Study of Nuclear TMDs in SIDIS from RG-D

CLAS Collaboration Meeting

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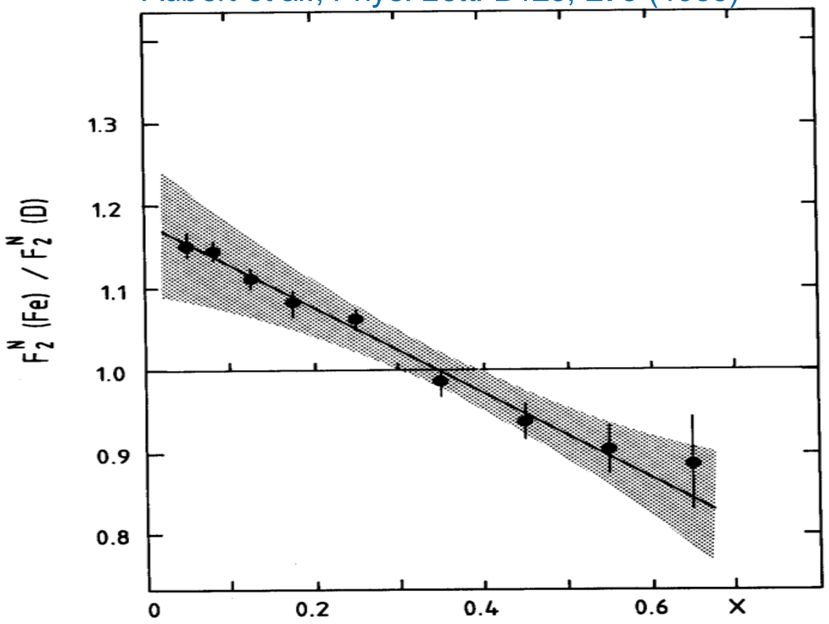
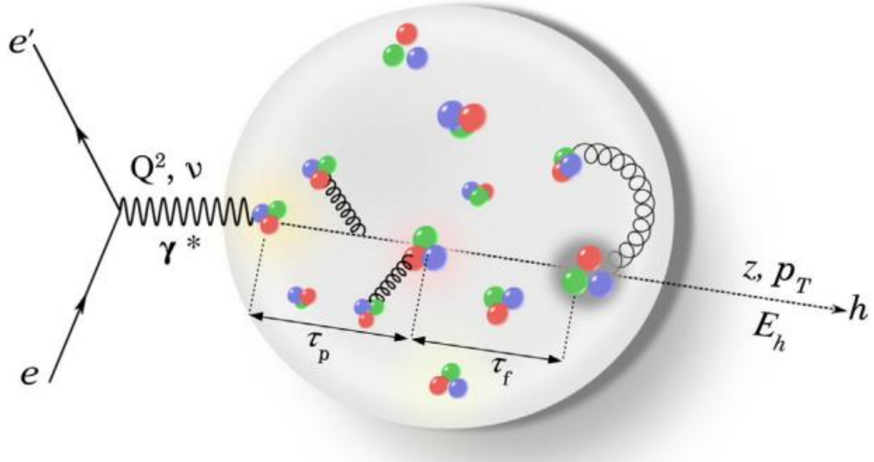
Physics Motivation

✓ How are partons modified inside nuclei?

- Inclusive DIS established that parton distributions are modified in nuclei (EMC effect).
- However, the origin of this nuclear modification is still not fully understood.
- SIDIS provides access to observables sensitive to partonic transverse motion and hadronization in the nuclear medium.
- These observables can be interpreted in the framework of nuclear Transverse Momentum Dependent Parton Distribution Functions (TMDs).
- Therefore, SIDIS may help us understand the origin of the nuclear modification observed in DIS

Aubert et al., Phys. Lett. B123, **275** (1983)





Picture adapted from T. Chetry et al., Phys. Rev. Lett. 130, **142301** (2023)

Semi-inclusive Deep Inelastic Scattering

✓ SIDIS process is considered as;

$$e(l) + p(P) \rightarrow e'(l') + h(P_h) + X$$

✓ **Kinematical Variables**

DIS Variables:

$\boldsymbol{Q^2} = -q^2$: squared momentum transfer of the virtual photon

$\boldsymbol{x_B} = Q^2/2M\nu$: Bjorken variable

$y = \nu/E$: fraction of beam energy transferred to the target

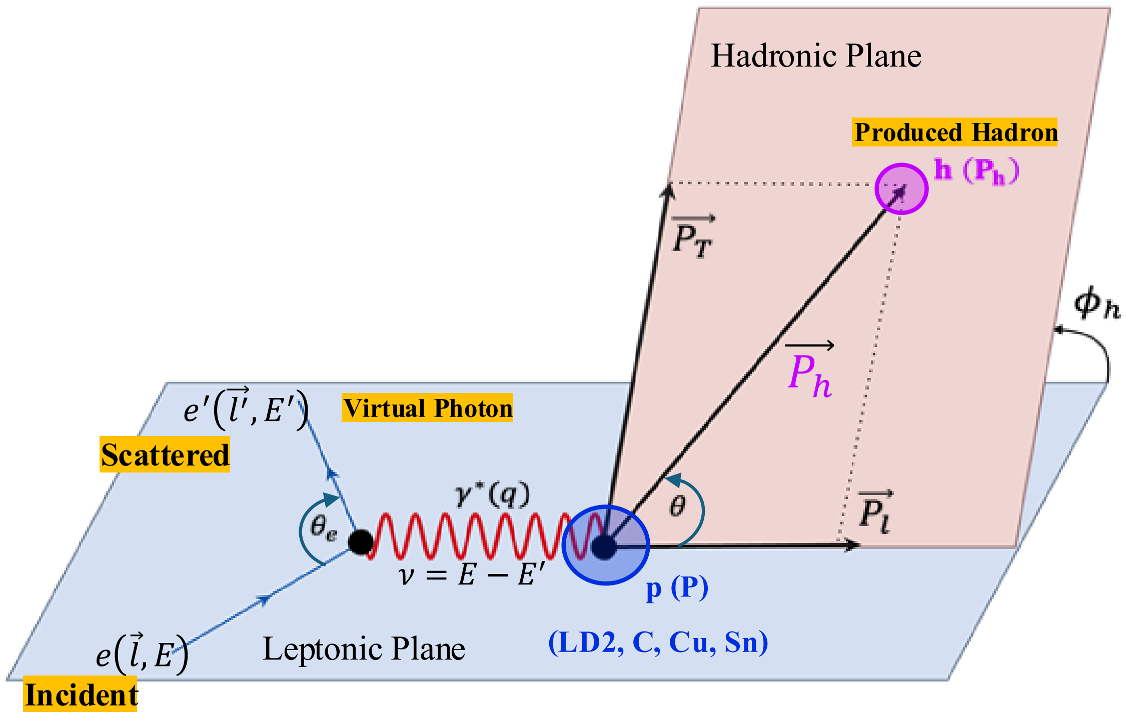
$W = \sqrt{M^2 - Q^2 + 2M\nu}$: invariant mass of the hadronic final state

Hadron Variables:

$\boldsymbol{z_h} = E_h/\nu$: fraction of virtual-photon energy carried by the hadron

$\boldsymbol{P_T^2} = \left(|\vec{q} \times \vec{P_h}|/|\vec{q}|\right)^2$: squared transverse momentum of hadron h

$\boldsymbol{\phi_h}$: Angle between leptonic plane and hadronic plane



"A. Bacchetta et al., J. High Energy Phys. 02, 093 (2007)"

➢ $\boldsymbol{Q^2}$, $\boldsymbol{x_B}$, $\boldsymbol{z_h}$, $\boldsymbol{P_T}$, and $\boldsymbol{\phi_h}$ are used for multidimensional binning

Experimental Observables

✓ **Multiplicity Ratio:**

$$\boldsymbol{R_M^h = \frac{(N_h/N_e)_A}{(N_h/N_e)_D}}$$; where, N_h: number of SIDIS hadrons, N_e: number of DIS electrons,

A: nuclear target, D: LD2

✓ **Transverse Momentum Broadening:**

$\boldsymbol{\Delta P_T^2 = \langle P_T^2 \rangle_A - \langle P_T^2 \rangle_D}$; where, $\langle P_T^2 \rangle$ = the mean P_T square

✓ **Azimuthal Moment:**

SIDIS cross section for unpolarized target: $d\sigma = d\sigma_0(1 + A_{UU}^{cos\phi_h} cos\phi_h + A_{UU}^{cos2\phi_h} cos(2\phi_h) + \lambda_e A_{LU}^{sin\phi_h} sin\phi_h)$

- The cross section contains three azimuthal modulations: $cos\phi_h, cos(2\phi_h), sin\phi_h$
- Here I focus only on the $\langle \cos 2\phi_h \rangle$ moment.

  $$\boldsymbol{\langle cos\, 2\phi_h \rangle = \frac{\sum_i cos\, 2\phi_{h,i}}{N_h}}$$; where the sum runs over hadrons in a given bin

- Comparing $\langle cos\, 2\phi_h \rangle_A$ and $\langle cos\, 2\phi_h \rangle_D$ checks whether the nuclear medium modifies the $\cos 2\phi_h$ modulation

All observables shown here are calculated at the detector level.

Preliminary Analysis Results

✓ Data Selection for this Analysis:

- RG-D Pass-1 Data (~ 4% of of the full RG-D data)
- Targets: LD2, Dual carbon foils (CxC), Copper foil (Cu), Tin foil (Sn)

✓ Electron Selection

- PID = 11
- Detected in Forward detector
- |chi2pid | < 5
- Sampling fraction (SF)

  SF =$(E_{PCAL}+E_{ECIN} + E_{ECOUT})/p$; $\mu(p) - 3\sigma \le SF \le \mu(p) + 3\sigma$
- PCAL fiducial and energy cuts

  $v_{PCAL} > 9$ cm , $w_{PCAL} > 9$ cm , $E_{PCAL} > 0.06$ GeV
- DC edge cuts

Target	Region 1 (cm)	Region 2 (cm)	Region 3 (cm)
LD2	1.68	2.00	8.75
CxC	1.70	2.02	8.92
CuSn	1.69	2.00	8.89

- Vertex Vz

✓ Positive pion (π^+) Selection

- PID = 211
- Detected in Forward detector
- |chi2pid | < 10
- Vertex Vz

Target	V_z [cm]
LD2	(-20.00, 5.00)
CxC	(-10.53, 5.00)
Cu	(-9.76, -5.16)
Sn	(-4.64, 5.00)

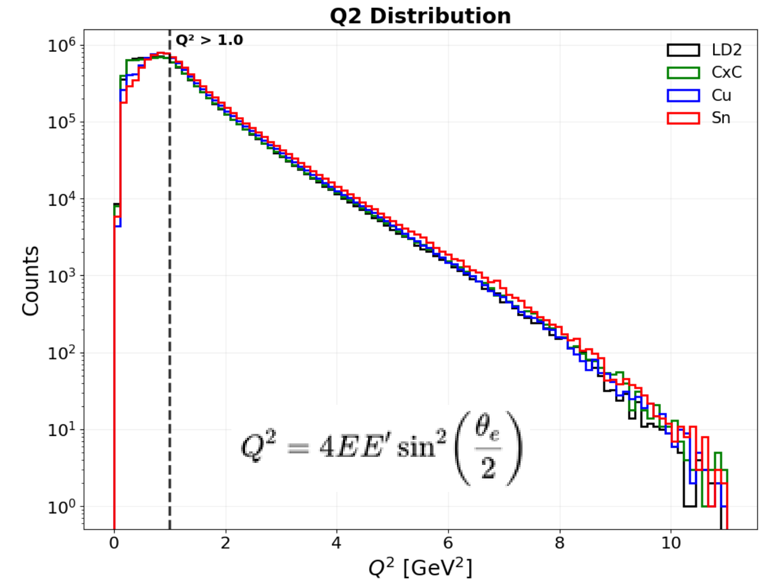
- $\Delta V_z \in [-20, 20]$cm, loose cut for now
- Fiducial cuts yet to be implemented

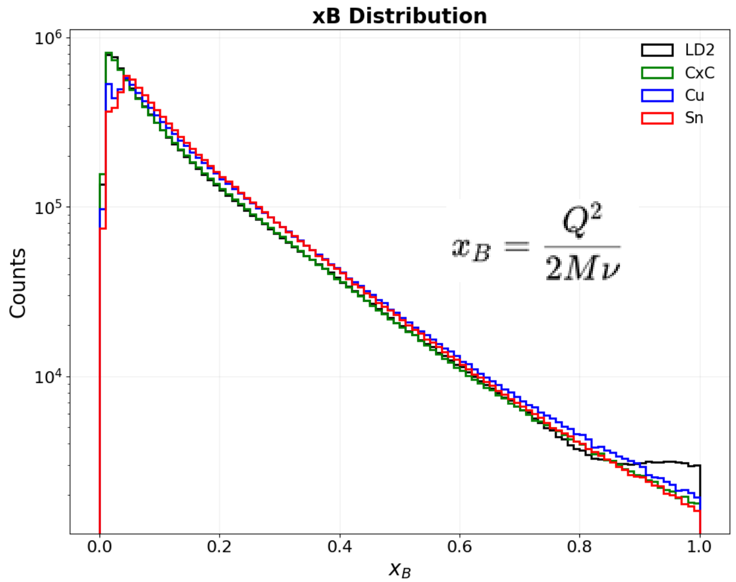
Vertex V_z & fiducial cuts: Credit of Mathieu Ouillon (See his talk)

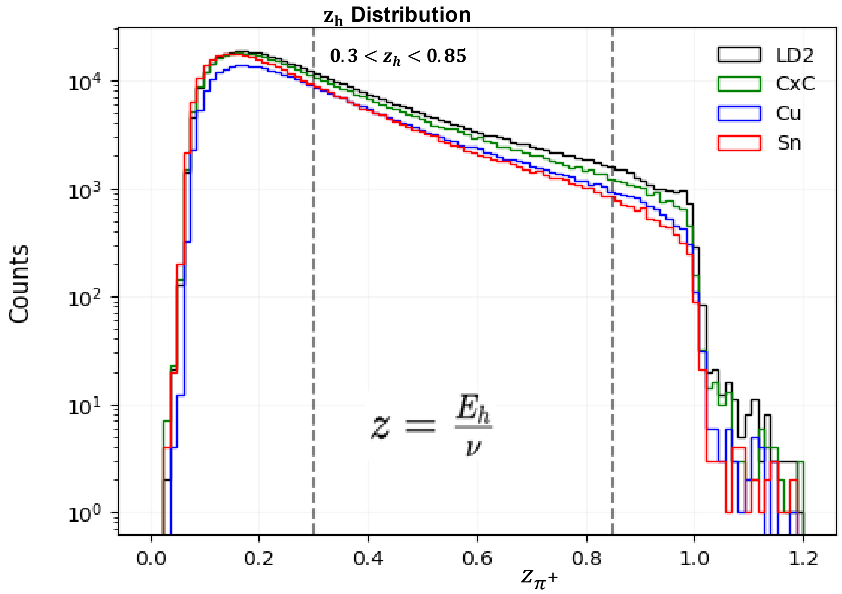
Preliminary Analysis Results (Cont'd)

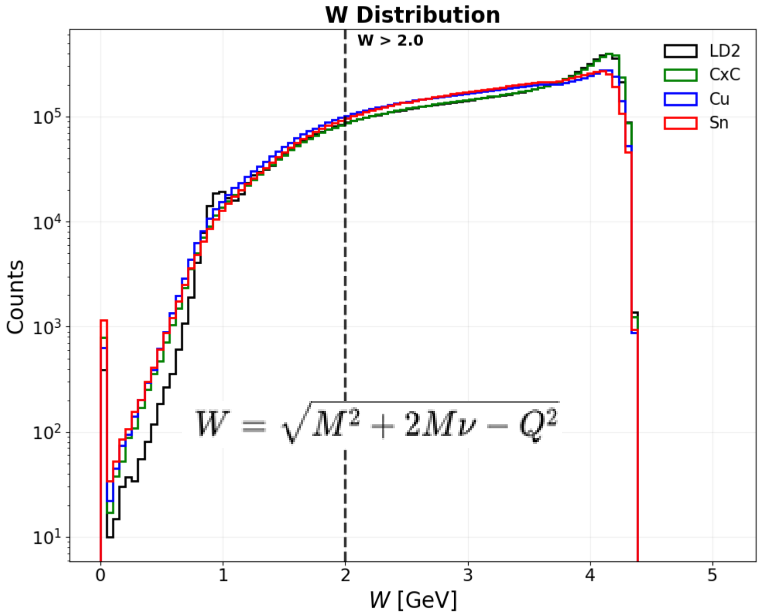
$h \to \pi^+$

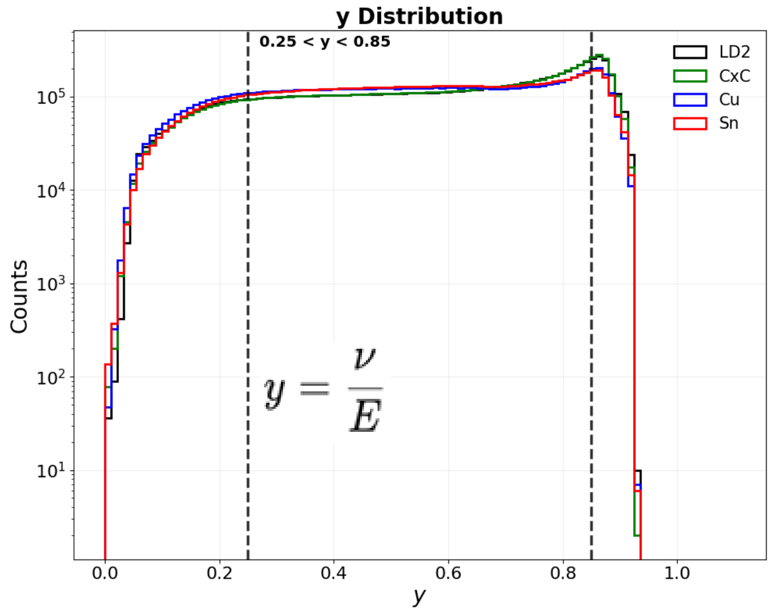
✓ **Kinematic variables and coverage:**

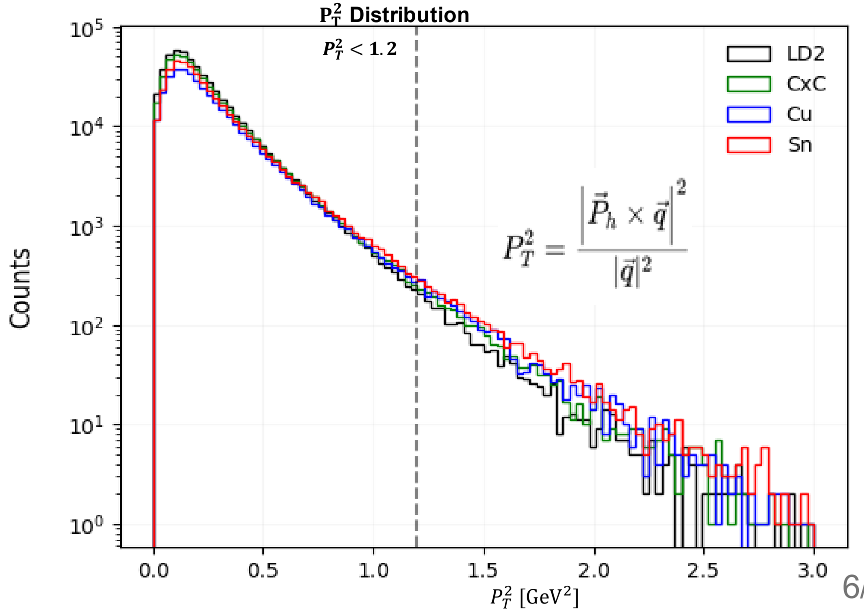






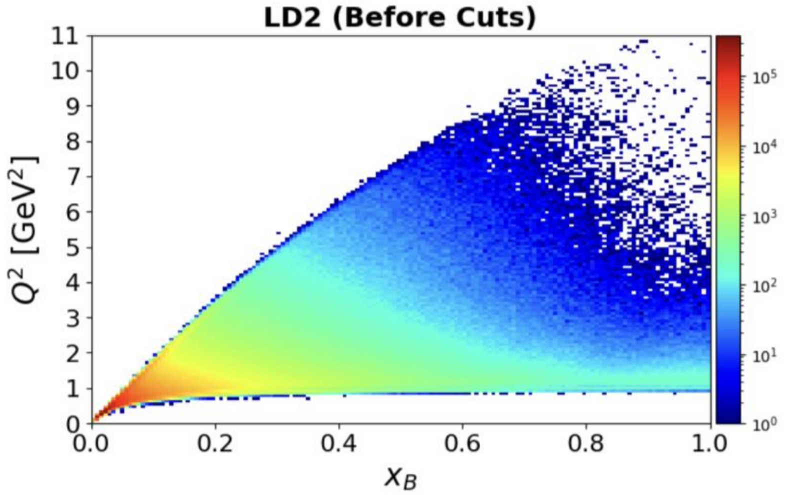


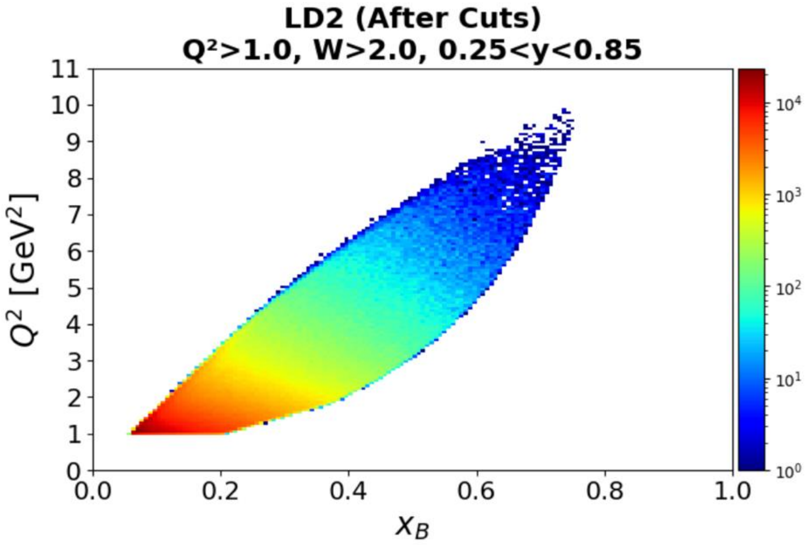




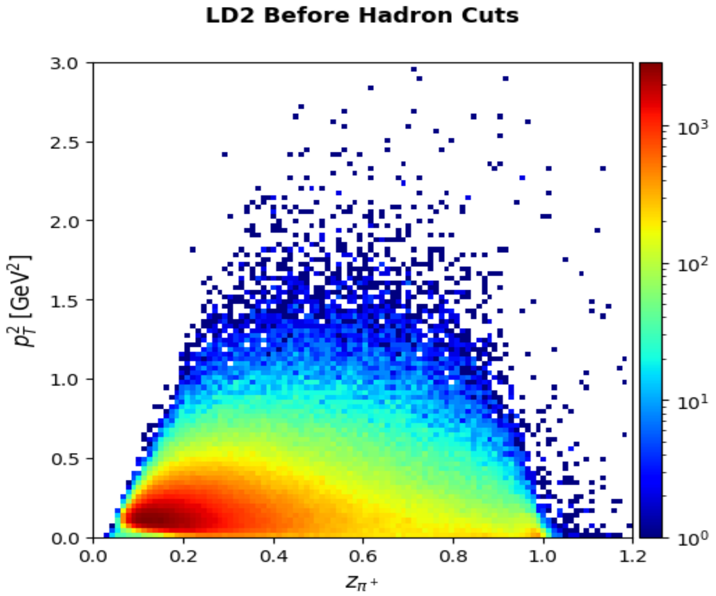
Preliminary Analysis Results (Cont'd)

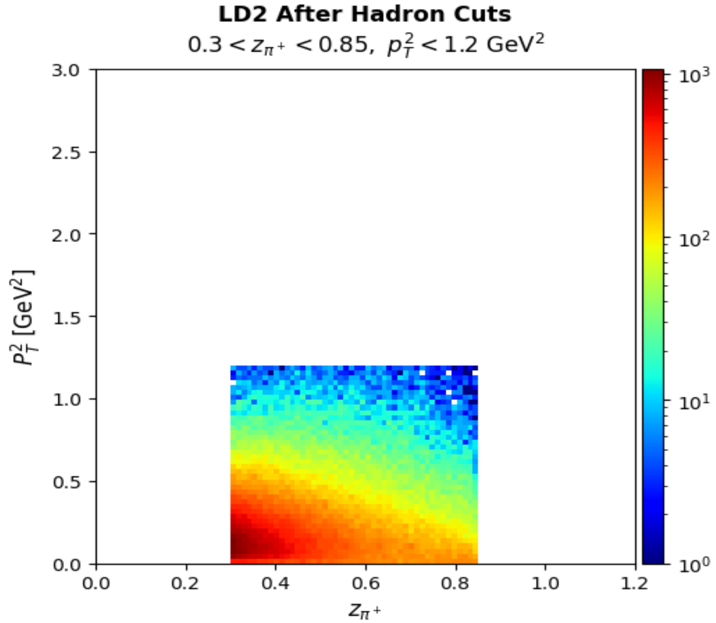
✓ **DIS $Q^2 - x_B$ phase space:**





✓ **SIDIS $P_T^2 - z_h$ phase space:** h→ π^+



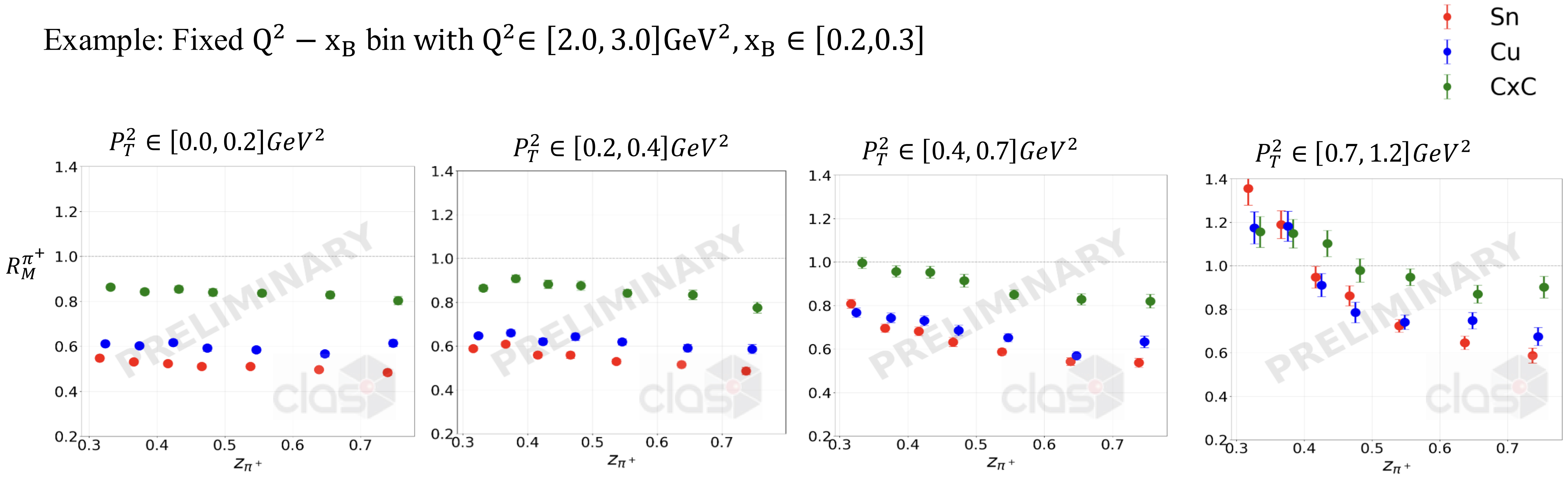


Preliminary Analysis Results (Cont'd)

✓ Multiplicity Ratio: $R_M^h(Q^2, x_B, z, P_T^2) = \dfrac{\dfrac{N_A^h(Q^2, x_B, z, P_T^2)}{N_A^e(Q^2, x_B)}}{\dfrac{N_D^h(Q^2, x_B, z, P_T^2)}{N_D^e(Q^2, x_B)}}$

$z_h = \dfrac{E_h}{\nu}$ h→ π^+

Example: Fixed $Q^2 - x_B$ bin with $Q^2 \in [2.0, 3.0]\,\mathrm{GeV}^2$, $x_B \in [0.2, 0.3]$



- ➢ $R_M^{\pi^+}$ tends to decrease with increasing z_{π^+}
- ➢ $R_M^{\pi^+}$ tends to be lower for heavier nuclei (larger A)
- ➢ $R_M^{\pi^+}$ shows an enhancement with increasing P_T^2

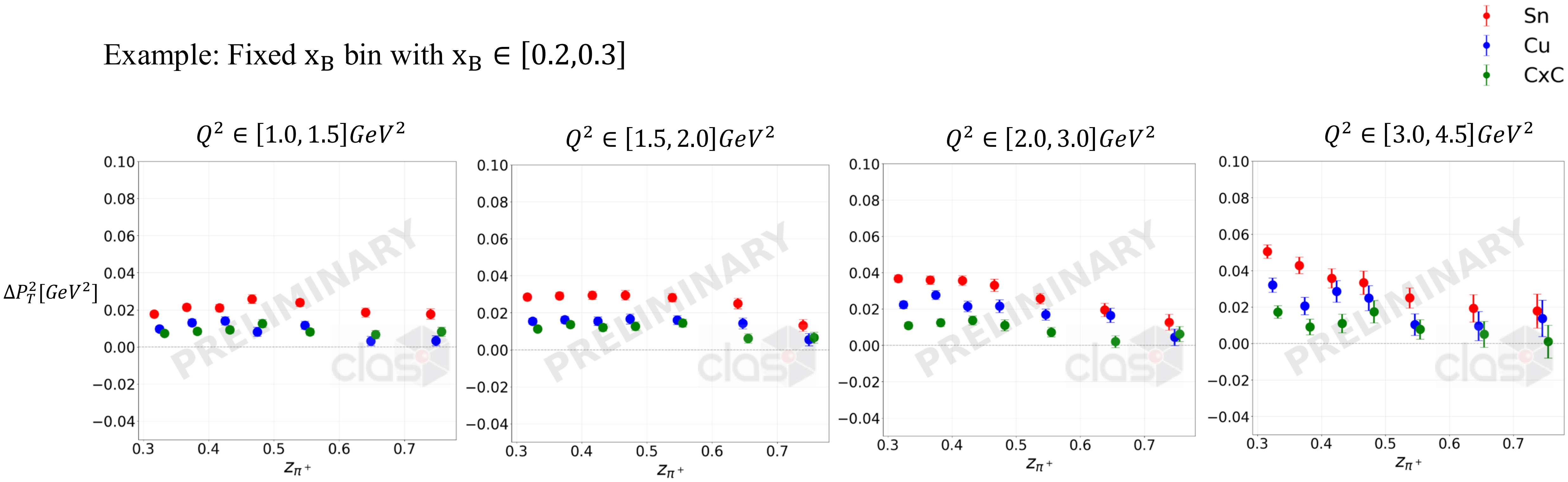
❖ Error bars are statistical uncertainties only.

Preliminary Analysis Results (Cont'd)

✓ Transverse Momentum Broadening ΔP_T^2:

$$\Delta P_T^2(Q^2, x_B, z) = \left\langle P_T^2(Q^2, x_B, z)\right\rangle_A - \left\langle P_T^2(Q^2, x_B, z)\right\rangle_D$$

Example: Fixed x_B bin with $x_B \in [0.2, 0.3]$

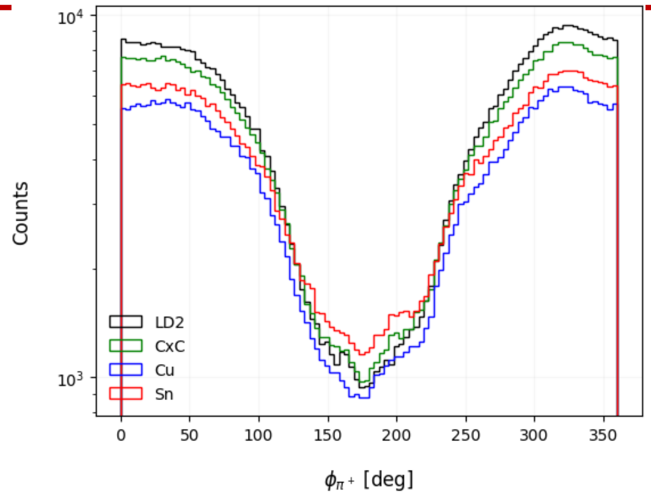


- ➢ ΔP_T^2 tends to be larger for heavier nuclei (Sn > Cu > CxC)
- ➢ ΔP_T^2 tends to increase with Q^2 and decrease mildly with z

❖ Detailed systematics study will follow to confirm these tendencies.

Preliminary Analysis Results (Cont'd)

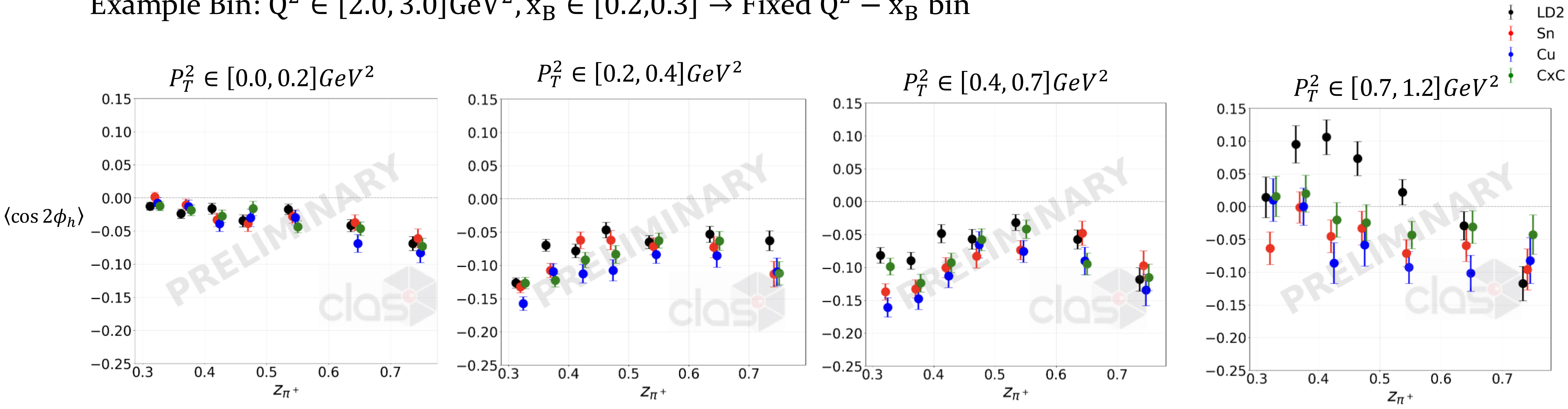
$h \rightarrow \pi^+$



✓ Azimuthal Moment:

$$\langle cos\ 2\phi_h \rangle = \frac{\sum_i cos\ 2\phi_{h,i}}{N_h}$$; where the sum runs over hadrons in a given bin

Example Bin: $Q^2 \in [2.0, 3.0]\mathrm{GeV}^2, x_B \in [0.2, 0.3] \rightarrow$ Fixed $Q^2 - x_B$ bin



- These are detector-level quantities, which are a good estimate of the truth-level quantities
- A careful study of the systematics is required before any quantitative discussion can take place.

Summary and Outlook

- ✓ Studied multiplicity ratio R and transverse momentum broadening, azimuthal moment $\langle \cos 2\phi_h \rangle$
- ✓ Heavier nuclei show stronger hadron suppression and more transverse momentum broadening
- ✓ With about 4 % of the full RG-D data the preliminary results show that it is feasible to perform a multidimensional study of nuclear SIDIS over a broad kinematic phase space.
- ✓ We will continue this analysis toward the study of nuclear TMDs through the following steps:
  1. Improve the analysis
     - Apply radiative and acceptance corrections (work in-progress)
     - Estimate systematic uncertainties
     - Optimize multidimensional binning
     - Study tighter event-selection cuts
  2. Include more observables
     - $\langle \cos \phi_h \rangle$: more sensitive to acceptance correction
     - $\langle \sin \phi_h \rangle$: through beam − spin asymmetry
  3. Simulation: The event generator is ready. Simulation was tested with RG-D configuration. We will request the large simulation priority for the osg.
- ✓ Rough timeline (2026)
  - April–June: produce simulation datasets
  - June–August: acceptance corrections
  - August–October: radiative corrections
  - October–November: systematic studies