TMDs: Towards a Synergy between Lattice QCD and Global Analysis

Jun 21 – 23, 2023

Center for Frontiers in Nuclear Science, Stony Brook University

Accessing TMDs from single pion and kaon SIDIS with CLAS12

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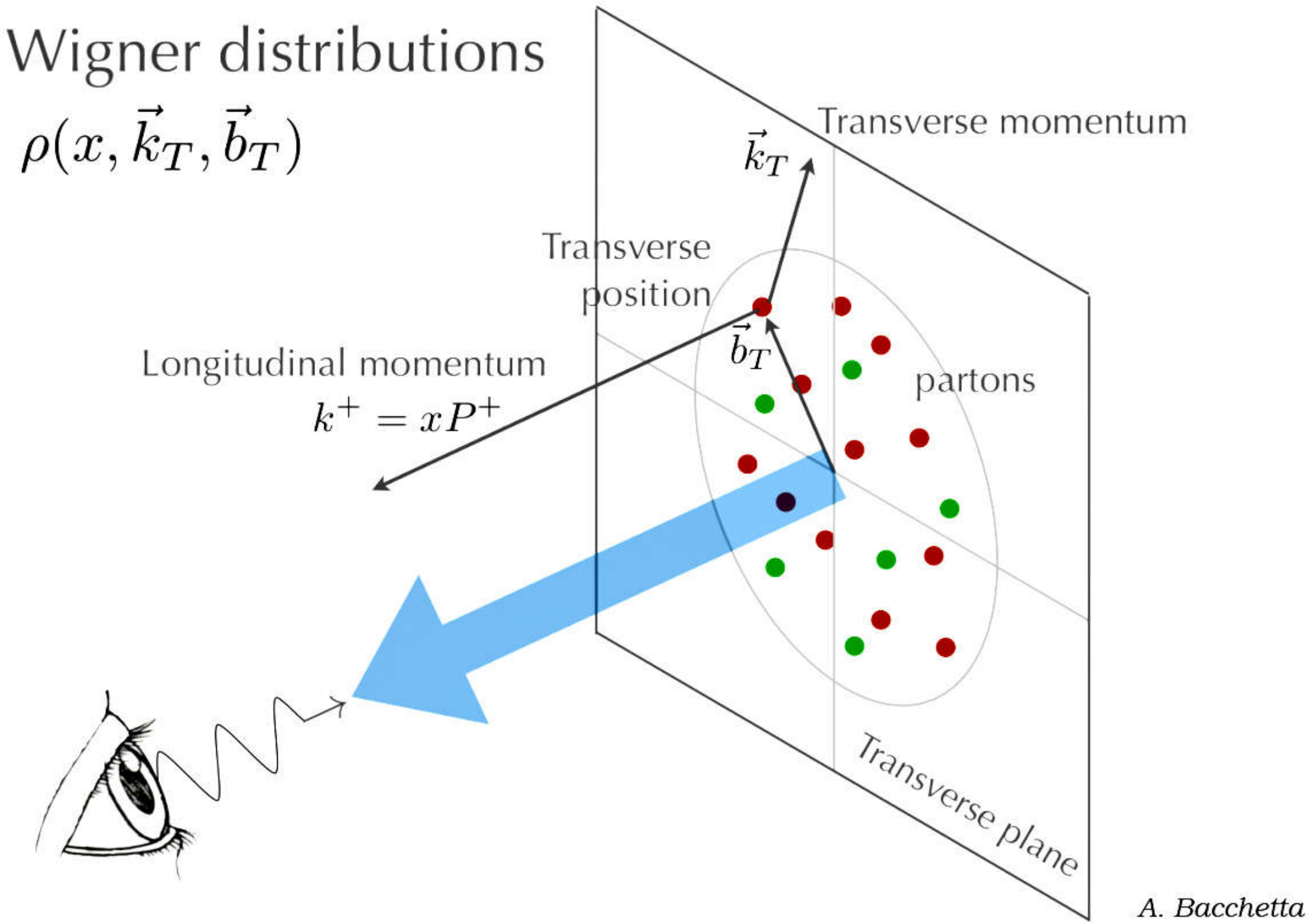
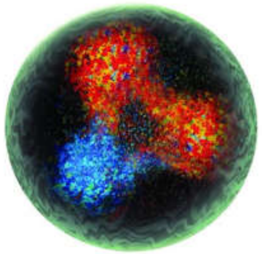
3-Dimensional Imaging of Quarks and Gluons



3-Dimensional Imaging of Quarks and Gluons



Wigner function: full phase space parton distribution of the nucleon $\rho(x, \vec{k}_T, \vec{b}_T)$ **5D**

$\int d^2 k_T$ → **3D** Generalised Parton Distributions (GPDs)

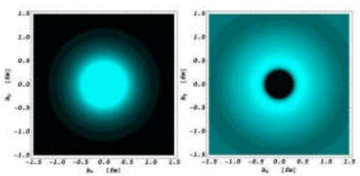
$\int d^2 b_T$ → Transverse Momentum Distributions (TMDs) **3D**

GPDs: $\int dx$ → Form Factors *eg*: $G_{E,}$ G_M **2D**

GPDs: $\int d^2 b_T$ → Parton Distribution Functions (PDFs)

TMDs: $\int d^2 k_T$ → Parton Distribution Functions (PDFs) **1D**

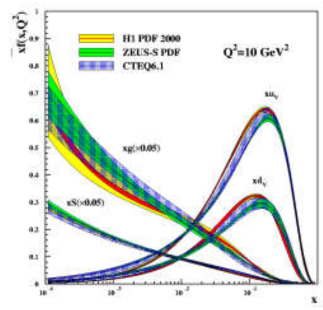
2D



Form Factors

eg: $G_{E,}$ G_M

Parton Distribution Functions (PDFs)



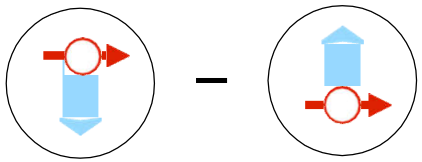
1D

Transverse Momentum Distributions (TMDs)

- Spin-dependent 3D **momentum space** images

quark pol. / nucleon pol.

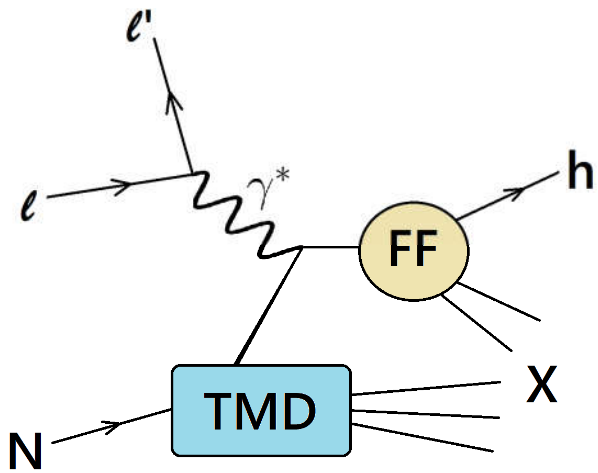
	U	L	T
U	f_1		$h^{\perp}_1$
L		g_1	$h^{\perp}_{1L}$
T	$f^{\perp}_{T}$	g_{1T}	h_1, $h^{\perp}_{1T}$



Boer-Mulders

➔ Net polarization in direction i carried by the partons inside an unpolarized proton

TMDs can be accessed in semi-inclusive deep-inelastic scattering (SIDIS)



W > 2 GeV

$P_T/(z\ Q) \ll 1$

$Q^2 \gg 1\ \mathrm{GeV}^2$

The Single Hadron SIDIS Cross Section

Longitudinally polarized beam and unpolarized target:

$$\frac{d\sigma}{dx\, dQ^2\, dz\, dP^2_{h\perp}\, d\phi_h} \sim F_{UU,T} + \epsilon\, F_{UU,L} + \sqrt{2\epsilon(1+\epsilon)}\, \cos\phi_h\, F_{UU}^{\cos\phi_h} + \epsilon\, \cos 2\phi_h\, F_{UU}^{\cos 2\phi_h} + \lambda_e \sqrt{2\epsilon(1-\epsilon)}\, \sin\phi_h\, F_{LU}^{\sin\phi_h}$$

twist 3: $F_{UU,T} = \zeta[f_1 D_1]$ $\quad F_{UU,L} = 0$ **twist 4:** $\mathcal{O}(M^2/Q^2, P_T^2/Q^2)$ $\quad F_{UU,L} \sim \frac{M^2}{Q^2}\zeta\left(\frac{4k_T^2}{M^2} f_1 D_1 + \ldots\right)$

$$F_{UU}^{\cos\phi_h} = \frac{2M}{Q}\,\zeta\left(-\frac{\hat{\mathbf{h}}\cdot\mathbf{k}_T}{M_h}\left(x\, h\, H_1^\perp + \frac{M_h}{M}\, f_1\, \frac{\widetilde{D}^\perp}{z}\right) + \frac{\hat{\mathbf{h}}\cdot\mathbf{p}_T}{M}\left(x\, f^\perp\, D_1 + \frac{M_h}{M}\, h_1^\perp\, \frac{\widetilde{H}}{z}\right)\right)$$

$$F_{UU}^{\cos 2\phi_h} = \zeta\left[-\frac{2(\hat{\mathbf{h}}\cdot\mathbf{k}_T)(\hat{\mathbf{h}}\cdot\mathbf{p}_T) - \mathbf{k}_T\cdot\mathbf{p}_T}{M\, M_h} h_1^\perp H_1^\perp + \frac{1}{Q^2} f_1 D_1 + ???\right]$$

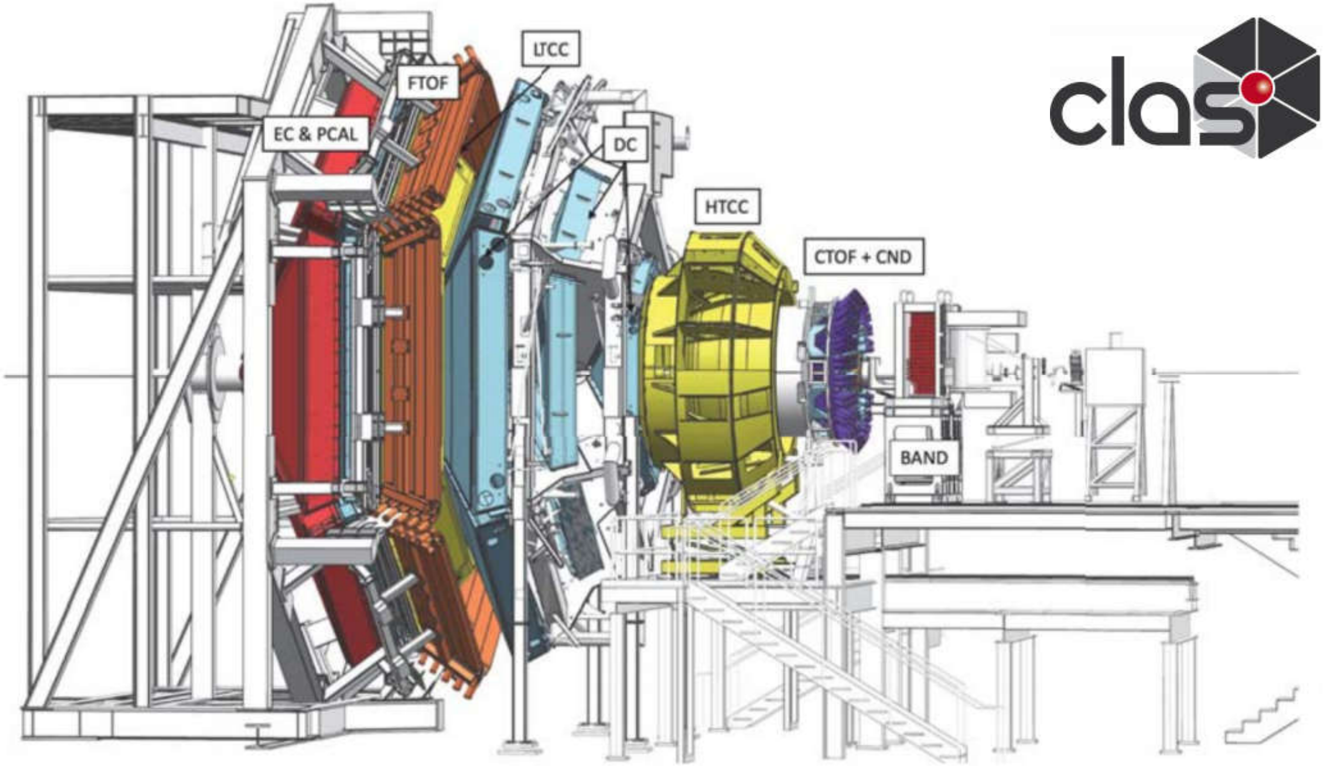
Cahn effect

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

twist-3 pdf; Collins FF; unpolarized dist. function; twist-3 FF; twist-3 t-odd dist. funcion; Boer-Mulders; twist-3 FF

➔ TMDs and Fragmentation functions

CLAS12 at JLAB



V. Burkert et al., Nucl. Instr. Meth. A 959, 163419 (2020)

➔ Data recorded with CLAS12 during fall 2018 and spring 2019 (RG-A)

- ➔ 10.6 GeV / 10.2 GeV electron beam ~ 86 % average polarization
- ➔ liquid H_2 target

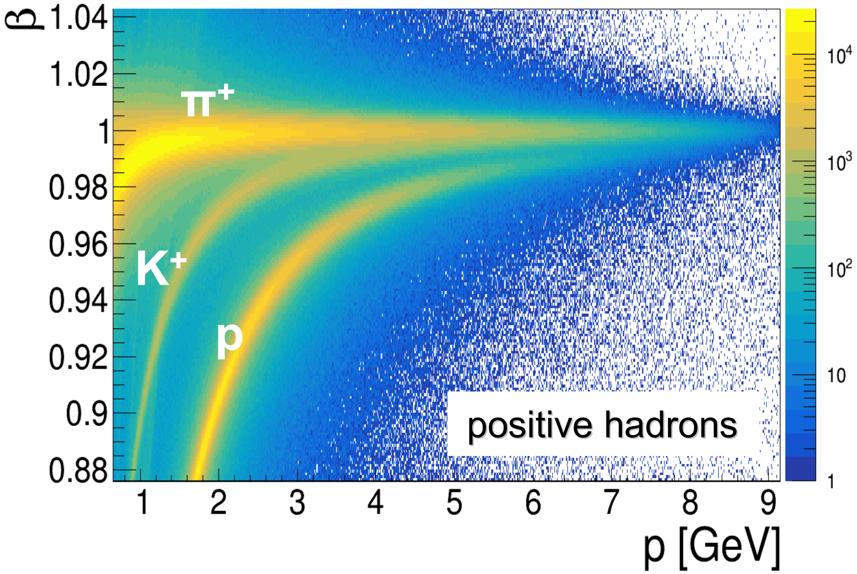
Particle ID and Kinematic Cuts

Electron ID

→ Based on the electromagnetic calorimeter and the cherenkov counters

Hadron ID

→ Based on β vs momentum correlation from TOF



Kinematic cuts: $1.25\ \text{GeV} < P_{\pi,K} < 5.0\ \text{GeV}$ $y < 0.75$

$Q^2 > 1\ \text{GeV}^2$ $W > 2\ \text{GeV}$

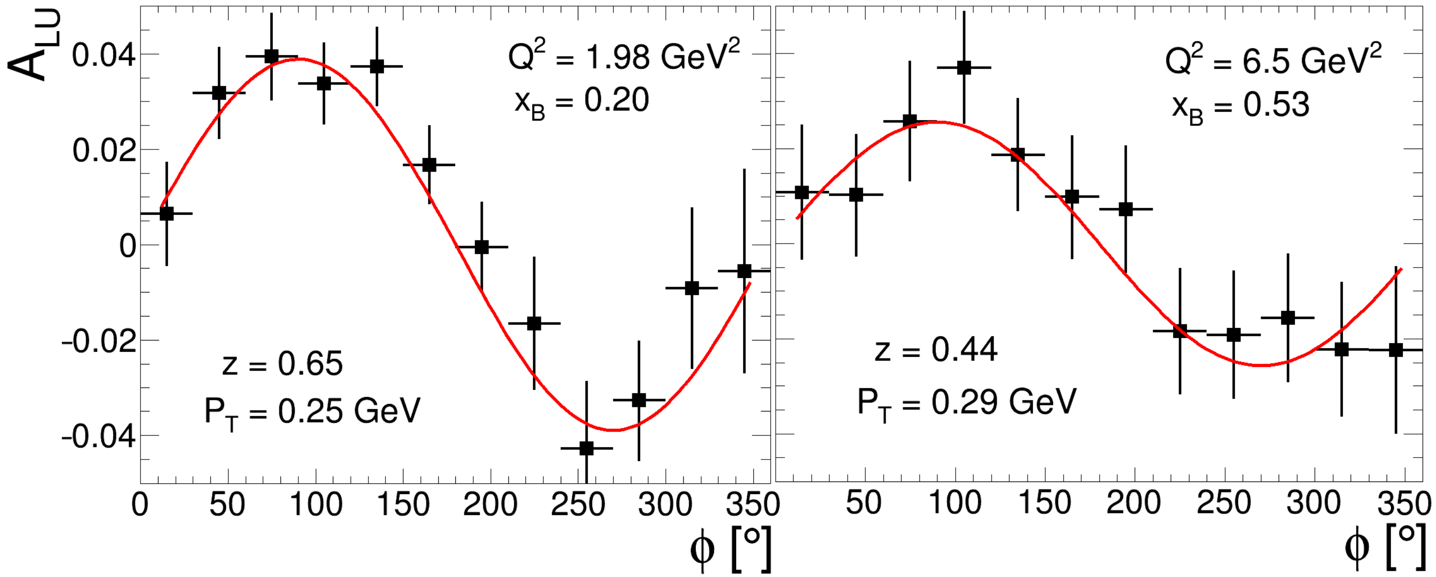
Cut on the emX missing mass to remove exclusive events: $\begin{cases} M_{e\pi X} > 1.5\ \text{GeV} \\ M_{eKX} > 1.6\ \text{GeV} \end{cases}$

1 D study: $z > 0.3$ removes "target fragmentation region"

Beam Spin Asymmtries

$$A_{LU}(x_B, Q^2, z, P_T, \phi) = \frac{d\sigma^+ - d\sigma^-}{d\sigma^+ + d\sigma^-} = \frac{\sqrt{2\epsilon(1-\epsilon)}\,\frac{F_{LU}^{\sin\phi}}{F_{UU}}\sin\phi}{1 + \sqrt{2\epsilon(1+\epsilon)}\,\frac{F_{UU}^{\cos\phi}}{F_{UU}}\cos\phi + \epsilon\,\frac{F_{UU}^{\cos 2\phi}}{F_{UU}}\cos 2\phi}$$

π^+:



Theoretical Predictions for $F_{LU}^{\sin(\varphi)}/F_{UU}$

Twist 3: $$F_{UU} = F_{UU,T} + F_{UU,L} = \zeta[f_1 D_1] + 0$$

→ Well known from theoretical caculations and global fits to unpolarized SIDIS cross sections and DY data

For a recent global fit see i.e.:

A. Bacchetta et al. J. High Energ. Phys. 10, 127 (2022). https://doi.org/10.1007/JHEP10(2022)127

To be extracted from BSA measurements:

$$F_{LU}^{\sin\phi_h} = \frac{2M}{Q}\zeta\left(-\underbrace{\frac{\hat{\mathbf{h}}\cdot\mathbf{k}_T}{M_h}\Bigg(x}\ e\ H_1^{\perp} + \underbrace{\frac{M_h}{M}}\ f_1\ \frac{\widetilde{G}^{\perp}}{z}\Bigg) + \underbrace{\frac{\hat{\mathbf{h}}\cdot\mathbf{p}_T}{M}\Bigg(x}\ g^{\perp}\ D_1 + \underbrace{\frac{M_h}{M}}\ h_1^{\perp}\ \frac{\widetilde{E}}{z}\Bigg)\right)$$

➔ The 4 terms have different kinematic dependencies ➔ 4D study!
and a dependence on the final state meson / hadron

➔ Multidimensional high precision studies will help us to disentangle them!

Theoretical Predictions for $F_{LU}^{\sin(\varphi)}/F_{UU}$

$eH_1^{\perp}$ and $g^{\perp}D_1$ terms

model 1 + 2: W. Mao and Z. Lu, Eur. Phys. J. C 73, 2557 (2013).
W. Mao and Z. Lu, Eur. Phys. J. C 74, 2910 (2014).
→ Calculations by C. Roberts and *Shu-Sheng* Xu

➔ Proton is described as an active quark plus spectator scalar and axial-vector diquarks.

➔ Different propagators for the axial-vector diquark and different masses of these correlations.

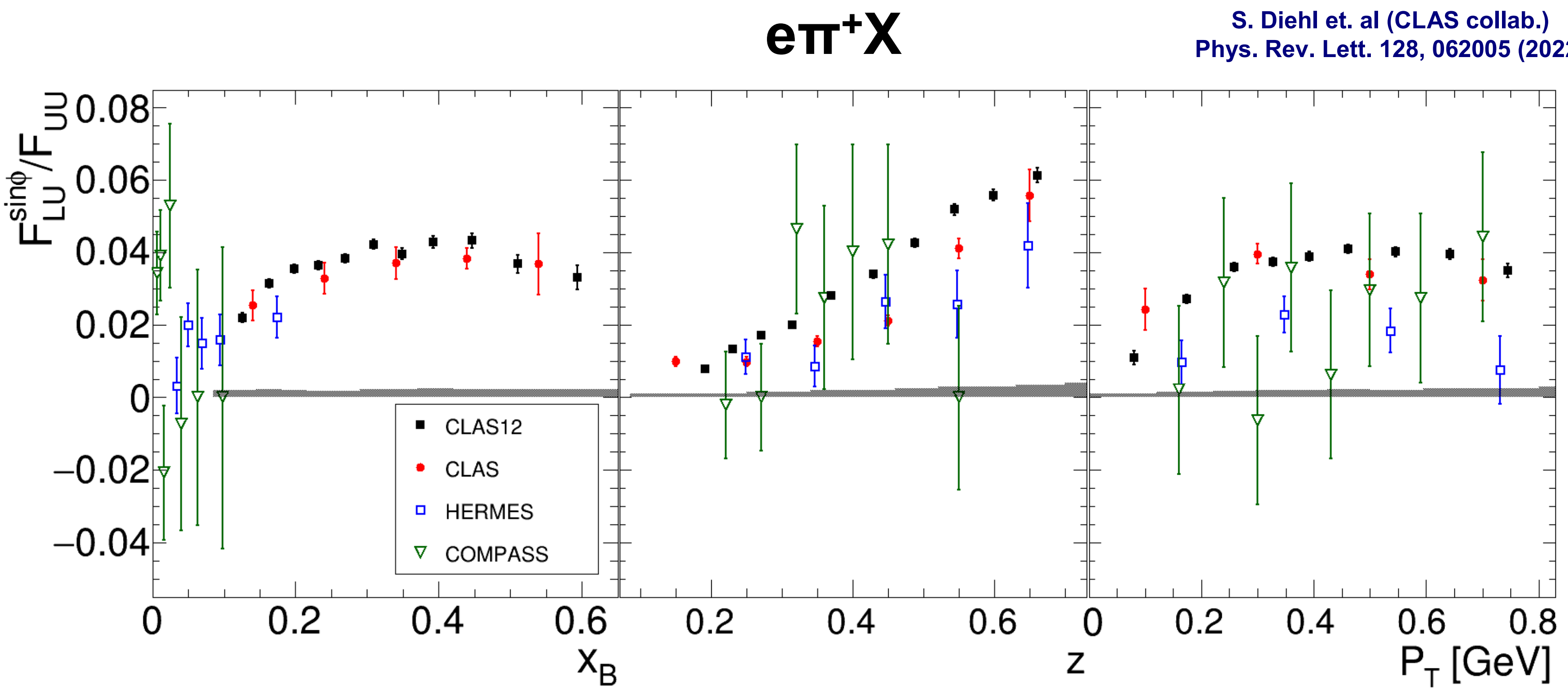
model 3: S. Bastami, K. Tezgin, A. Prokudin, P. Schweitzer (2020).

➔ Only $eH_1^{\perp}$ term ➔ *e*(*x*) based on the chiral quark soliton model.

➔ Only model predicting the experimentally not measurable *δ*(*x*)-contribution in *e*(*x*) expected in QCD and related to the pion-nucleon sigma term.

Beam Spin Asymmtries

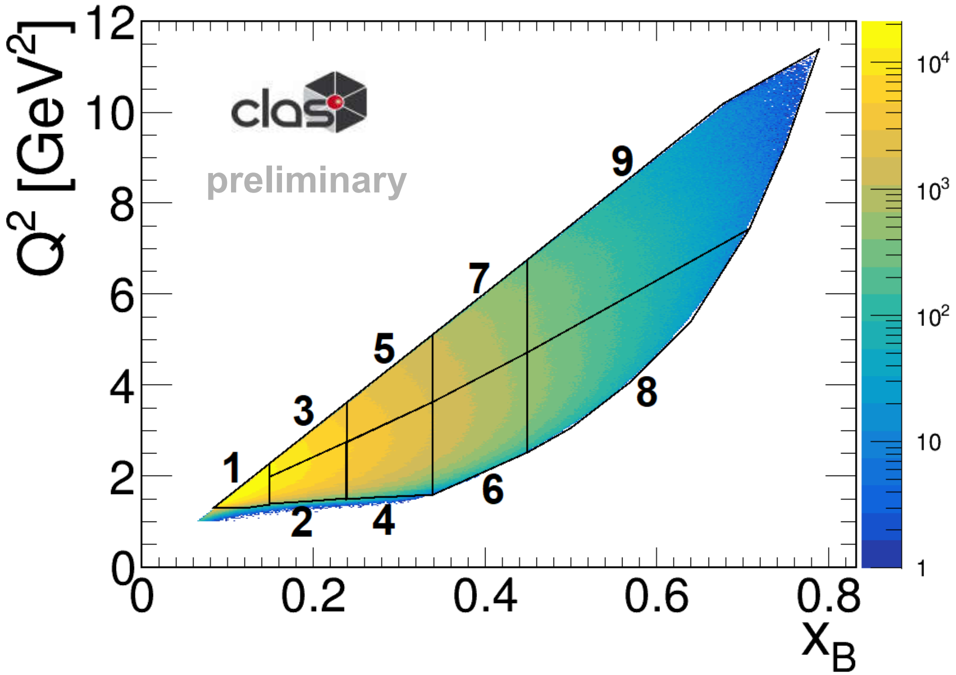
S. Diehl et. al (CLAS collab.)
Phys. Rev. Lett. 128, 062005 (2022)



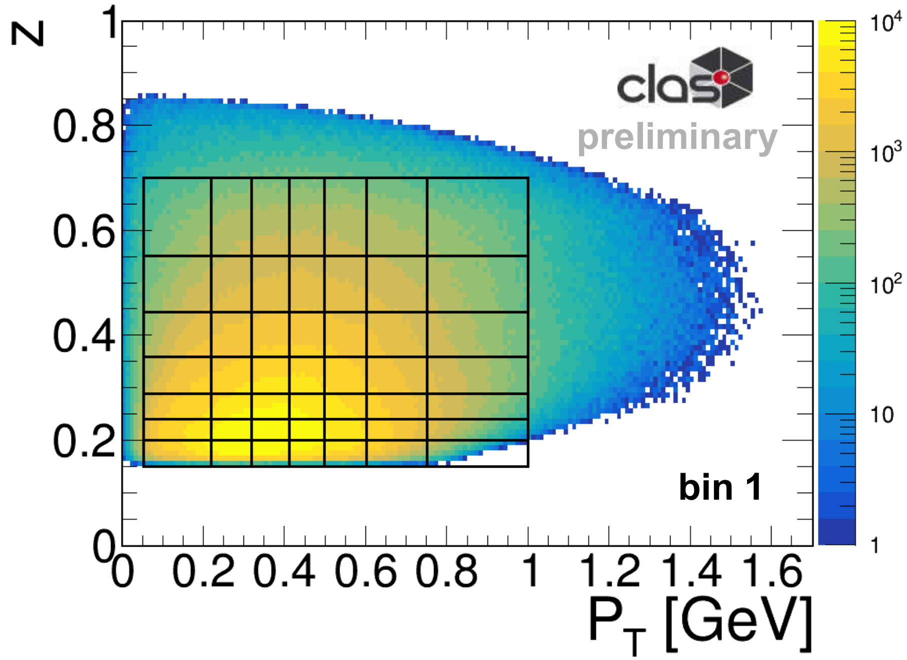
■ CLAS12 [PRL 128 (2022)]	■ CLAS [PRD 98 (2014)]
□ HERMES [Phys. Let. B 797 (2019)]	▽ COMPASS [Nucl. Phys. B 886 (2014)]

CLAS12: A multidimensional study in Q^2, x_B, z and P_T for $\pi^{\pm}$, π^0 and $K^{\pm}$

A Fully Multidimensional Binning



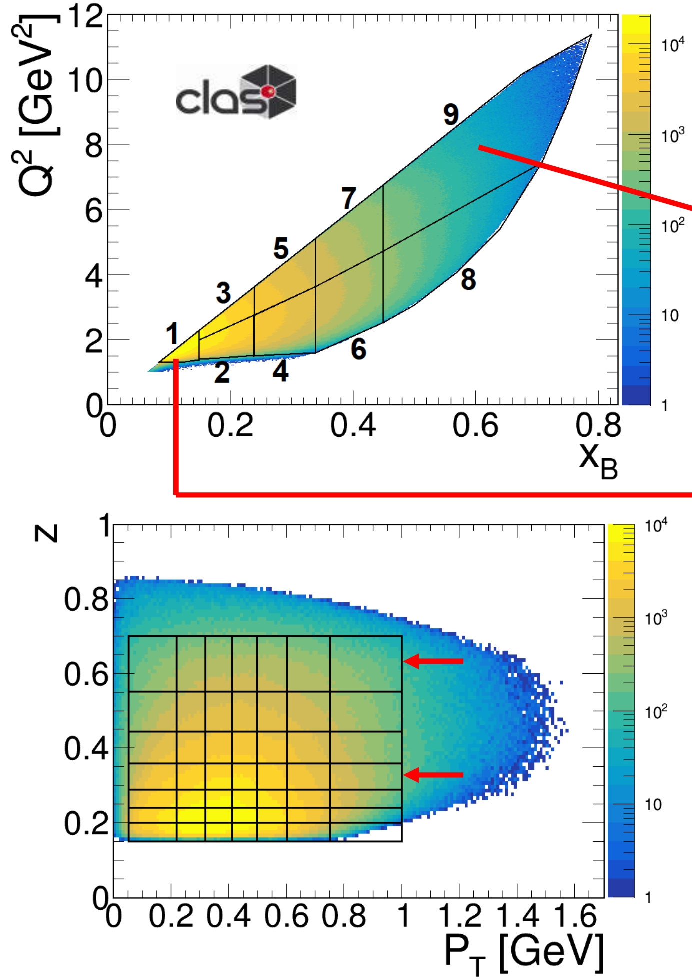
9 bins in Q^2 - x_B

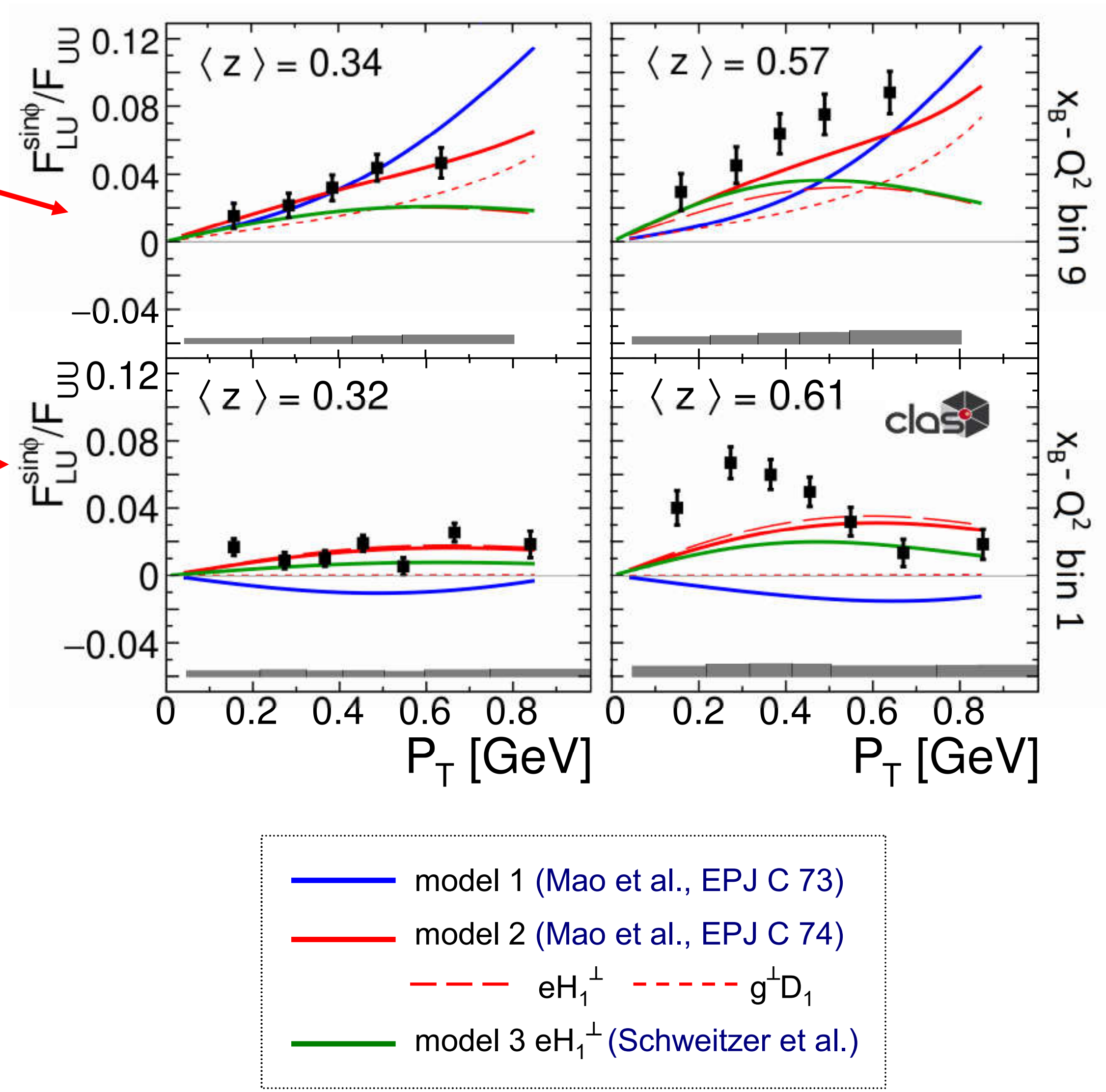


up to 7 x 7 bins in z - P_T
for each Q^2 - x_B bin

in total: 344 bins x 12 bins in Φ ~ 4130 BSA bins

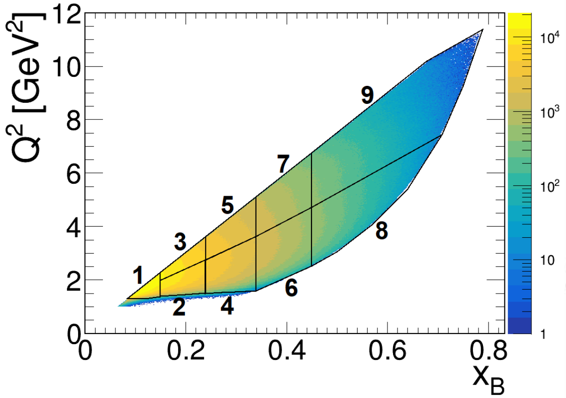
Multidimensional (4D) Single π⁺ SIDIS with CLAS12

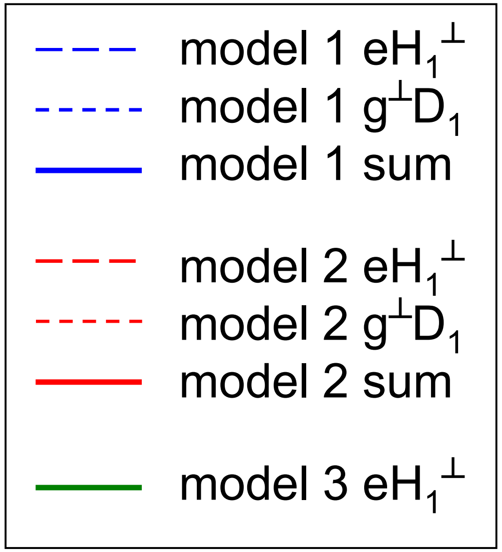


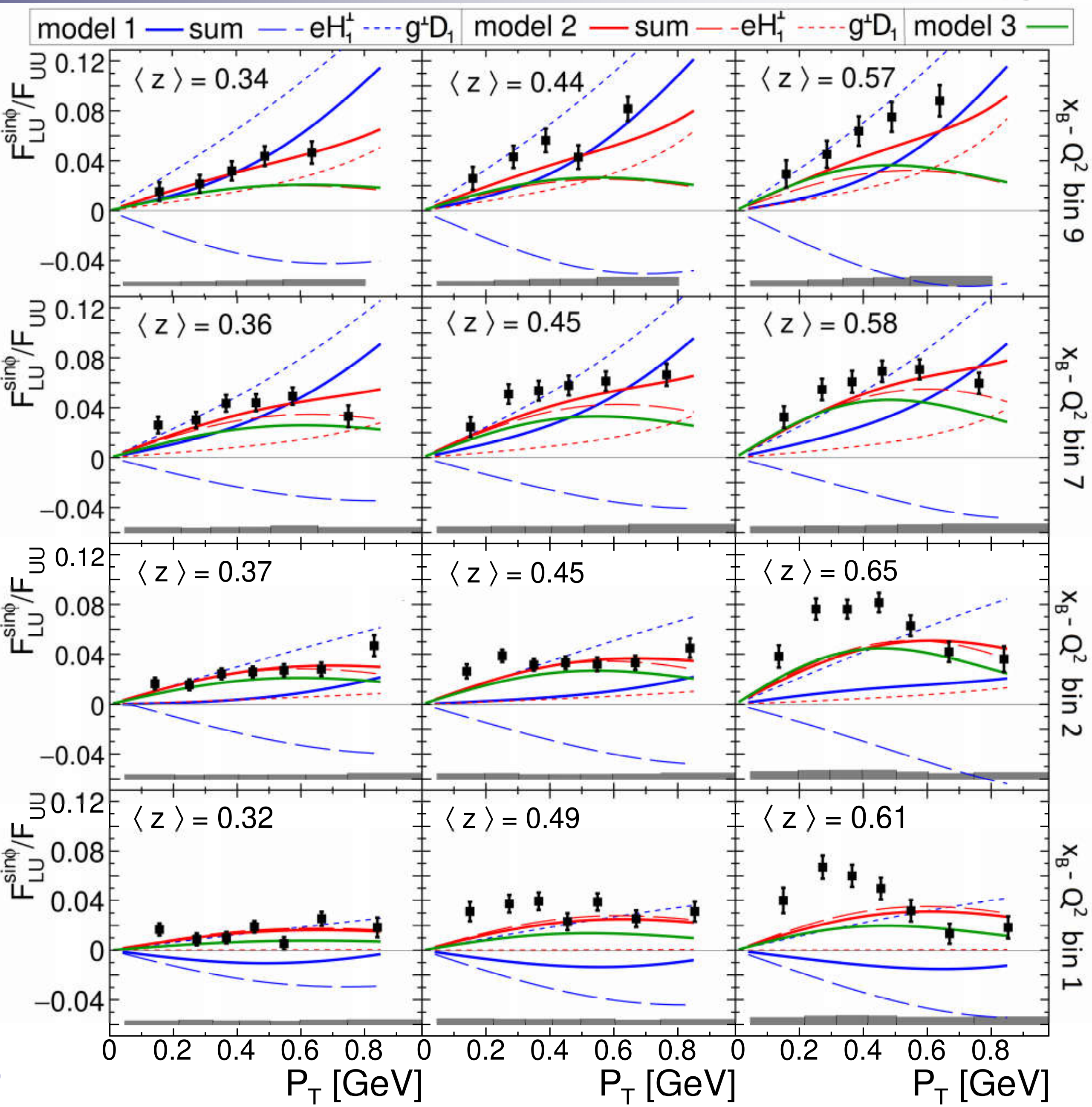


S. Diehl et. al (CLAS collab.), Phys. Rev. Lett. 128, 062005 (2022)

π^+ P_T Dependence

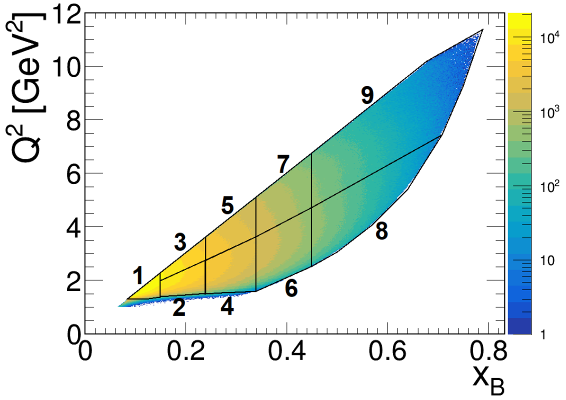




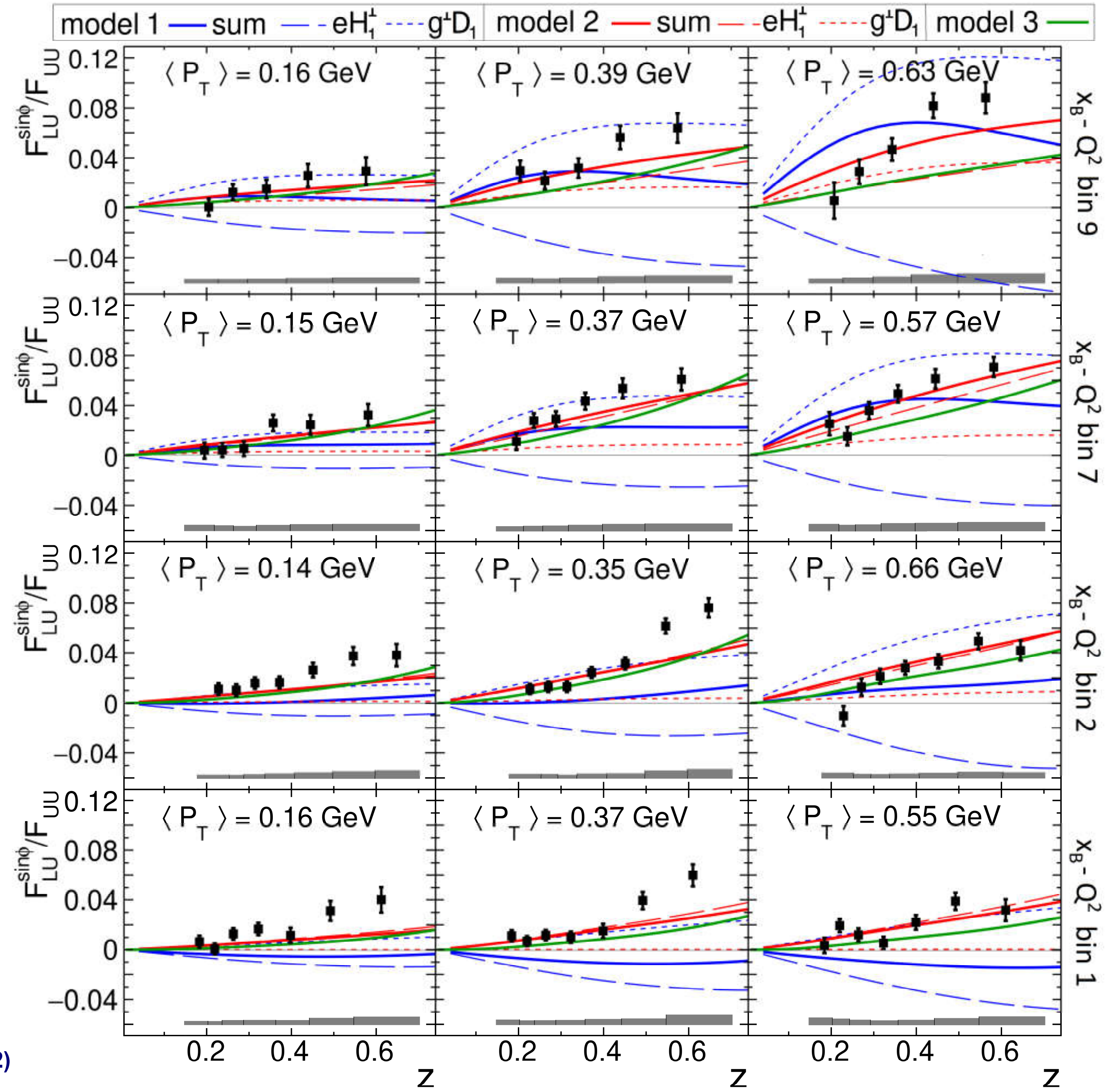


S. Diehl et. al (CLAS collab.) Phys. Rev. Lett. 128, 062005 (2022)

π⁺ z Dependence



model 1 eH₁⊥
model 1 g⊥D₁
model 1 sum
model 2 eH₁⊥
model 2 g⊥D₁
model 2 sum
model 3 eH₁⊥

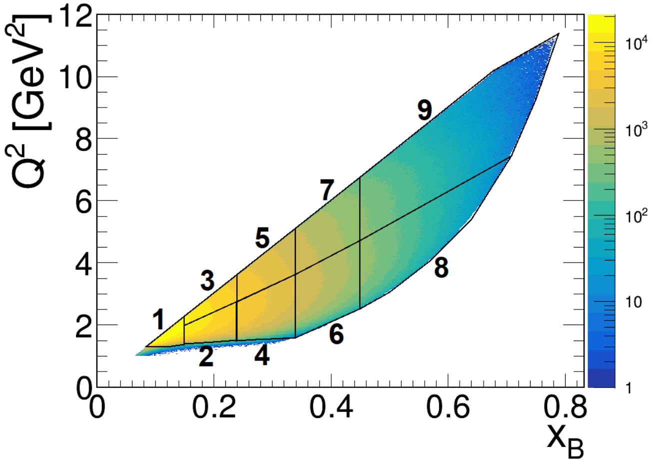


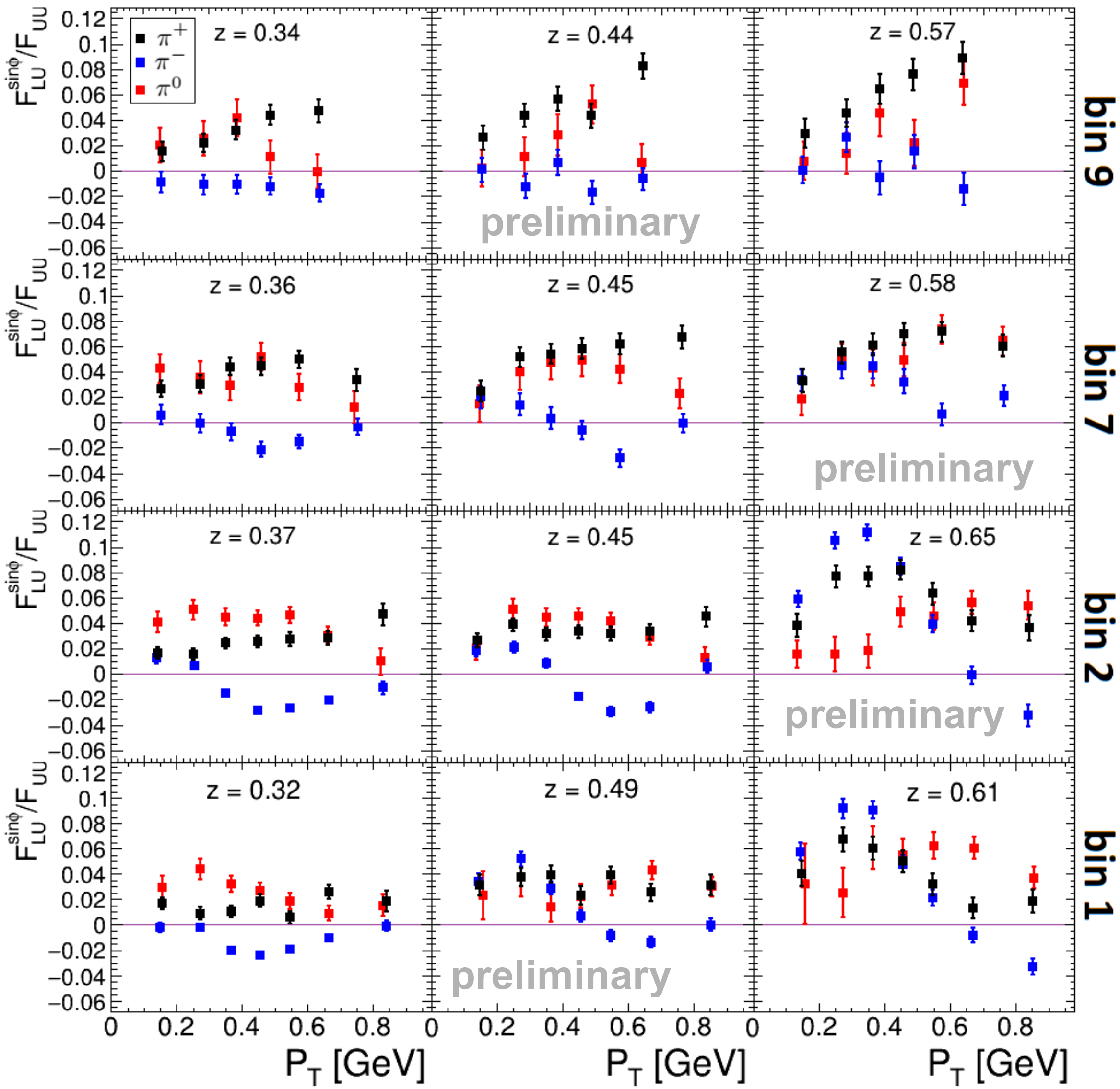
clas

S. Diehl et. al (CLAS collab.) Phys. Rev. Lett. 128, 062005 (2022)

Flavour Effects in Single Pion SIDIS

➔ Measurement of all 3 pions allows a flavor decomposition of TMDs and FFs





clas

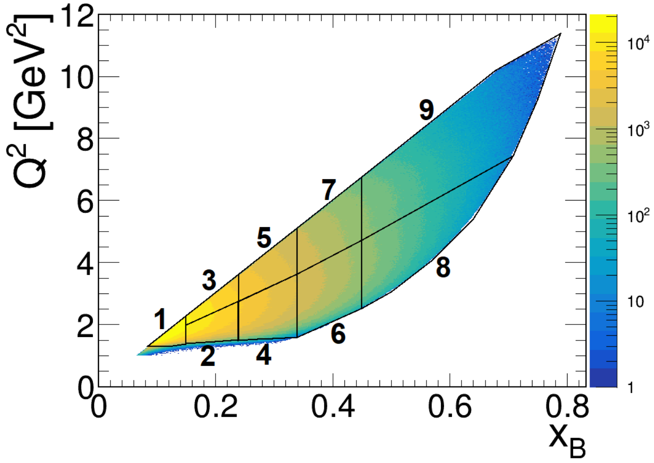
preliminary

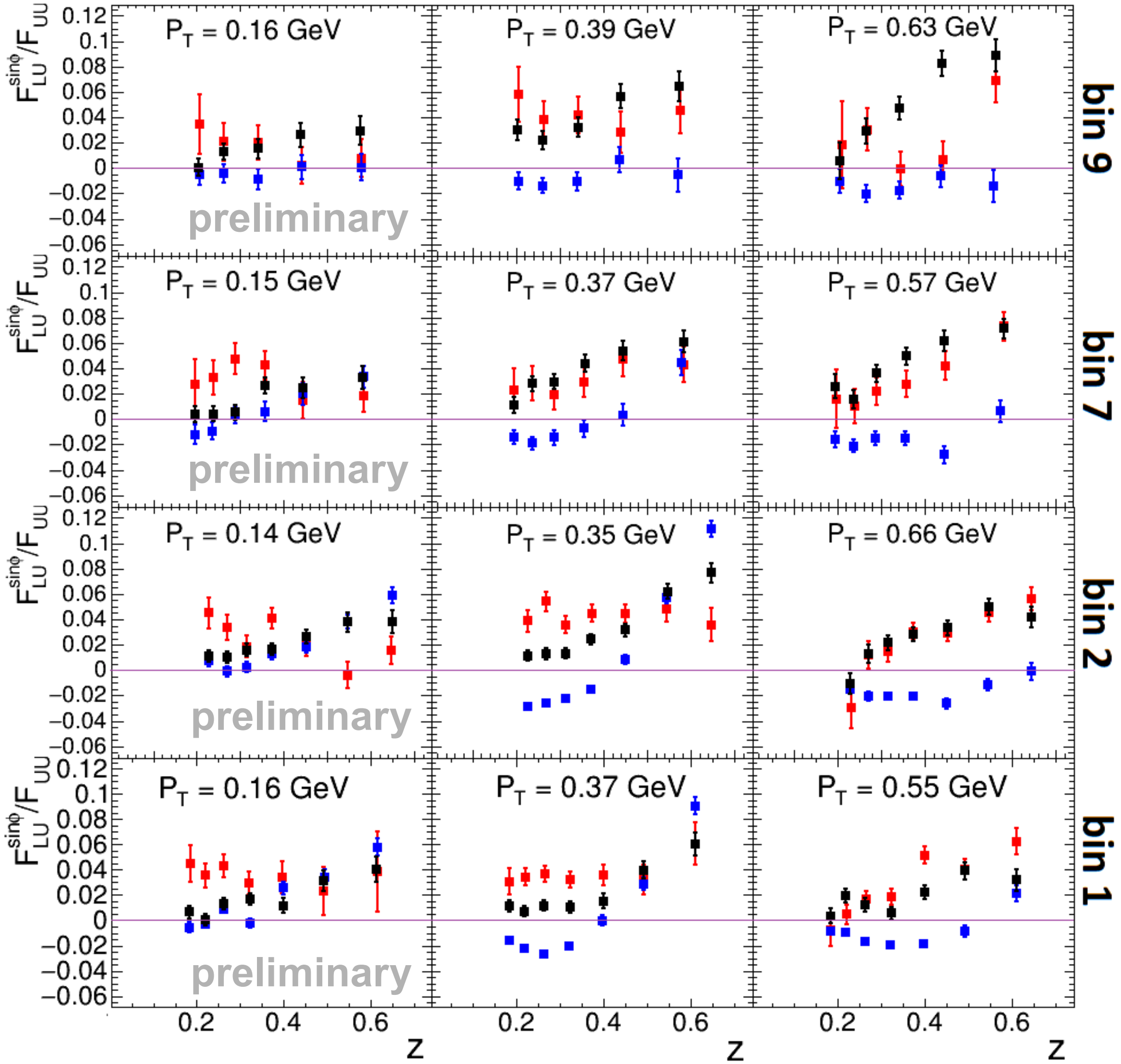
■ π^+
■ π^0
■ π^-

S. Diehl (JLU + UConn)

Flavour Effects in Single Pion SIDIS

→ Measurement of all 3 pions allows a flavor decomposition of TMDs and FFs



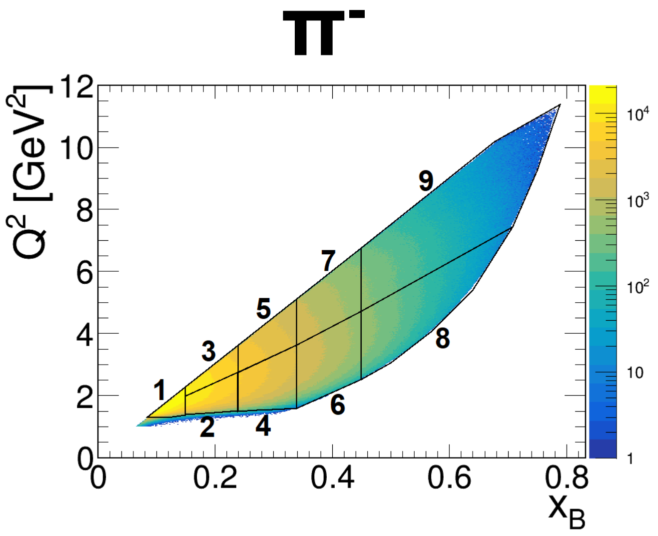


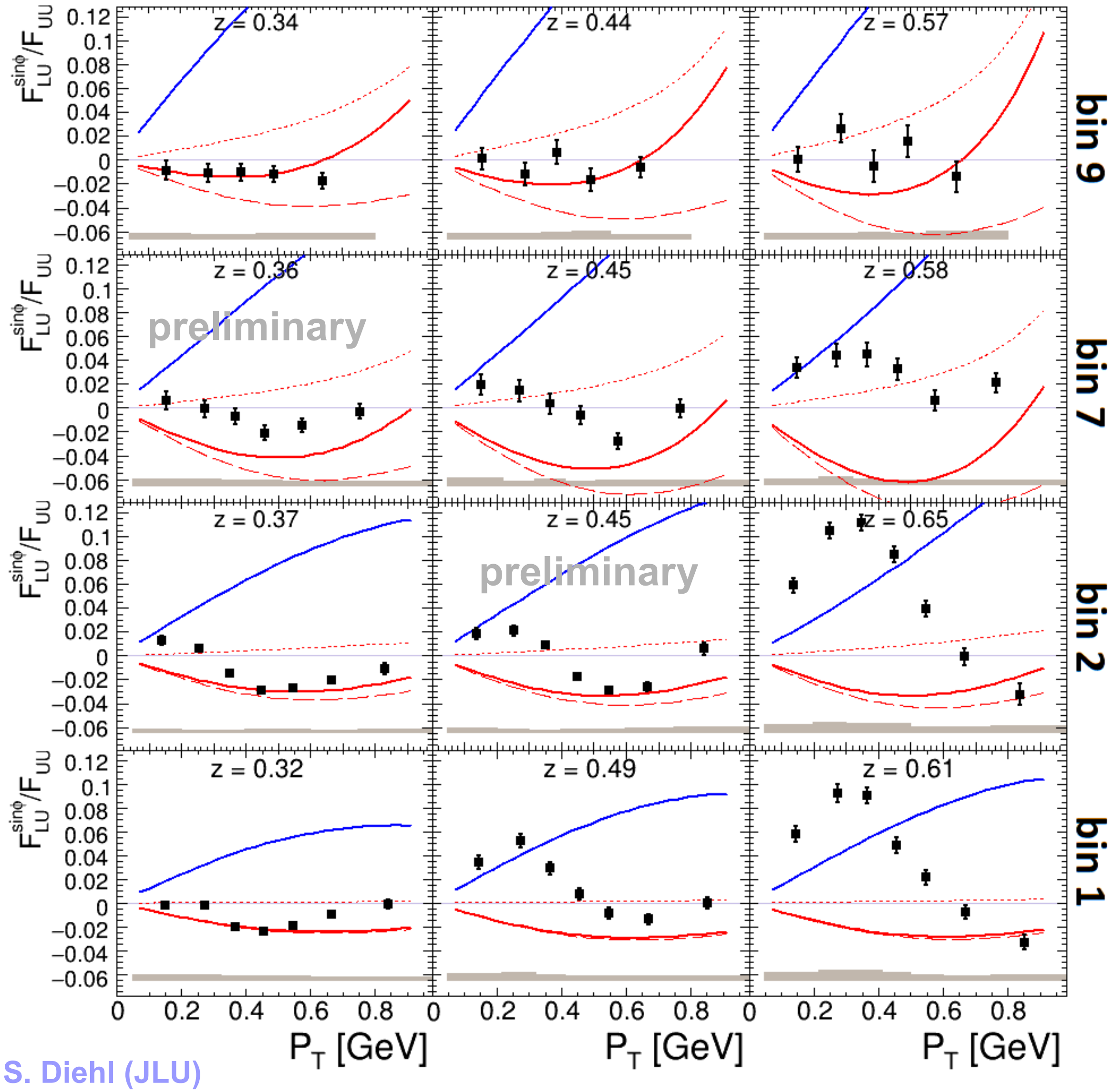
preliminary

■ π^+
■ π^0
■ π^-

S. Diehl (JLU + UConn)

Multidimensional Single Pion SIDIS with CLAS12





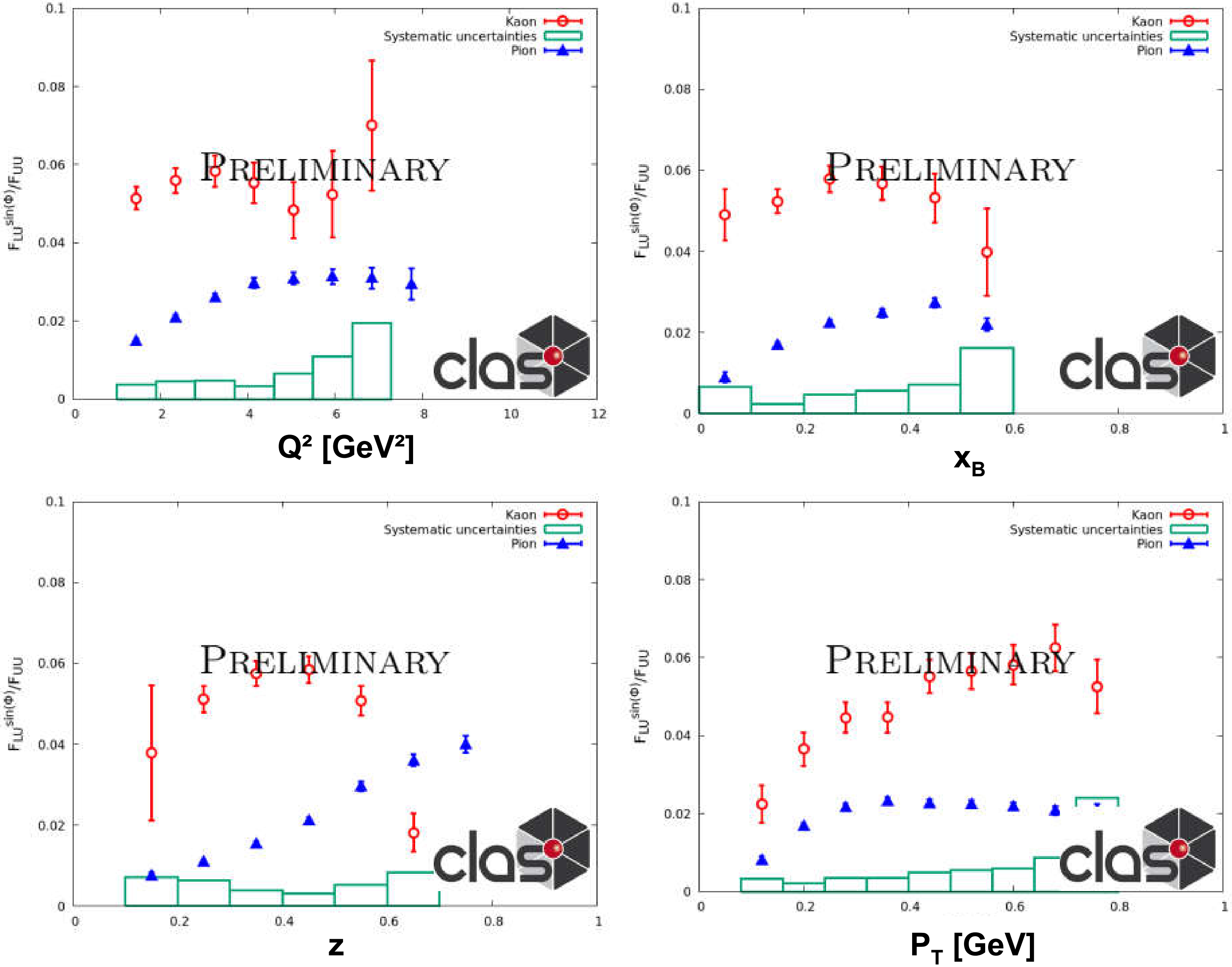
- Agreement of model 2 improves at high Q² and high P_T
- Higher twist effects

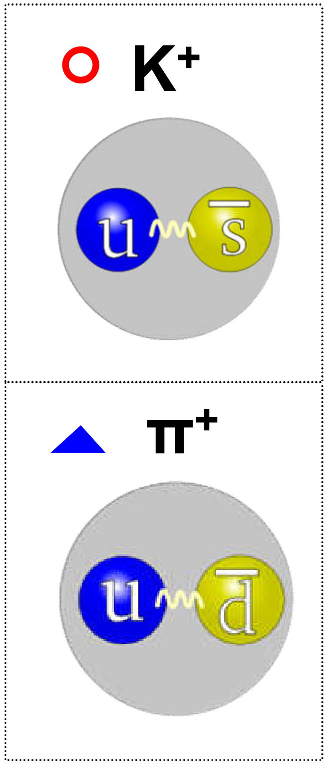
$$\mathcal{O}(M^2/Q^2, P_T^2/Q^2)$$

model 1 (Mao et al., EPJ C 73)
model 2 (Mao et al., EPJ C 74)
$eH_1^\perp$ $g^\perp D_1$

S. Diehl (JLU)

Charged Kaon SIDIS with CLAS12



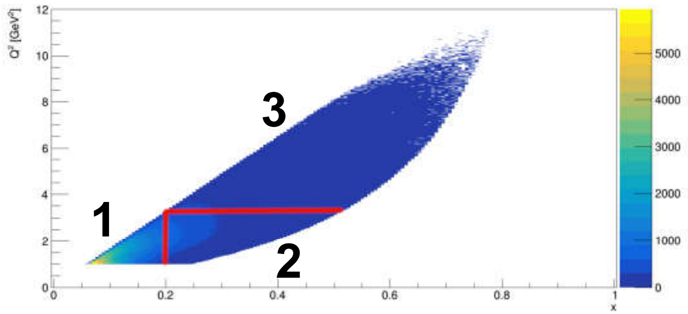


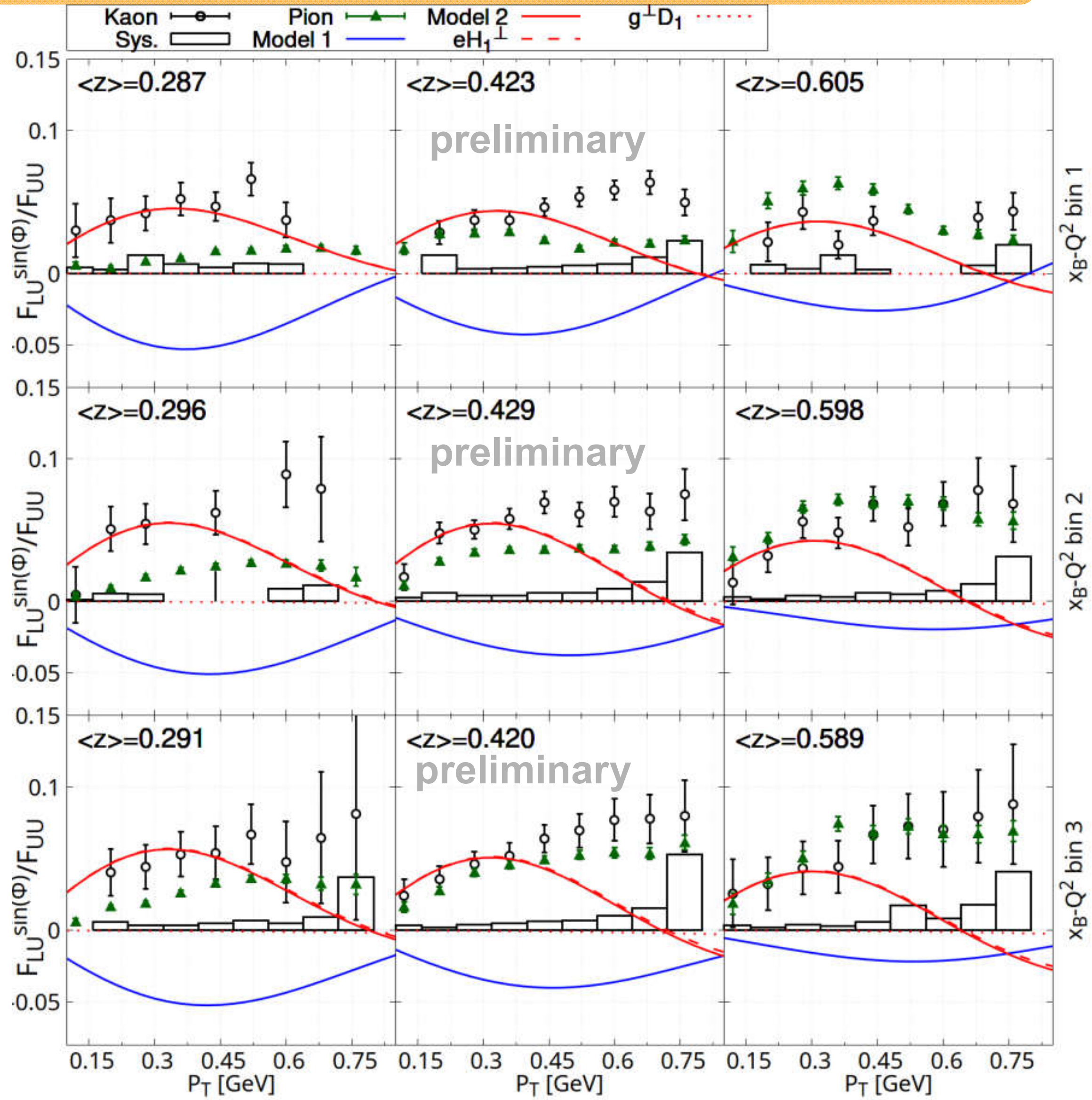
A. Kripko, S. Diehl
(JLU Giessen)

Kaon SIDIS with CLAS12

A. Kripko, S. Diehl (JLU Giessen)

K+





□ K^+

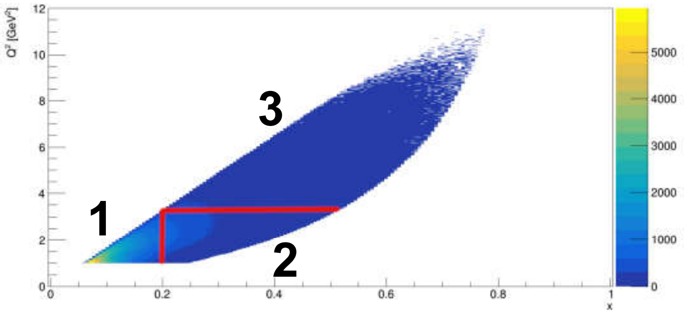
■ π^+

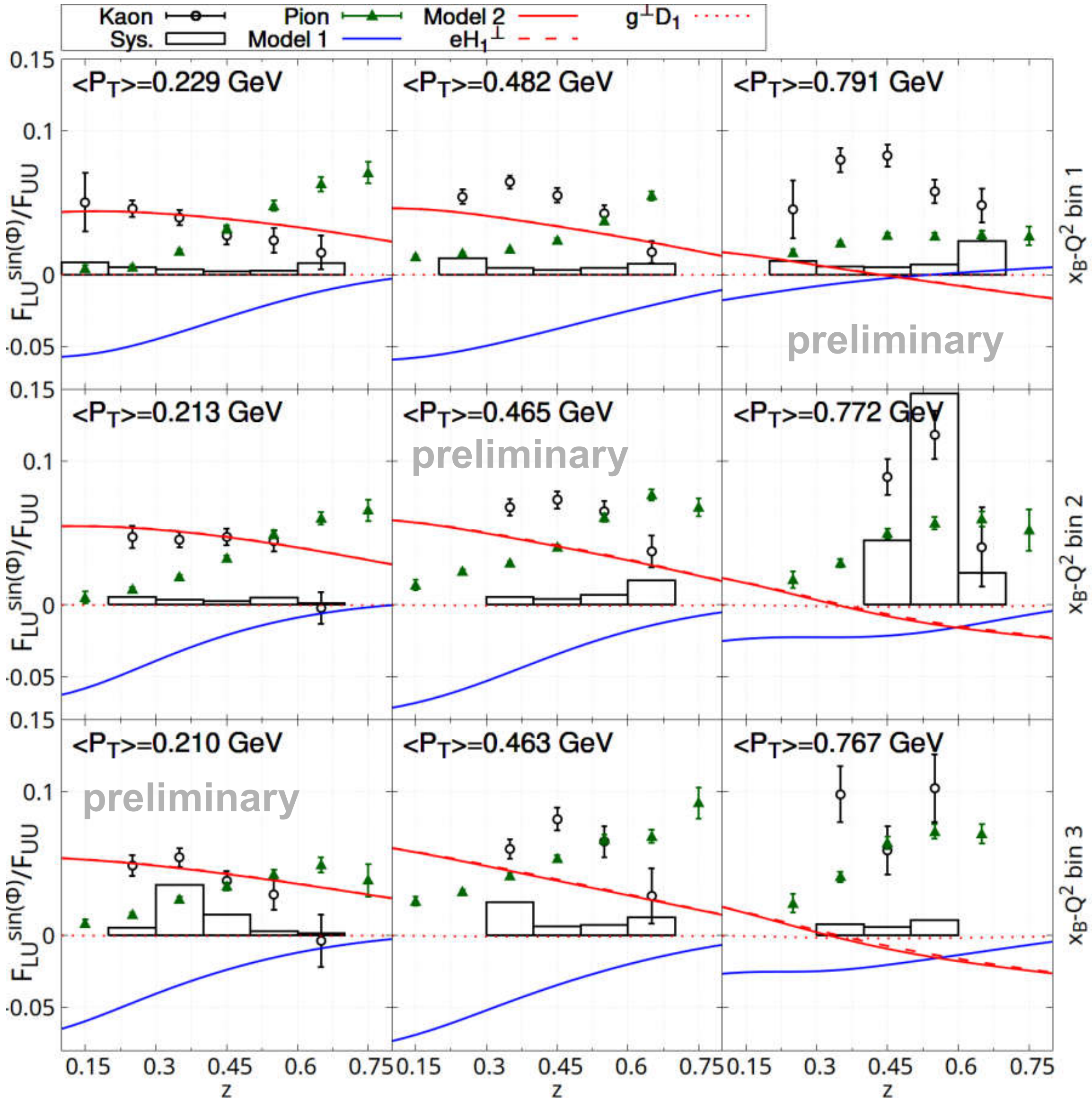
- model 1 (Mao et al., EPJ C 73)
- model 2 (Mao et al., EPJ C 74)
- $eH_1^{\perp}$ $g^{\perp}D_1$

Kaon SIDIS with CLAS12

A. Kripko, S. Diehl (JLU Giessen)

K^+





□ K^+

■ π^+

model 1 (Mao et al., EPJ C 73)

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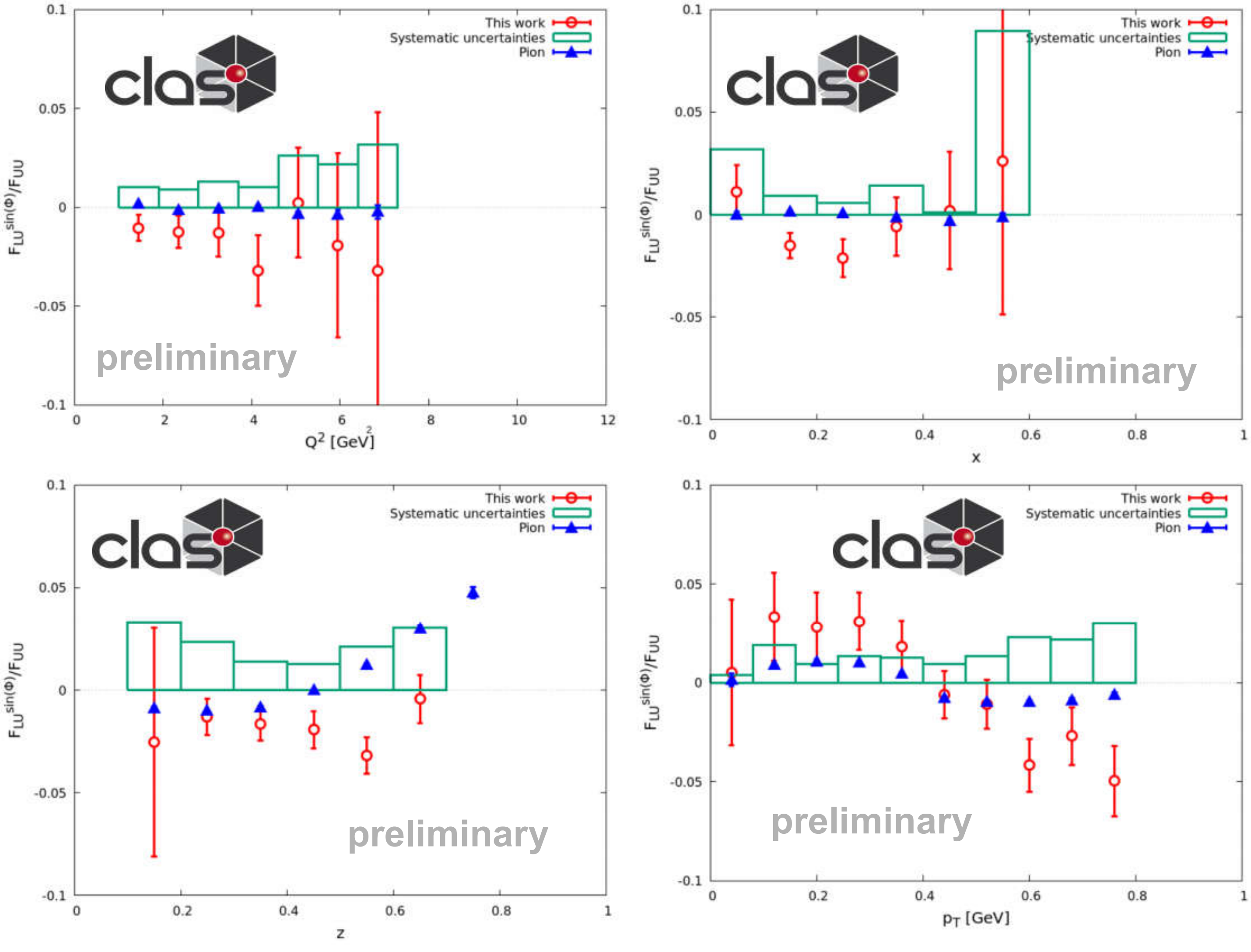
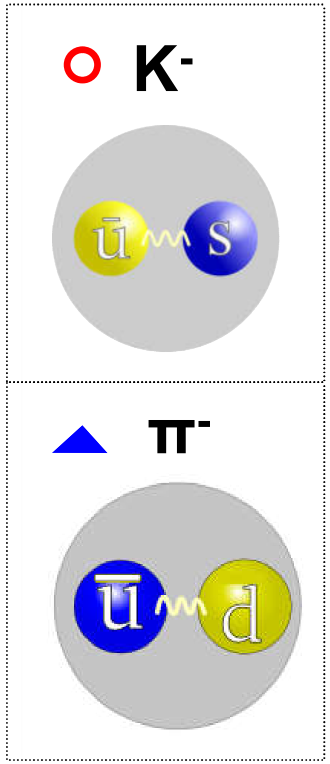
$eH_1^\perp$ $g^\perp D_1$

Kaon SIDIS with CLAS12

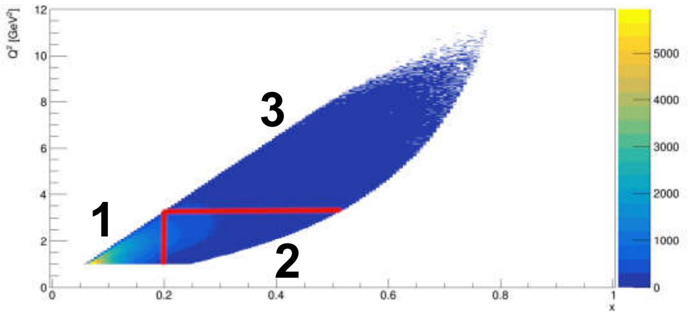


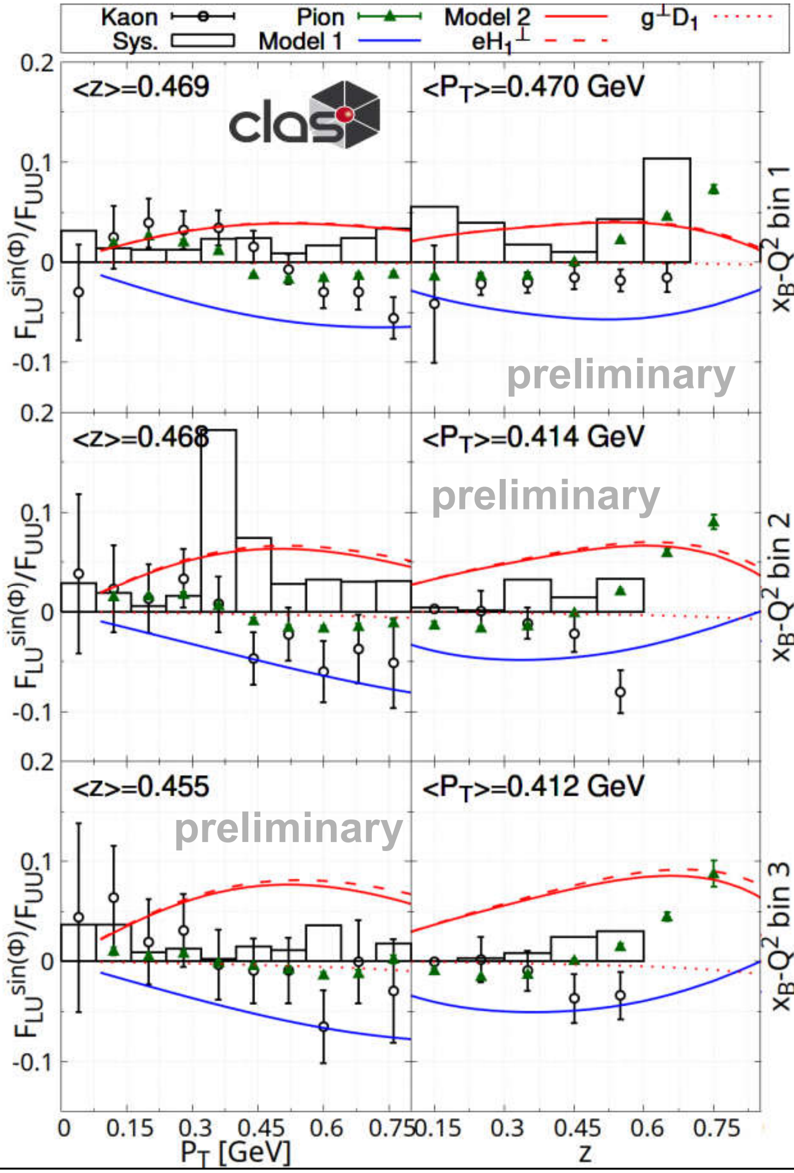


A. Kripko, S. Diehl (JLU Giessen)

Kaon SIDIS with CLAS12

K-





- Agreement of model 2 improves at low P_T
- Higher twist effects

$$\mathcal{O}(M^2/Q^2, P_T^2/Q^2)$$

model 1 (Mao et al., EPJ C 73)

model 2 (Mao et al., EPJ C 74)

$eH_1^\perp$ $g^\perp D_1$

Outlook: cos(φ) and cos(2φ) Moments for eπ⁺X

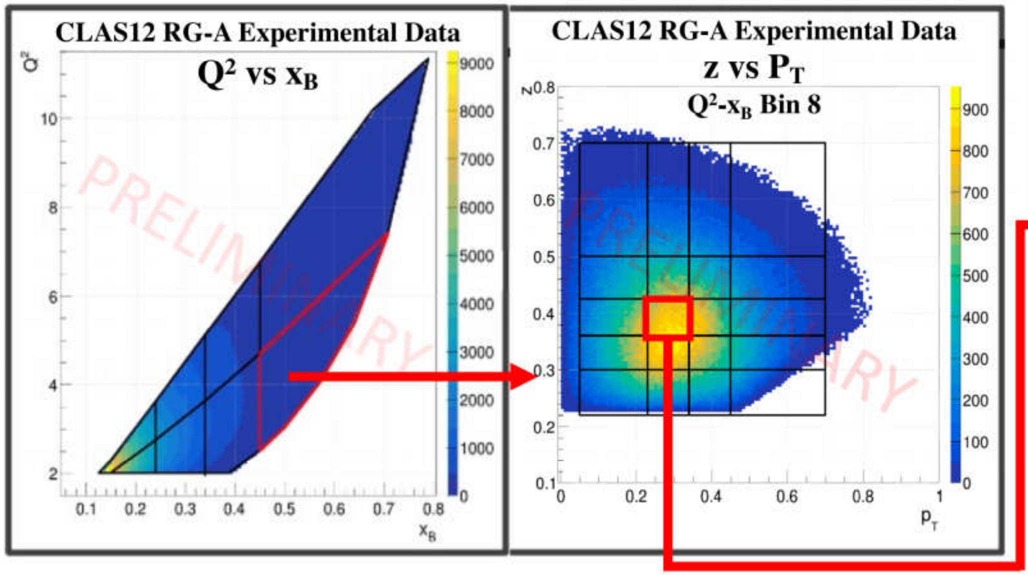
$$F_{UU}^{\cos\phi_h} = \frac{2M}{Q}\,\zeta\left(-\frac{\hat{\mathbf{h}}\cdot\mathbf{k}_T}{M_h}\left(x\,h\,H_1^{\perp} + \frac{M_h}{M}\,f_1\,\frac{\widetilde{D}^{\perp}}{z}\right) + \frac{\hat{\mathbf{h}}\cdot\mathbf{p}_T}{M}\left(x\,f^{\perp}\,D_1 + \frac{M_h}{M}\,h_1^{\perp}\,\frac{\widetilde{H}}{z}\right)\right)$$

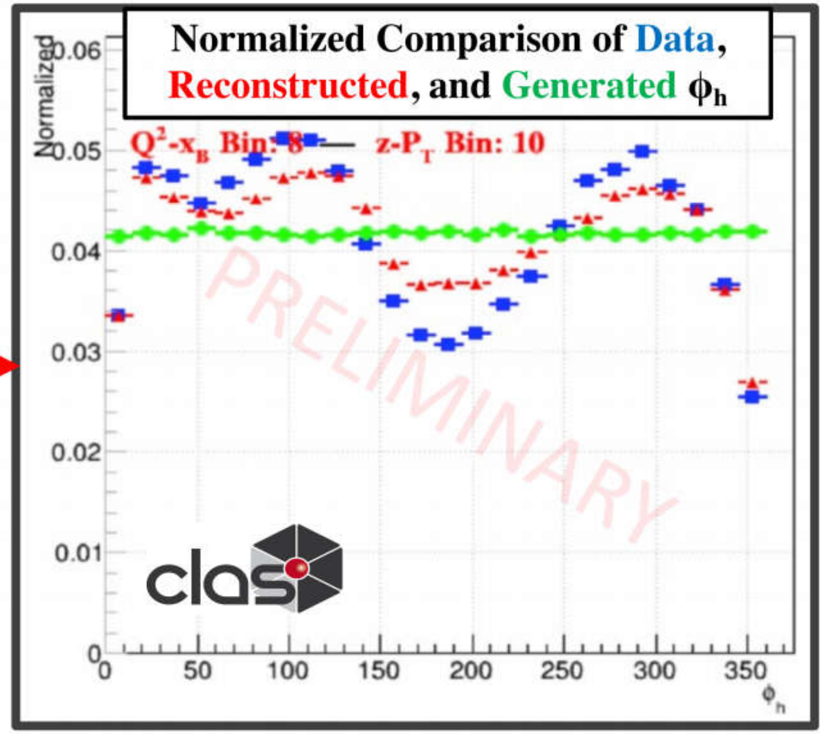
$$F_{UU}^{\cos 2\phi_h} = \zeta\left[-\frac{2(\hat{\mathbf{h}}\cdot\mathbf{k}_T)(\hat{\mathbf{h}}\cdot\mathbf{p}_T) - \mathbf{k}_T\cdot\mathbf{p}_T}{M\;M_h} h_1^{\perp} H_1^{\perp} \;+\; \frac{1}{Q^2} f_1 D_1 \;+\; ???\right]$$

Multidimensional Kinematic Binning (5 Dimensions)

8 Q^2-x_B Bins Total – 20-49 z-P_T Bins (per Q^2-x_B bin)

ϕ_h distribution for the Q^2-x_B-z-P_T bin shown in red

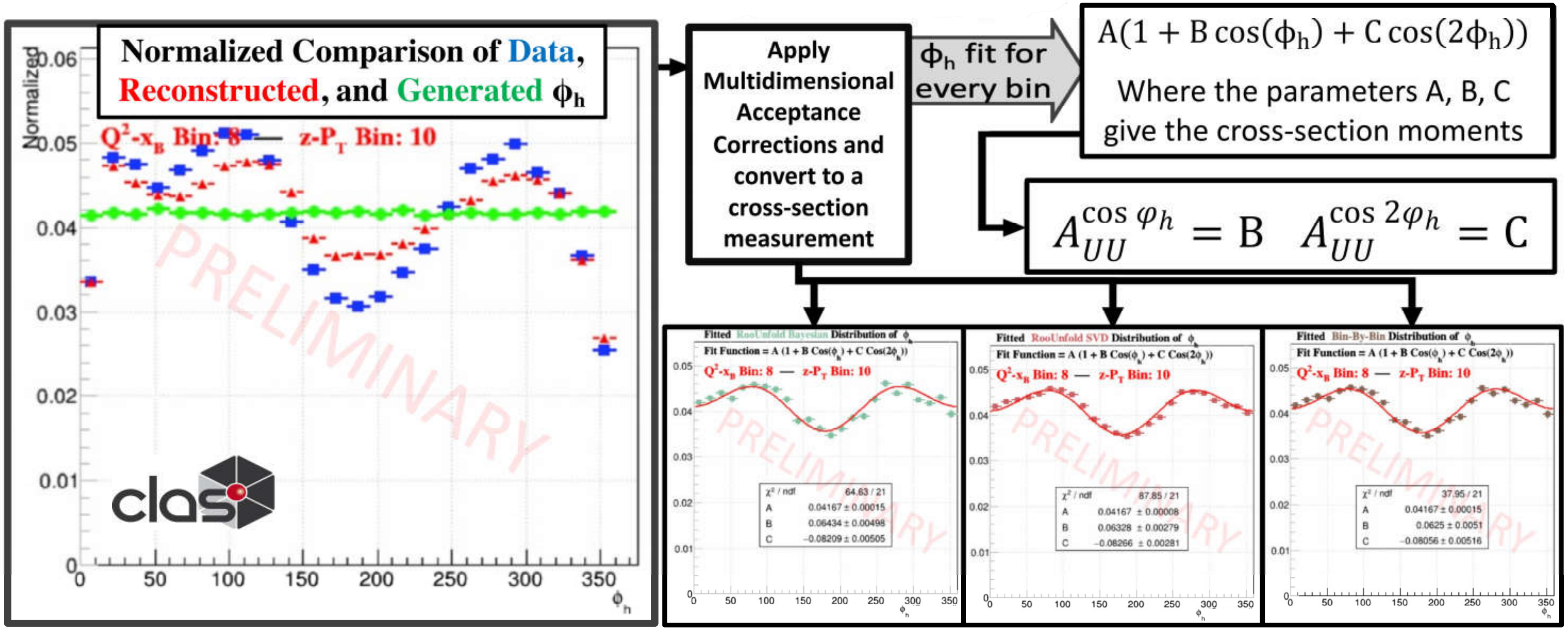




ongoing study by R. Cappobianco (UConn)

Outlook: cos(φ) and cos(2φ) Moments for eπ⁺X

Using the Multidimensional Kinematic Bin from prior example

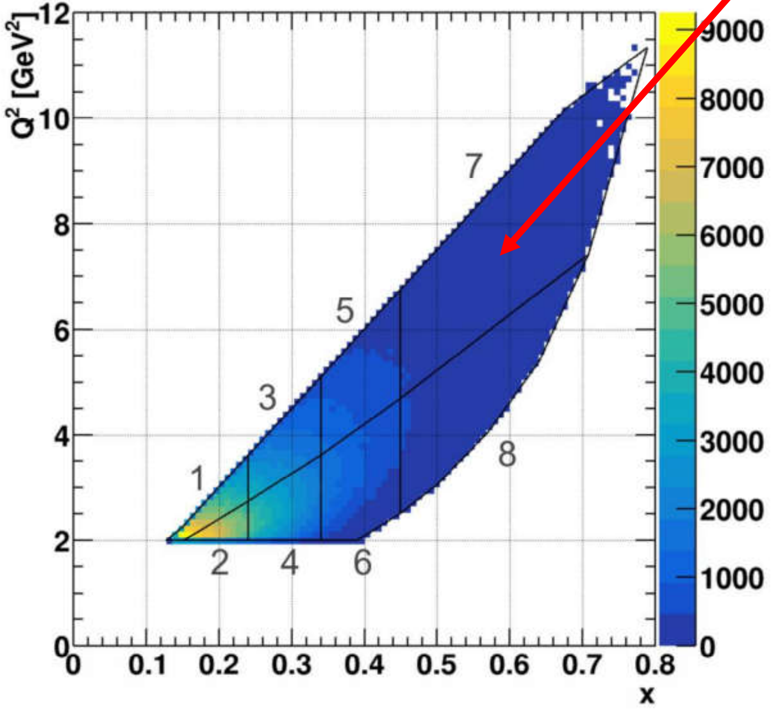


ongoing study by R. Cappobianco (UConn)

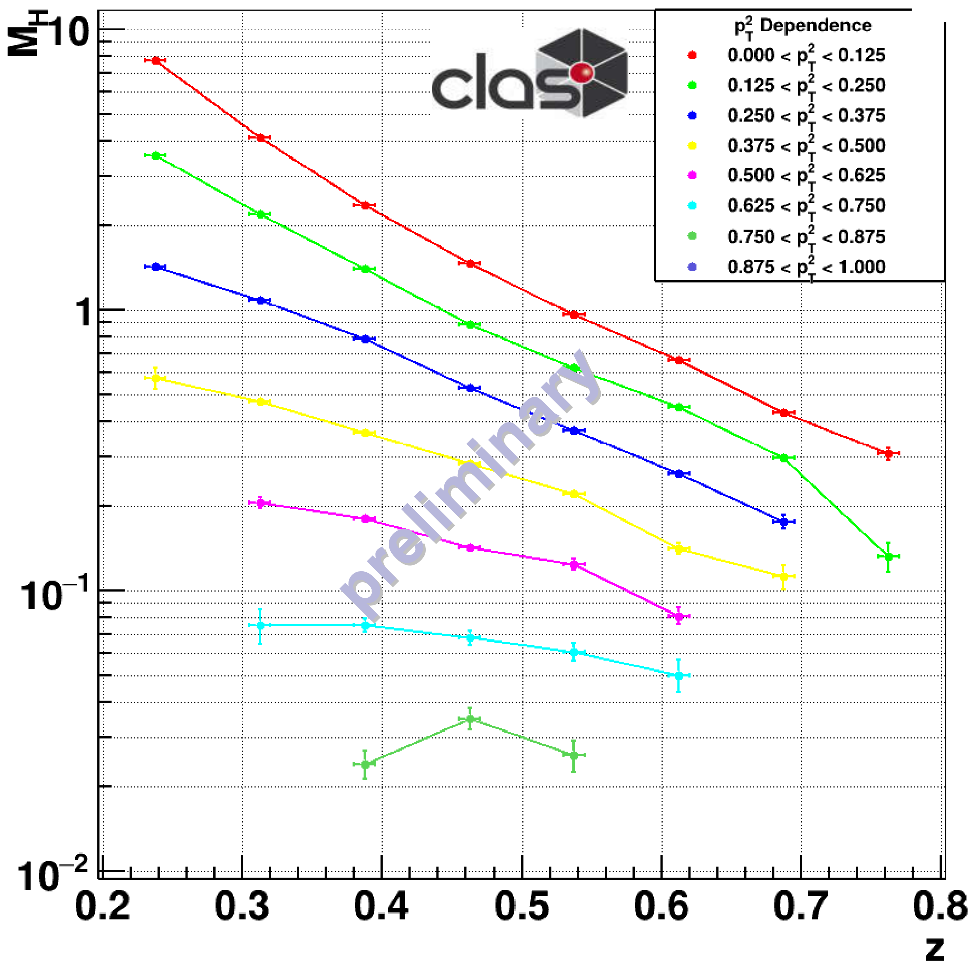
➔ **Similar studies are ongoing for π^- and $K^\pm$ (S. Diehl, A. Kripko, JLU)**

Outlook: π^0 Multiplicities

$$\frac{d^2 M^h(x, Q^2, z, P_{hT}^2)}{dz P_{hT}^2} = \left(\frac{d^4\sigma^h}{dx dQ^2 dz dP_{hT}^2}\right) / \left(\frac{d^2\sigma^{DIS}}{dx dQ^2}\right)$$



x-Q^2 Bin 7 : $M_H(z)$



ongoing study by M. Scott (Argonne)

Outlook: LT separation of the SIDIS cross section

$$\frac{d\sigma}{dx\, dQ^2\, dz\, dP_{h\perp}^2\, d\phi_h} \sim F_{UU,T} + \epsilon\, F_{UU,L}$$

twist 3: $F_{UU,T} = \zeta[f_1 D_1]$ $\quad F_{UU,L} = 0$

twist 4: $\mathcal{O}(M^2/Q^2, P_T^2/Q^2)$ $\quad F_{UU,L} \sim \frac{M^2}{Q^2}\zeta\left(\frac{4k_T^2}{M^2} f_1 D_1 + ...\right)$

Goal: Separate the contributions from longitudinal and transverse virtual photons via a Rosenbluth separation

➔ Proposal for a measurement with CLAS12 submitted to PAC this year

➔ Planed measurement in hall C at JLAB

➔ **Final clarification of higher twist contributions and their kinematic dependence!**

Summary

- TMDs provide a unifying framework to study the 3-D quark and gluon structure of the nucleon
- 3-D imaging of nucleons uncovers the rich dynamics of QCD
- CLAS12 allows high precision measurements of TMDs with large kinematic coverages in the valence quark regime!
- More results for the unpolatized proton target and results for a longitudinally polarized target (A_{UL}, A_{LL}) as well as results for a neutron target (deuteron) will follow from CLAS12

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