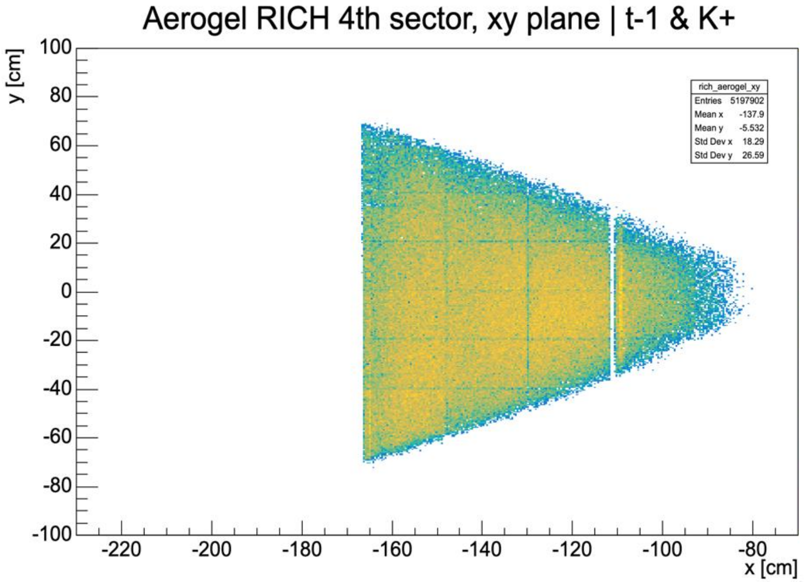
Highlight correlation among spin and angular motion of the quark thanks to its mixing with LO TSA such as Sivers and Collins .

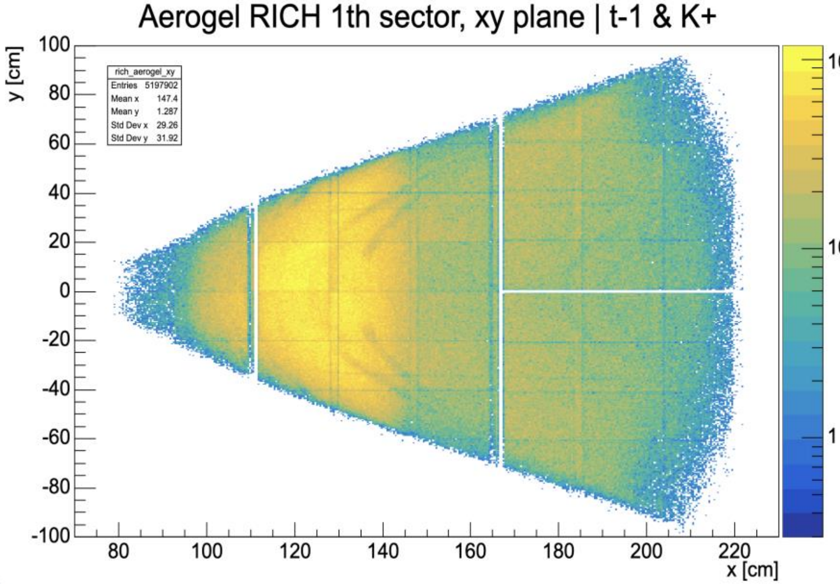
TWO RICH DETECTORS

RGC will also use two **RICH detectors** to cover **high momentum range**, up to **~7** GeV (since the ToF provide strong π/K separation until **~3** GeV).

BUT the RICH calibrations is still ongoing, this analysis is **conservative** and use a naïve handmade data selection.







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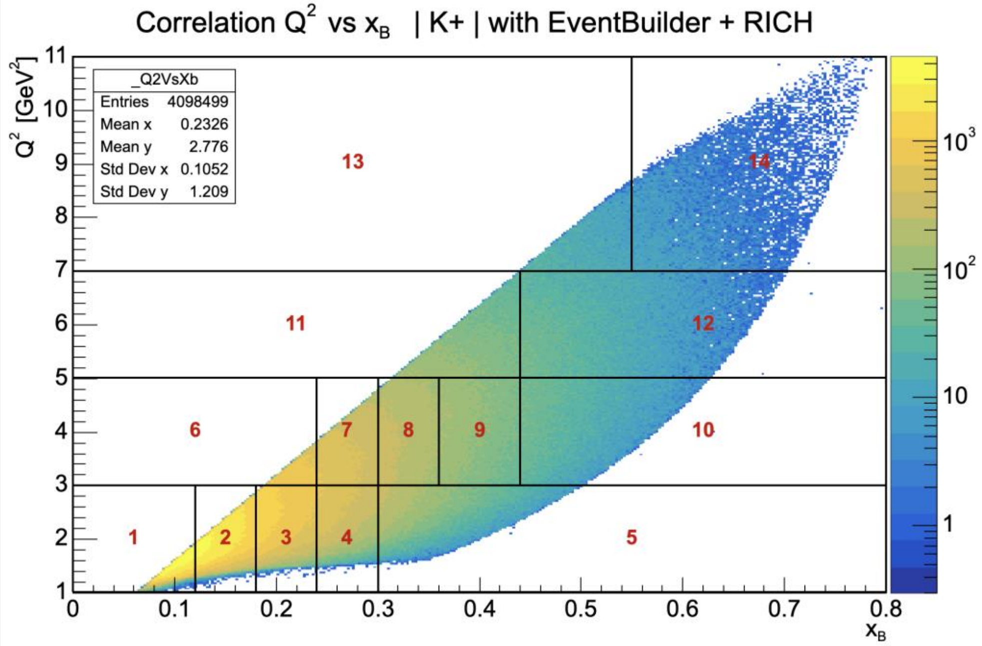
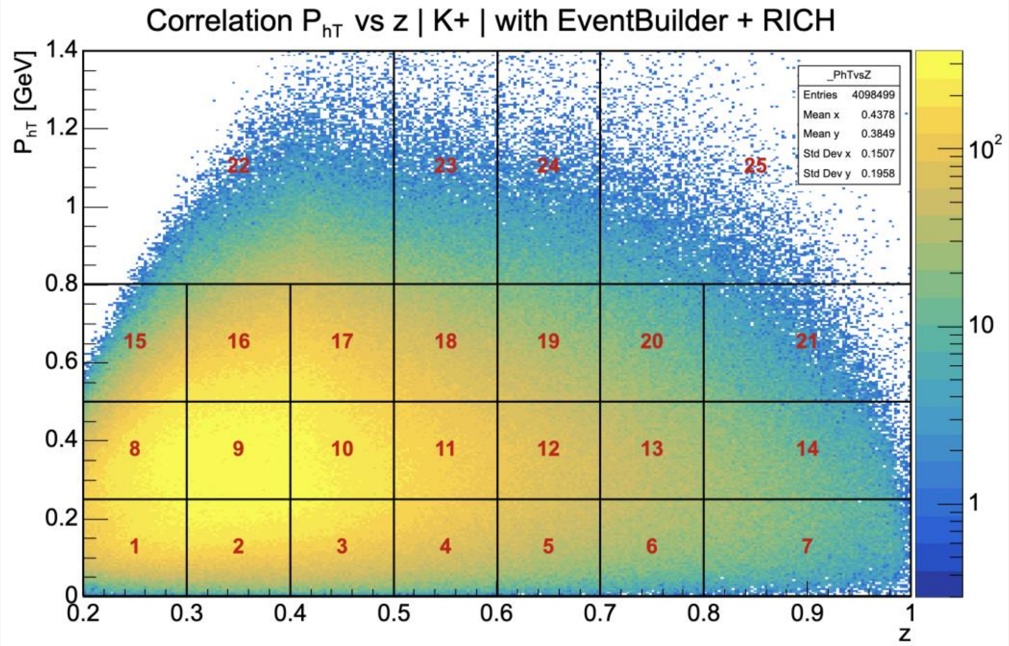
RICH coverage. Here is present ONLY the region covered by the RICH, it's not our total statistics.

KINEMATIC RANGE

CLAS12 will access **multi-dimensional** SIDIS measurement in **unexplored kinematic region** of $\boldsymbol{x_B, Q^2, z, P_{hT}}$, complementary to the ones covered by **COMPAS** and **HERMES**.





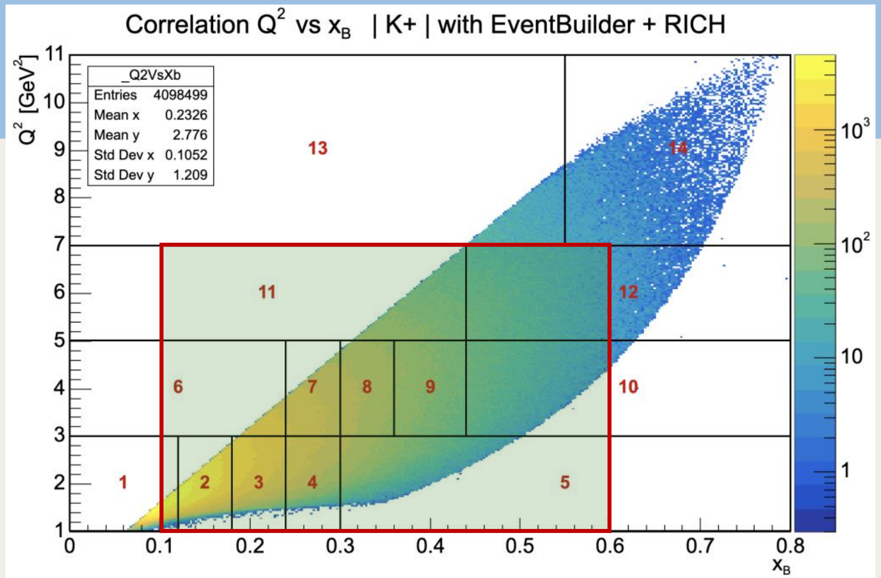
We used $z \geq 0.2$ & $y \leq 0.8$

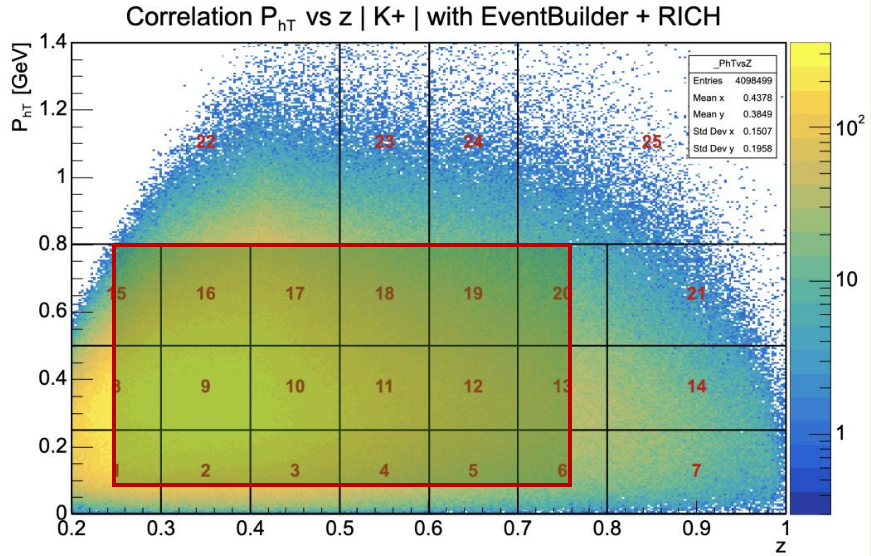
TMD REGIONS

The region that we are more interested in are the ones where **TMD calculations** can be performed, such as:

- $\mathbf{1 \leq Q^2 \leq 7}$ **GeV** $^{\mathbf{2}}$: TMDs evolution effects.
- $\mathbf{0.1 \leq x_B \leq 0.6}$: to cover the region dominated by valence quark.
- $\mathbf{0.25 \leq z \leq 0.75}$: to be ouside the fragmentation region, still avoiding exclusive and resonance effects.
- $\mathbf{0.1 \leq P_{hT} \leq 0.8}$: higher value will lead to collinear pQCD. Also, a valid TMD regime is when $P_{hT} \ll Q$.

$P_{hT}/zQ \leq 1$ is usually used





Asymmetry extraction

https://arxiv.org/pdf/1801.01488

The asymmetry extrapolation take inspiration from COMPASS measurement, we have:

$$\frac{d\sigma}{dx\,dy\,dz\,dp_T\,d\phi_h} \propto (F_{UU,T} + \varepsilon F_{UU,L}) \Bigg\{ 1 + P_L - \text{independent azimuthal asymmetries}$$
$$+ P_L\left[\sqrt{2\varepsilon(1+\varepsilon)}\, A_{UL^l}^{\sin\phi_h} \sin\phi_h + \varepsilon\, A_{UL^l}^{\sin 2\phi_h} \sin 2\phi_h - A_{UL^l}^{\sin 3\phi_h} \sin 3\phi_h\right]$$
$$+ P_L\,\lambda\left[\sqrt{1-\varepsilon^2}\, A_{LL^l} + \sqrt{2\varepsilon(1-\varepsilon)}\, A_{LL^l}^{\cos\phi_h} \cos\phi_h - A_{LL^l}^{\cos 2\phi_h} \cos 2\phi_h\right]\Bigg\}. \quad (1)$$

We use:

$$D_{UL^l,i}^{\sin\phi} = \sqrt{2\,\varepsilon_i(1+\varepsilon_i)}, \qquad D_{UL^l,i}^{\sin 2\phi} = \varepsilon_i, \qquad D_{LL^l,i} = \sqrt{1-\varepsilon_i^2}, \qquad D_{LL^l,i}^{\cos\phi} = \sqrt{2\varepsilon_i(1-\varepsilon_i)}.$$

$$M_{UL}(i) = D_{UL,i}^{\sin\phi,i}\; A_{UL}^{\sin\phi}(i)\; \sin\phi_{h,i} + D_{UL,i}^{\sin 2\phi,i}\; A_{UL}^{\sin 2\phi}(i)\; \sin(2\phi_{h,i}) - A_{UL}^{\sin 3\phi}\; \sin(3\phi_{h,i}).$$

$$M_{LL}(i) = D_{LL,i}\; A_{LL}(i) + D_{LL,i}^{\cos\phi}\; A_{LL}^{\cos\phi}(i) \cos\phi_{h,i} - D_{LL,i}^{\cos 2\phi}\; A_{LL}^{\cos 2\phi} \cos(2\phi_{h,i}).$$

P_L indip. az. as. are not considered at the moment in our MLE

ASYMMETRY EXTRACTION

The spin-dependent part of the cross-section used for our **likelihood** is:

$$S_i = D_t P_L^i [M_{UL}(i) + \lambda_i M_{LL}(i)]$$

Here $\lambda_i = \pm 1$ is the beam helicity factor, P_L^i is the target polarization and D_t is the target dilution.

We also have to apply a **luminosity correction** since the ratio among the two spin states is not the same, and after defining $r = N_+/N_-$ to suppress the bias, we can express our probability as:

$$p_i = \begin{cases} \dfrac{r(1+S_i)}{r(1+S_i)+(1-S_i)} & \text{If spin} = +1 \\ 1 - p_i & \text{If spin} = -1 \end{cases}$$

$$L = \prod_i p_i \implies -logL = -\sum_i logp_i$$

Asymmetry Extraction

We perform a $\boldsymbol{\chi^2}$**-minimization** method in the **maximum-likelihood calculation** in order to cancel out the **detector acceptance** during the extrapolation (see: https://clas12-docdb.jlab.org/cgi-bin/DocDB/private/ShowDocument?docid=1176 by T. Hayward).

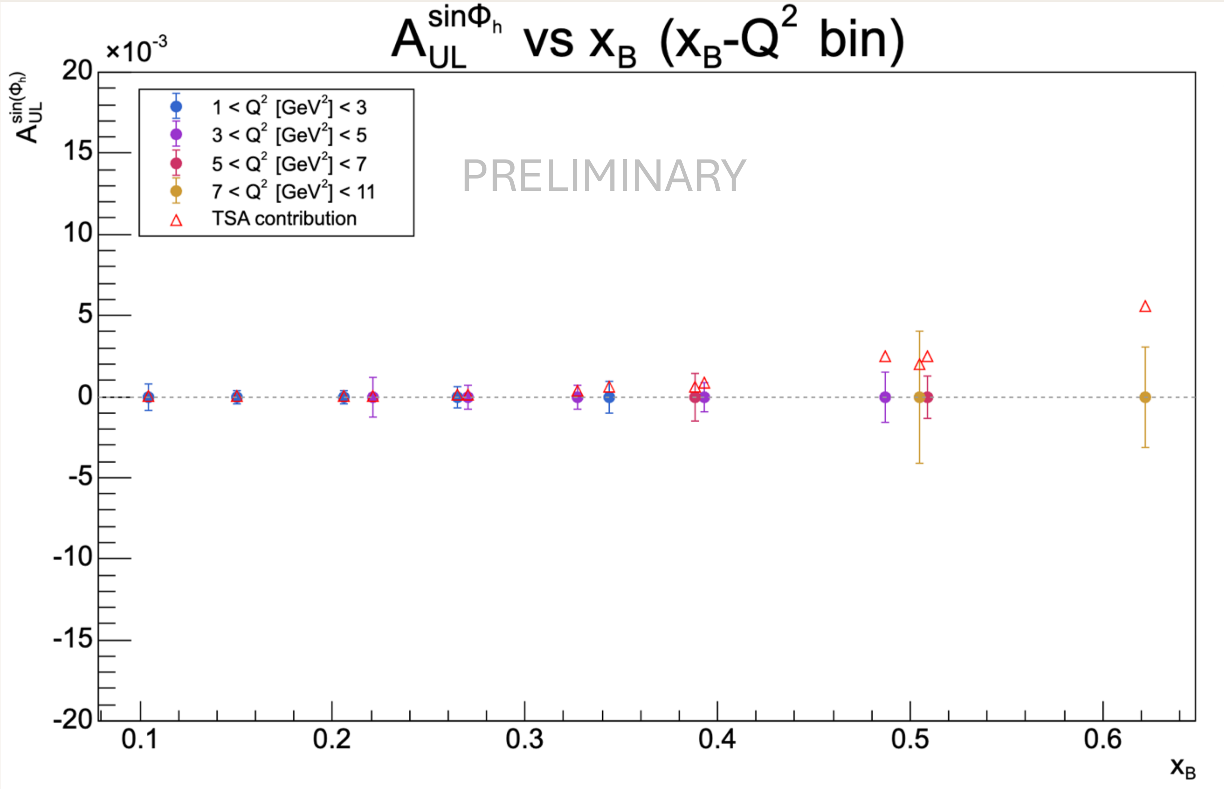
We also have to consider the **Longitudinal-Transverse corrections**, since the theory is defined along the γ-axis, while the lab. system is along the lepton frame. This **projection** allow for the **leakage of TSA into measured LSA**.

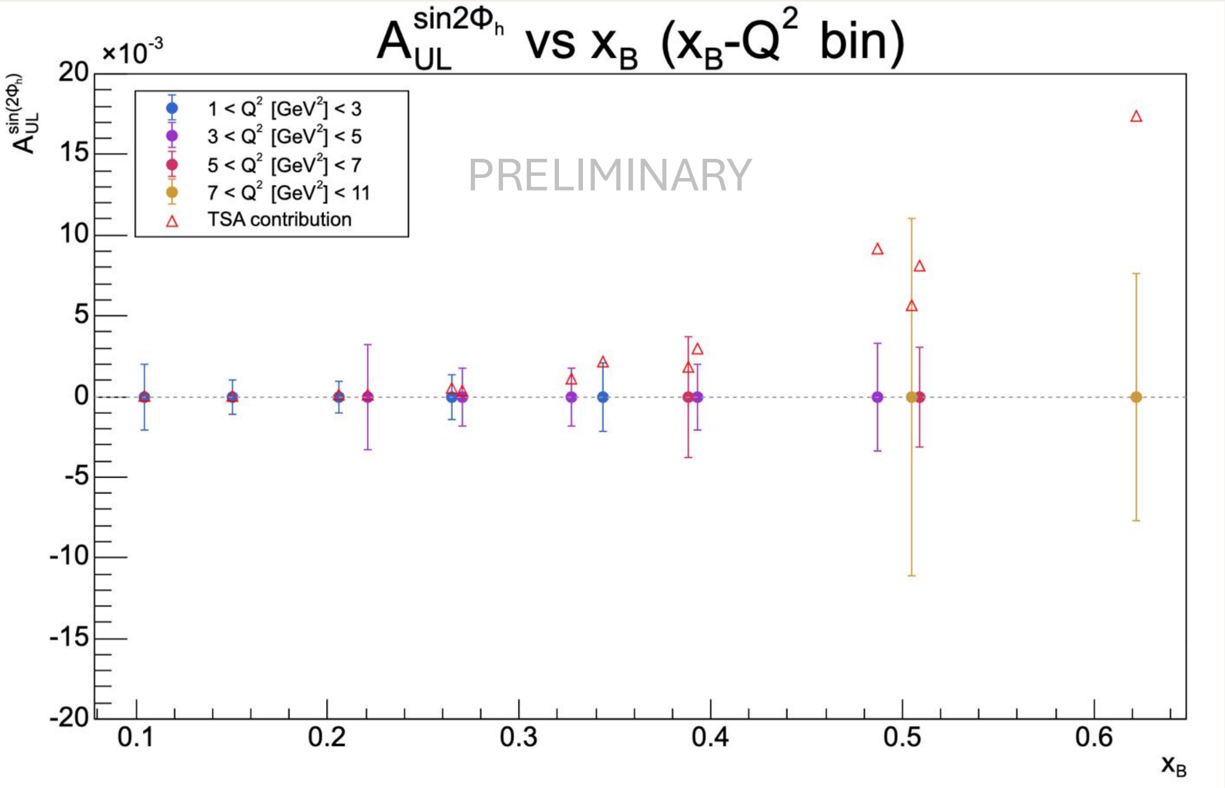
$$A_{UL^\gamma}^{\sin(2\phi_h)} \approx A_{UL^l}^{sin(2\phi_h)} + \sin\theta_i \frac{\sqrt{2\varepsilon_i(1+\varepsilon_i)}}{\varepsilon_i} A_{UT^l}^{sin(2\phi_h-\phi_s)}$$

$$A_{UL^\gamma}^{\sin\phi_h} \approx A_{UL^l}^{sin\phi_h} + \sin\theta_i \frac{\varepsilon_i}{\sqrt{2\varepsilon_i(1+\varepsilon_i)}} A_{UT^l}^{sin(\phi_h+\phi_s-\pi)}$$

2D Asymmetry extraction errors

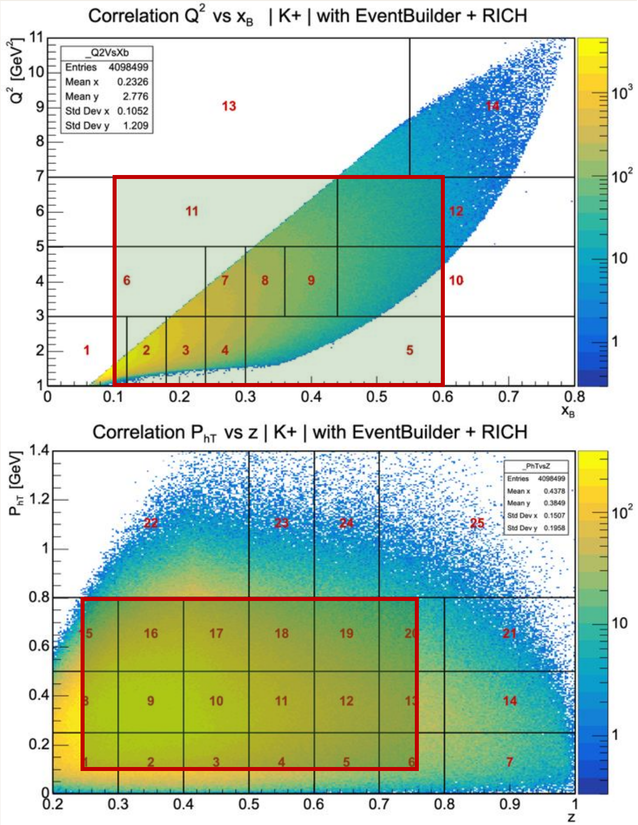
If we focus in the 2D asymmetries we could observe the generic statistical error for each point.

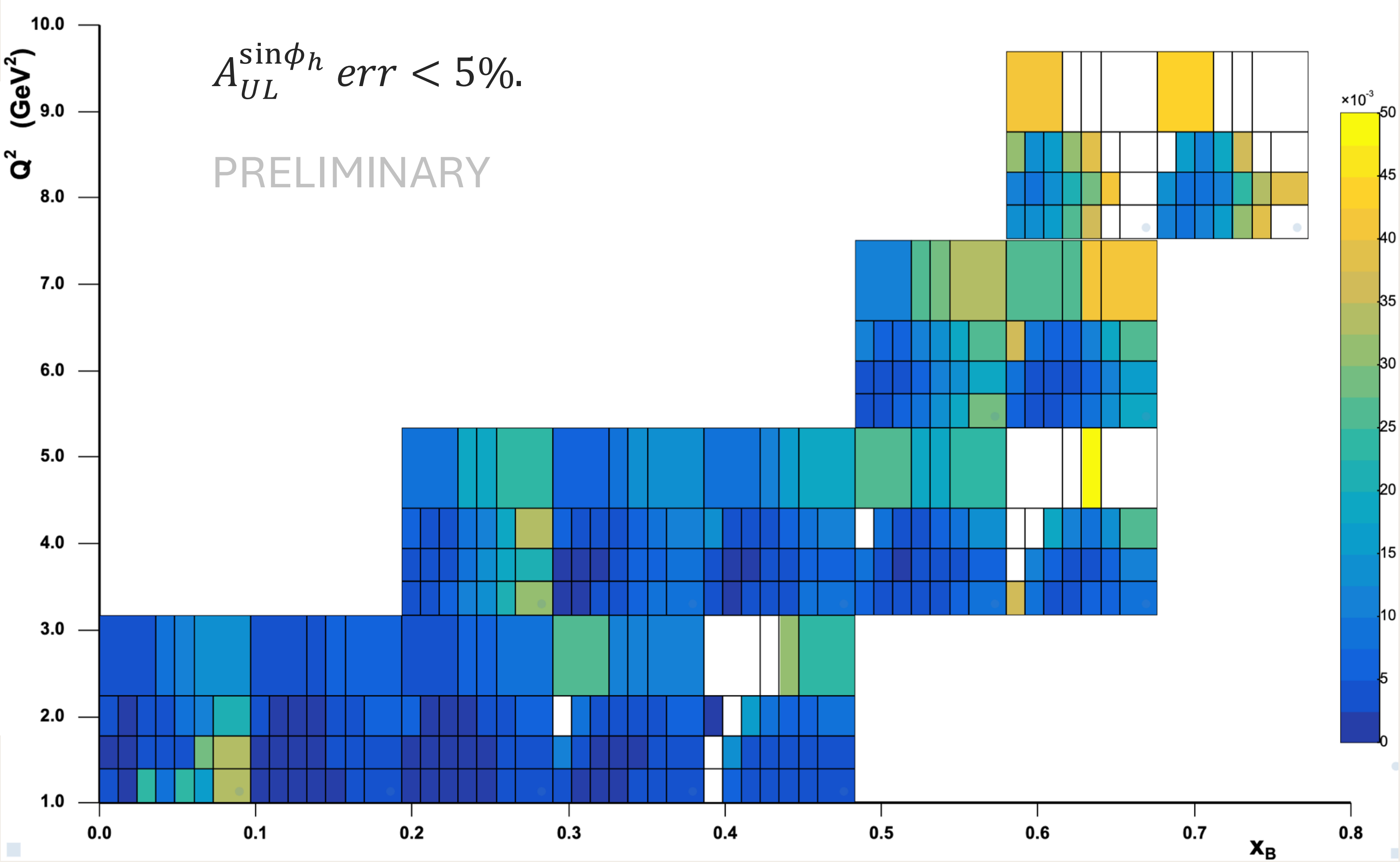




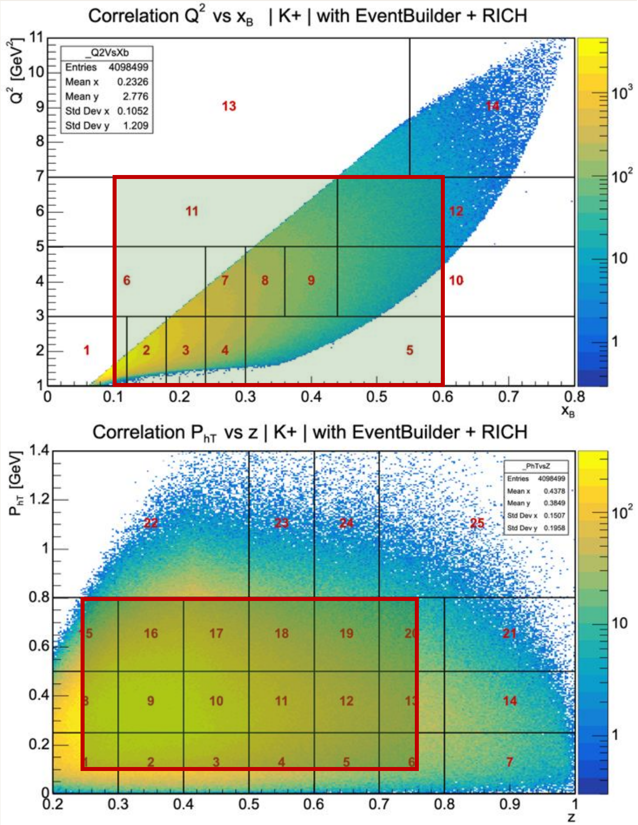
Here the TSA contribution was calculated using $A_{UT} = \bar{x}_B^4/4$.

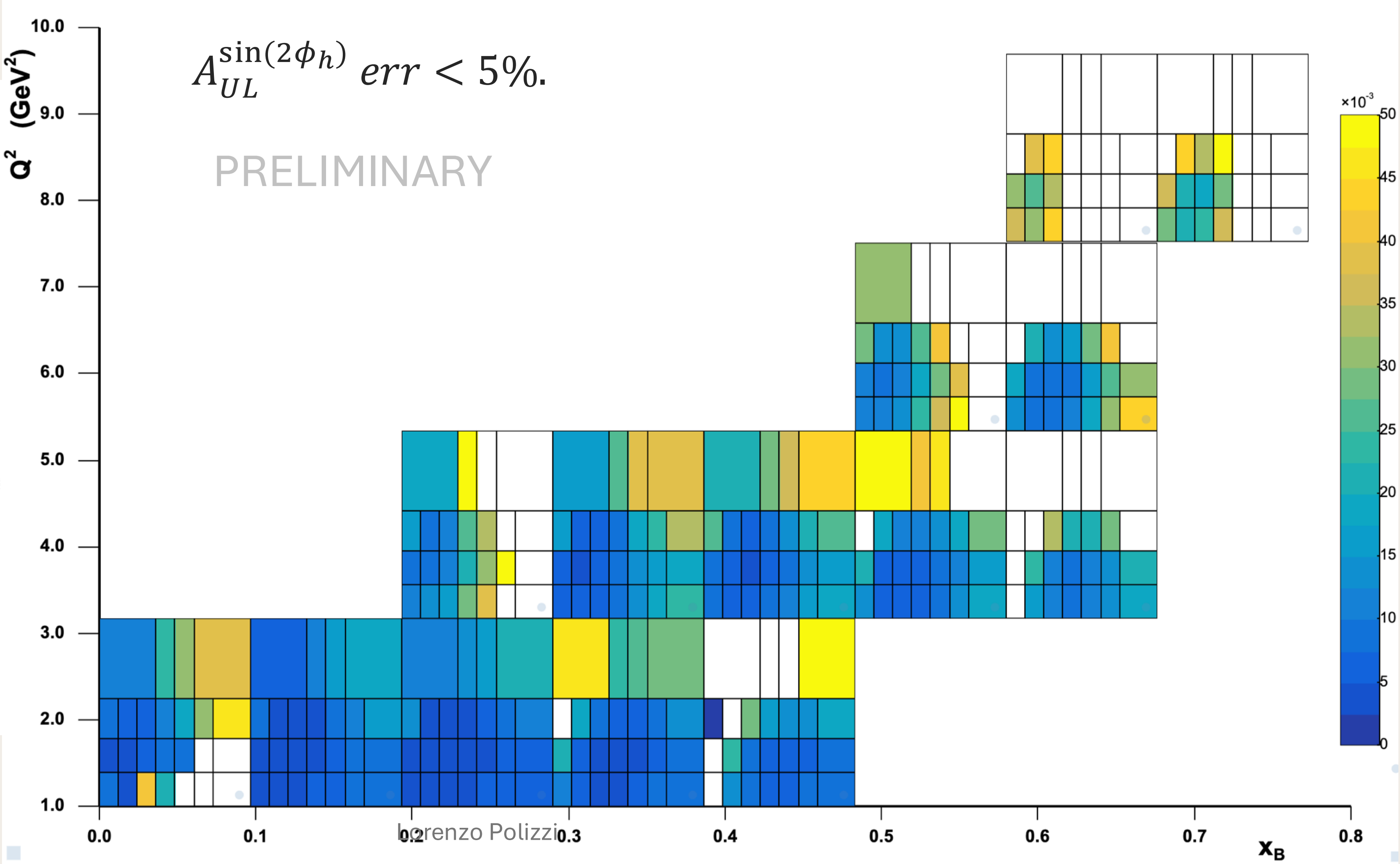
4D Asymmetry Extraction Errors





4D Asymmetry extraction errors

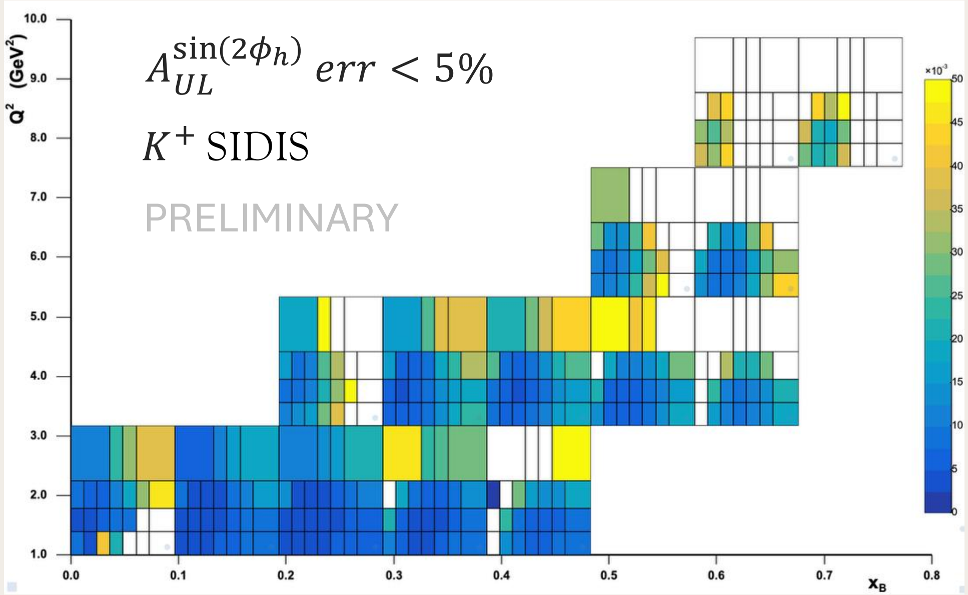


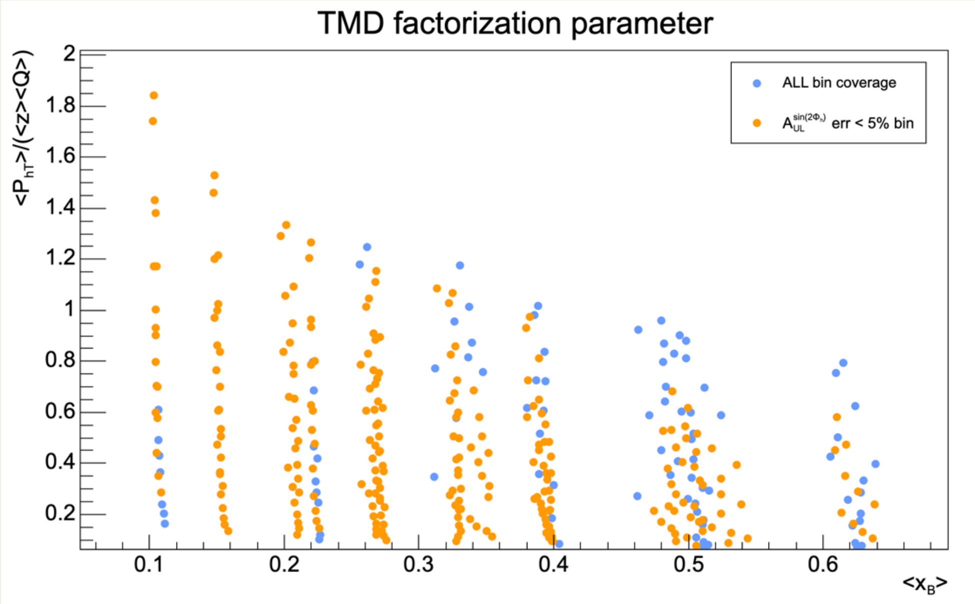


ASYMMETRY EXTRACTION 4D

From the previous plots we can evince that we have the capability to extract precise measurements in the TMD factorization region defined before for $A_{UL\gamma}^{\sin(2\phi_h)}$ asymmetries.

For these extractions our bin grid mostly populate the $P_{hT}/zQ < 1$ region.





Survived bin from the spin-asymmetry error cut.

CONCLUSION

RGC is able to extract and measure valid **4D longitudinal spin-asymmetries** with **high precision** in **complementary kinematic sectors** compared to previous experiment for **SIDIS processes**.

What's next:

- The **calibration** of the **RICH detectors** will be important in providing a strong coverage for the **higher momentum range** (above 3 GeV) and ensure strong PID.

- A further and more developed system for the MLE is required and **under development** to perform precise **extrapolation of** $\boldsymbol{A_{UL}^{sin(2\phi_h)}}$ (and $A_{UL}^{sin\phi_h}$) for the **RGC** experiment of **CLAS12**.

- **Still focus** on **UL asymmetries** to access **quark transverse dynamics**, calculate **TMDs** available only on SIDIS, and be sensitive to **strangeness**.

THANKS

BACKUP – CUT

Hadron cut:

- $1.2 < P_h < 8\,GeV$ && $M_x > 1.56$ GeV && $Q^2 > 1$ GeV^2 && $x_F > 0$ && $z > 0.2$ && $y < 0.80$
- $-10 < v_z^{inb} < 2.5$ cm && $-8 < v_z^{out} < 3$ cm && $|\chi^2_{ToF}| < 5$ && $W > 2\ GeV$
- $DC^{inb}: edge_1 > 3, edge_2 > 3, edge_3 > 7$ cm && $DC^{out}: edge_1 > 3, edge_2 > 3, edge_3 > 9$ cm

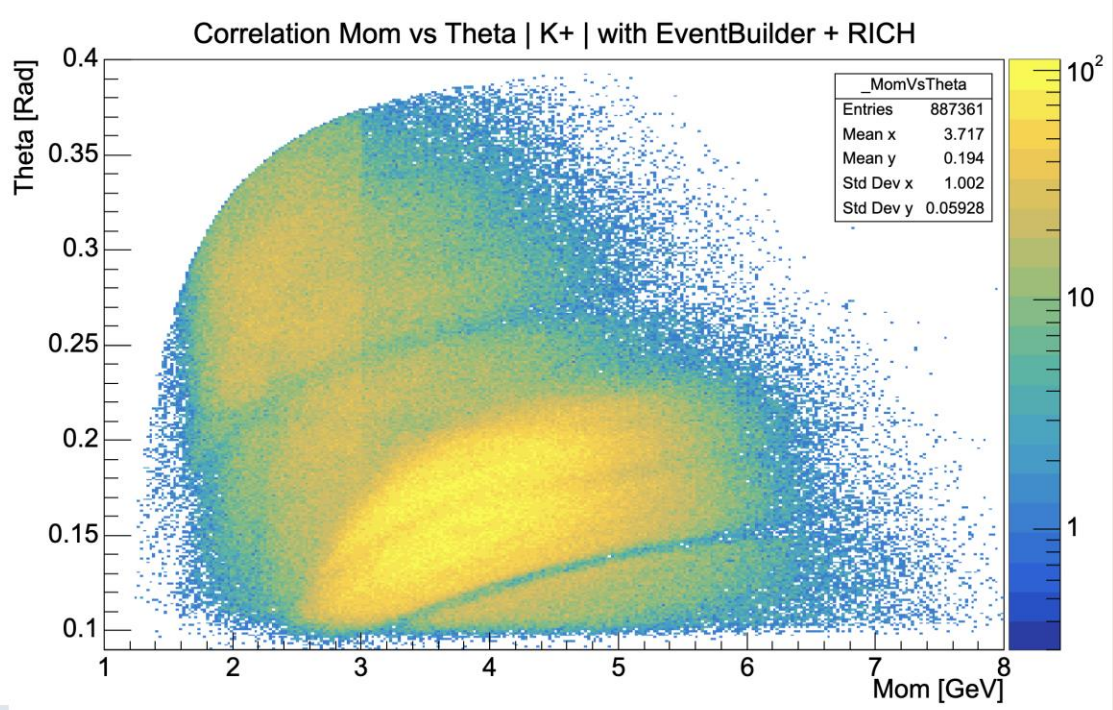
Rich cut:

$$\boldsymbol{n_\gamma > 2.5\ \ \&\ \ RQ > 0.1\ \&\ RL < 6 +}$$

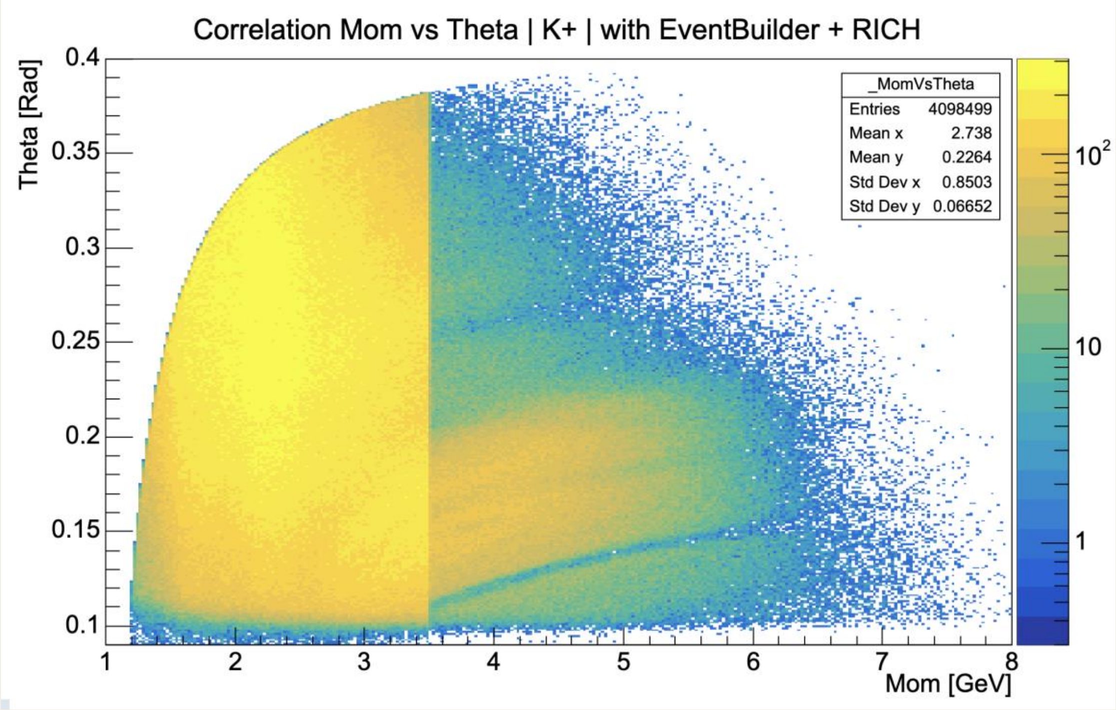
If $(PID_{RICH} \neq PID_{CLAS})$ or $(PID_{RICH} = PID_{CLAS}\ \&\ Mom > 3GeV)$:

- If $\boldsymbol{\chi^2_{RICH} < 50}$: $\boldsymbol{RQ} \geq 0.04\boldsymbol{RL} - 0.02$
- If $\boldsymbol{\chi^2_{RICH} > 50}$: $\boldsymbol{RQ} \geq 0.06\boldsymbol{RL} - 0.08$

Backup – RICH coverage



ToF usend only to calibrate the RICH in lower momentum region



Adding ToF reconstruction when the RICHes do no activate