SPECIAL RESEARCH CENTRE FOR THE SUBATOMIC STRUCTURE OF MATTER

The 4th International Workshop on Nucleon Structure at Large Bjorken x HiX2014

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TRANSVERSE PHYSICS: SIVERS EFFECT

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THE UNIVERSITY of ADELAIDE
SUB CRUCE LUMEN

OUTLOOK

- **Introduction and Motivation.**

- **SIDIS with Transversely Polarized Target:**
  - ***Sivers PDF from One- and Two- Hadron Production***
  - ***mLEPTO predictions for COMPASS SSAs.***
  - ***mPYTHIA predictions for CLAS12 and EIC SSAs.***

- **Conclusions.**

SIVERS PDF

D. Sivers: PRD 41, 83 (1990).

- *Sivers Effect* describes the correlation of the *unpolarized quark's TM* with the *transverse spin* of the nucleon

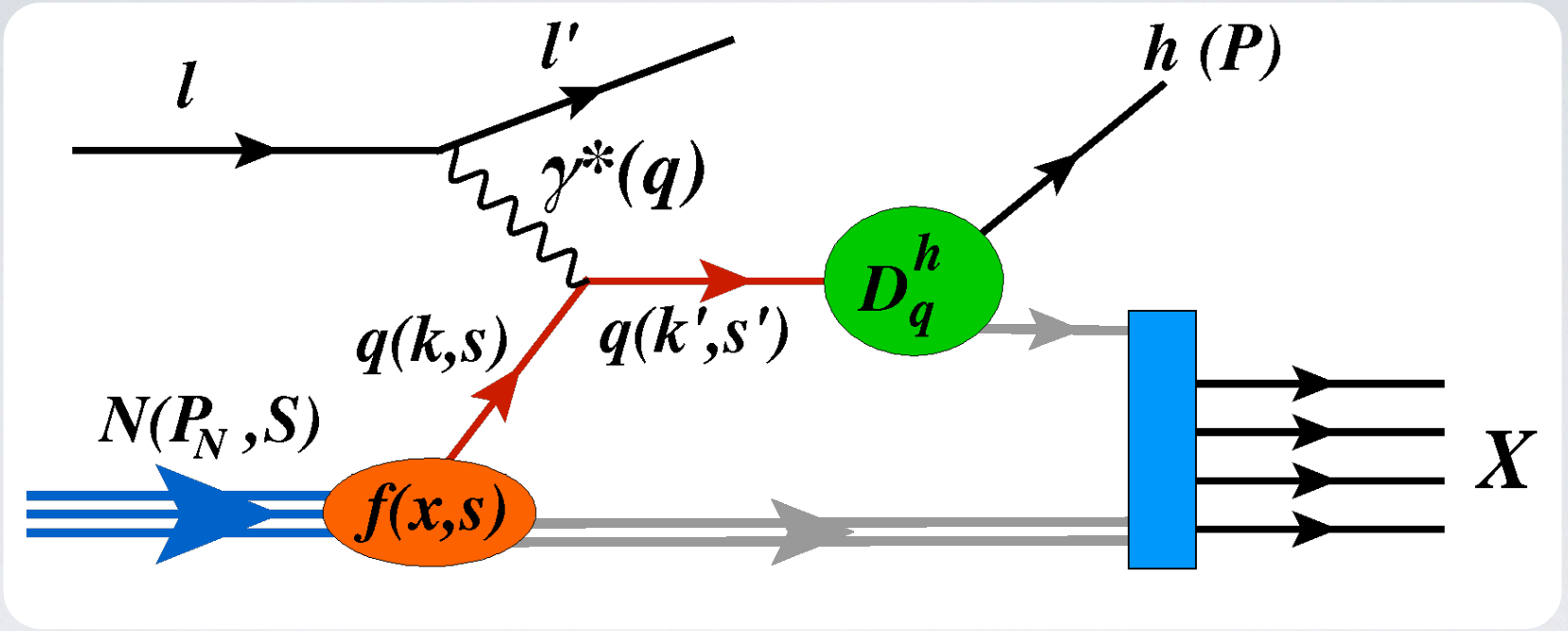
N/q	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	$g_{1T}^\perp$	$h_1 h_{1T}^\perp$

$$f_\uparrow^q(x, \boldsymbol{k}_T) = f_1^q(x, k_T) + \frac{[\boldsymbol{S} \times \boldsymbol{k}_T]_3}{M} f_{1T}^{\perp q}(x, k_T)$$

$$S_T k_T \sin(\varphi_k - \varphi_S)$$

- Naively *T-odd,* gauge-link should be included in the definition.
- **Accessible in Polarized SIDIS, Drell-Yan.**

$$f_{1T}^{\perp SIDIS} = -f_{1T}^{\perp DY}$$

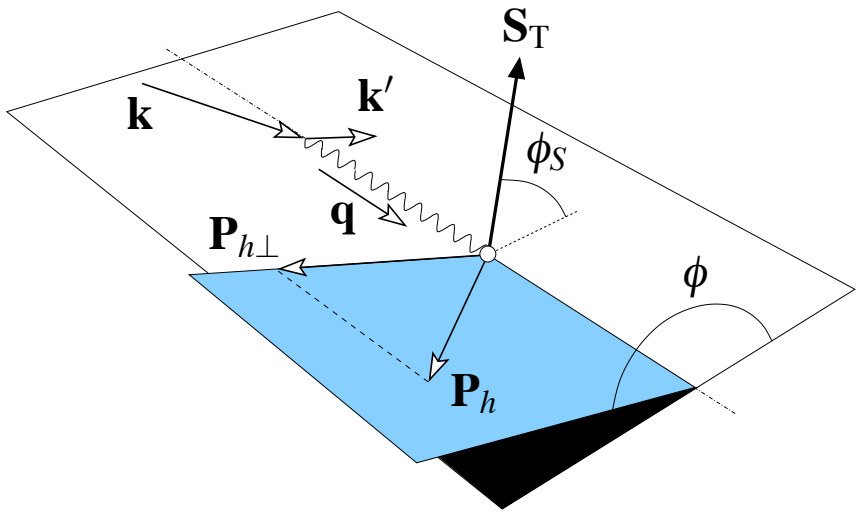


Sivers Effect in One Hadron SIDIS

SIDIS POLARIZED CROSS-SECTION

A. Bacchetta et. al.: JHEP08, 023 (2008).

- **For polarized SIDIS cross-section there are *18 terms* in leading twist expansion:**



$$\frac{d\sigma}{dx\,dy\,dz\,d\phi_S\,d\phi_h\,dP_{h\perp}^2} \sim F_{UU,T} + \varepsilon F_{UU,L} + \ldots$$

Sivers Term

$$+ |\boldsymbol{S}_\perp| \left[\sin(\phi_h - \phi_S) \left(F_{UT,T}^{\sin(\phi_h-\phi_S)} + \varepsilon\, F_{UT,L}^{\sin(\phi_h-\phi_S)} \right) + \varepsilon\, \sin(\phi_h + \phi_S)\, F_{UT}^{\sin(\phi_h+\phi_S)} + .. \right]$$

- **Extract the specific harmonics:**

$$F_{UU,T} \sim \mathcal{C}[f_1\ D_1]$$

$$F_{UT,T}^{\sin(\phi_h-\phi_S)} \sim \mathcal{C}[k_T f_{1T}^{\perp q}\ D_1]$$

$$\mathcal{C}[fg...] \equiv \sum_q \int d^2\boldsymbol{k}_T\ f\ g\ ...|_{\boldsymbol{P}_T=\boldsymbol{P}_\perp+z\boldsymbol{k}_T}$$

- *NEED TMD Fragmentation Function to access Sivers PDF from SIDIS!*

EMPIRICAL EXTRACTIONS OF SIVERS

M. Anselmino et. al.: PRD 72, 094007 (2005). PRD 86, 014028 (2012).

Talk by S. Melis

- *Sivers SSAs from SIDIS*
- Use LO expression for factorized cross-section.
- Parametrize PDFs and FFs.
- Use Gaussian TMD dependence.
- Also *TMD evolution* in 2012.

$$A^h_{Siv} \equiv 2\frac{\int d\varphi_S d\varphi_h\ (\sigma^h_\uparrow - \sigma^h_\downarrow)\sin(\varphi_h - \varphi_S)}{\int d\varphi_S d\varphi_h\ (\sigma^h_\uparrow + \sigma^h_\downarrow)}.$$

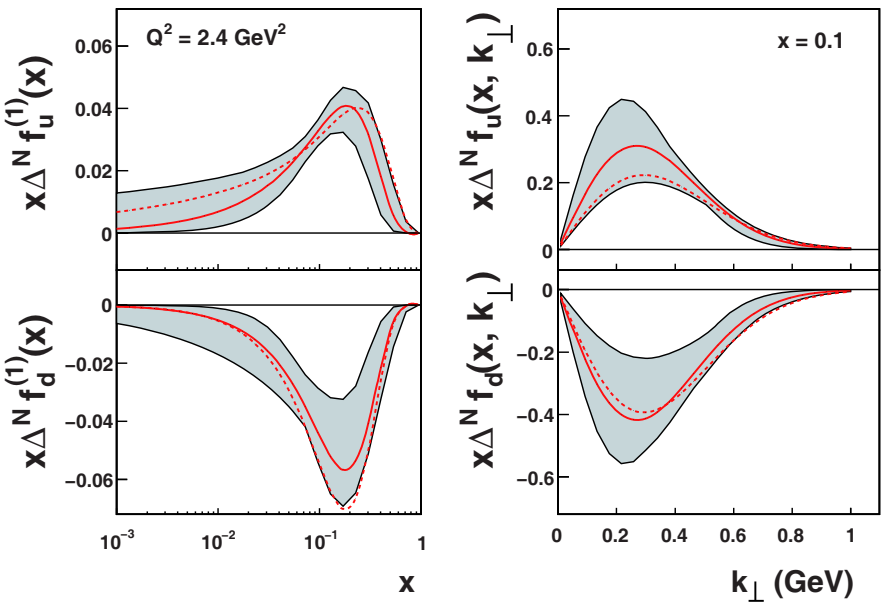
$$A^h_{Siv} \sim \mathcal{C}[k_T f^{\perp q}_{1T}\ D_1]/\mathcal{C}[f^q_1\ D^{h/q}_1]$$

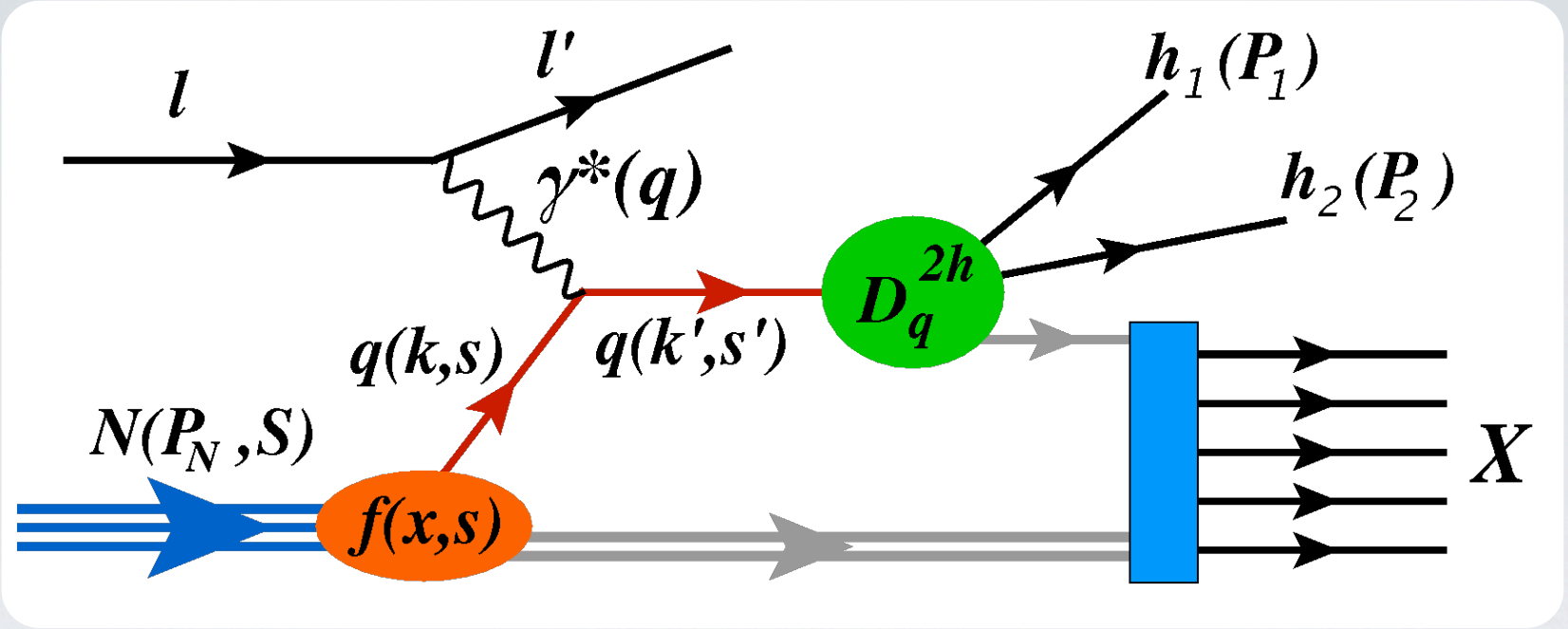
$$\Delta^N f_{q/p^\uparrow}(x,k_T) = \mathcal{N}_q(x)h(k_T)f^q_1(x,k_T)$$

$$\Delta^N f_{q/p^\uparrow} \equiv -\frac{2k_T}{M} f^{\perp q}_{1T}$$

$$f^q_1(x,k_T) = f_q(x)\frac{1}{\pi\mu^2}e^{-k_T^2/\mu^2}$$

- ***Fits to HERMES and COMPASS:***
- ***Current Data can only afford:***
  - ***Large*** uncertainties, esp. for sea.
  - Approximations: TM and flavor dependence of FF, etc.



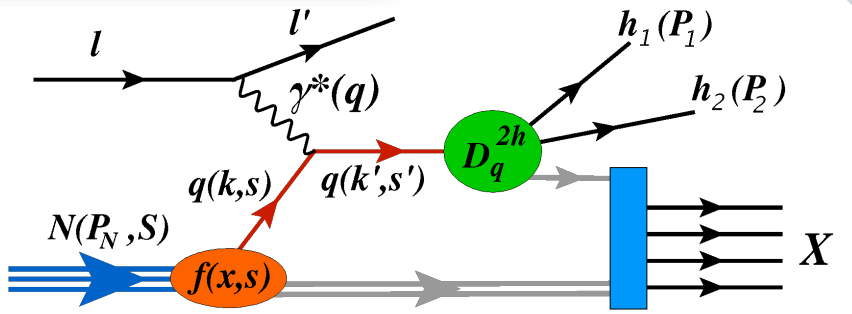


Sivers Effect in Two Hadron SIDIS

TWO-HADRON SIDIS

Kotzinian, H.M., Thomas: PRL.113, 062003 ; PRD.90, 074006 ; 1407.6572 (2014);

- Correlations of quark's TM transferred to **two hadrons.**



$$\frac{d\sigma^{h_1 h_2}}{dz_1\, dz_2\, d^2\boldsymbol{P}_{1T}\, d^2\ \boldsymbol{P}_{2T}} = C(x,Q^2)\,(\sigma_U + \sigma_S)$$

$$\sigma_U = \sum_q e_q^2 \int d^2\boldsymbol{k}_T\ f_1^q\ D_{1q}^{h_1 h_2} \qquad \sigma_S = \sum_q e_q^2 \int d^2\boldsymbol{k}_T \frac{[\boldsymbol{S}_T \times \boldsymbol{k}_T]_3}{M} f_{1T}^{\perp q}\ D_{1q}^{h_1,h_2}$$

- Unpolarized fully unintegrated dihadron Fragmentation Function

✦ **Single hadron** FF.

$$D_{1q}^{h}(z, P_\perp)$$

✦ **Dihadron** FF.

$$D_{1q}^{h_1,h_2}(z_1, z_2, P_{1\perp}, P_{2\perp}, \boldsymbol{P}_{1\perp}\cdot\boldsymbol{P}_{2\perp})$$

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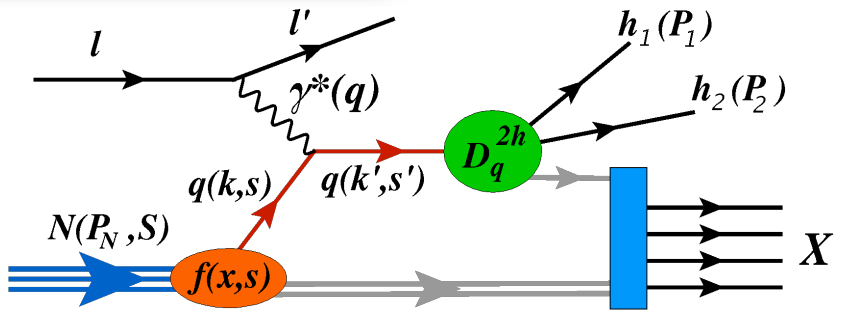


$$\frac{d\sigma^{h_1 h_2}}{dz_1\, dz_2\, d^2\boldsymbol{P}_{1T}\, d^2\,\boldsymbol{P}_{2T}} = C(x,Q^2)\,(\sigma_U + \sigma_S)$$

$$\sigma_U = \sum_q e_q^2 \int d^2\boldsymbol{k}_T\; f_1^q\; D_{1q}^{h_1 h_2} \qquad \sigma_S = \sum_q e_q^2 \int d^2\boldsymbol{k}_T \frac{[\boldsymbol{S}_T \times \boldsymbol{k}_T]_3}{M} f_{1T}^{\perp q}\; D_{1q}^{h_1,h_2}$$

- Unpolarized fully unintegrated dihadron Fragmentation Function

✦ **Single hadron** FF.

$$D_{1q}^{h}(z, P_\perp)$$

✦ **Dihadron** FF.

$$D_{1q}^{h_1,h_2}(z_1, z_2, P_{1\perp}, P_{2\perp}, \boldsymbol{P}_{1\perp}\cdot\boldsymbol{P}_{2\perp})$$

two-hadron correlations

TWO-HADRON SIDIS

- Cross Section in terms of **Total and Relative Momenta**

$$\boldsymbol{P}_h = \boldsymbol{P}_1 + \boldsymbol{P}_2 \qquad \boldsymbol{R} = \frac{1}{2}(\boldsymbol{P}_1 - \boldsymbol{P}_2)$$

- The Sivers term:

$$\sigma_S = S_T \left(\sigma_T \frac{P_{hT}}{M} \sin(\varphi_T - \varphi_S) + \sigma_R \frac{R_T}{M} \sin(\varphi_R - \varphi_S) \right)$$

$$\int d\varphi_R \, \sigma_S = S_T \left(\sigma_{T,0} \frac{P_{hT}}{M} + \sigma_{R,1} \frac{R}{2M} \right) \sin(\varphi_T - \varphi_S)$$

$$\int d\varphi_T \, \sigma_S = S_T \left(\sigma_{T,1} \frac{P_{hT}}{2M} + \sigma_{R,0} \frac{R}{M} \right) \sin(\varphi_R - \varphi_S)$$

- **Non-vanishing σ_R is new! Contradiction with earlier results** Bianconi et al: PRD62, 034008 (2000)**? No:** Kotzinian et al: 1407.6572 (2014)

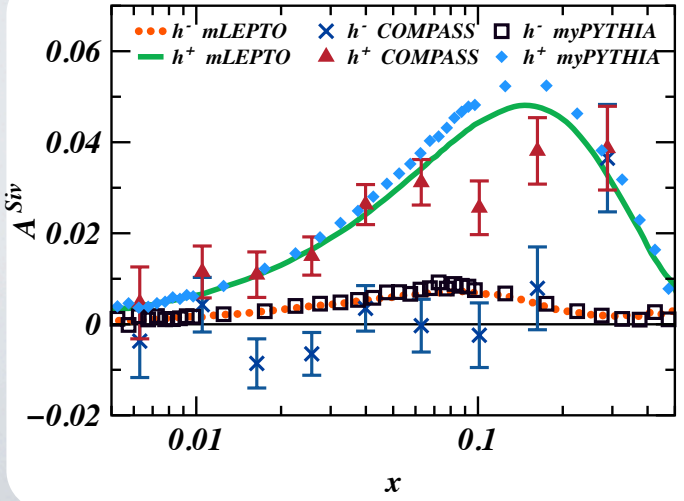
$$\boldsymbol{R}^P \equiv \boldsymbol{R} - (\boldsymbol{R} \cdot \hat{\boldsymbol{P}}_h)\hat{\boldsymbol{P}}_h \qquad \boldsymbol{R}^P \simeq \xi_2 \boldsymbol{P}_1 - \xi_1 \boldsymbol{P}_2$$

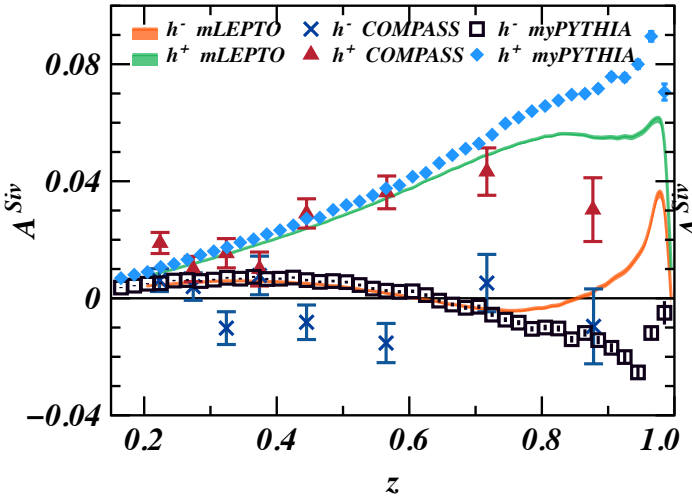
$$\boldsymbol{R}_T^P \simeq \xi_2 \boldsymbol{P}_{1\perp} - \xi_1 \boldsymbol{P}_{2\perp} \qquad \xi_i \equiv z_i/(z_1 + z_2)$$

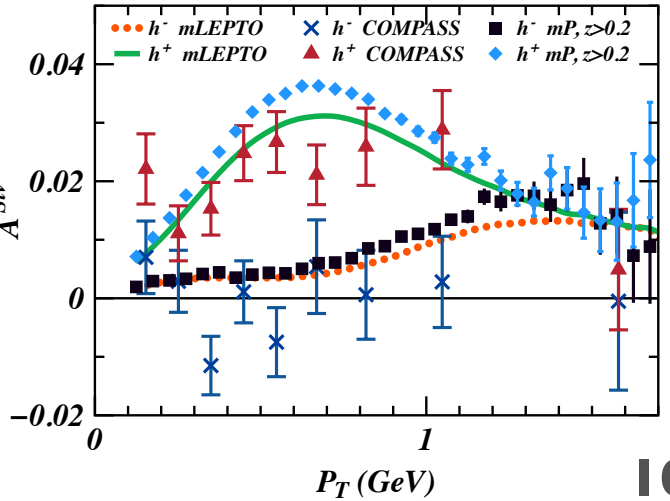
No k_T dependence at LO! No contradiction, different R !

EVENT GENERATORS + SIVERS EFFECT

- Two-hadron Sivers SSA *need* dihadron FF: yet unknown.
- Event generators allow to study *exp. kinematics effects*.
- Sivers effect modulates quark's azimuthal angle: *relatively easy* to include in MC generators.
- Use Sivers PDF extraction from *Torino group*.
- mLPETO used for COMPASS. Earlier studies + Cahn effect, also for CLAS.
- mLEPTO and mPYTHIA agree pretty well.

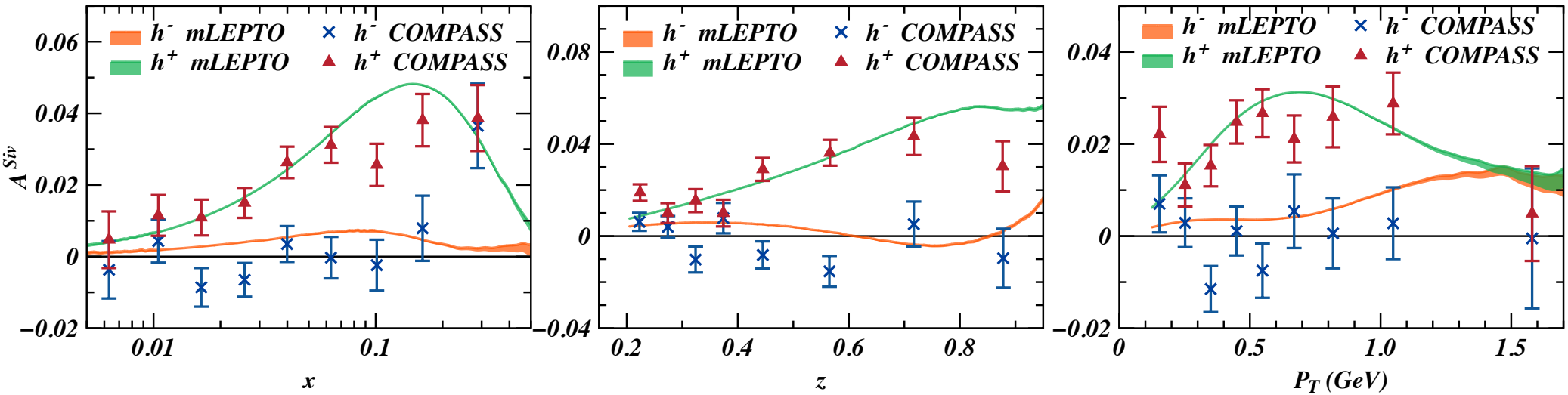




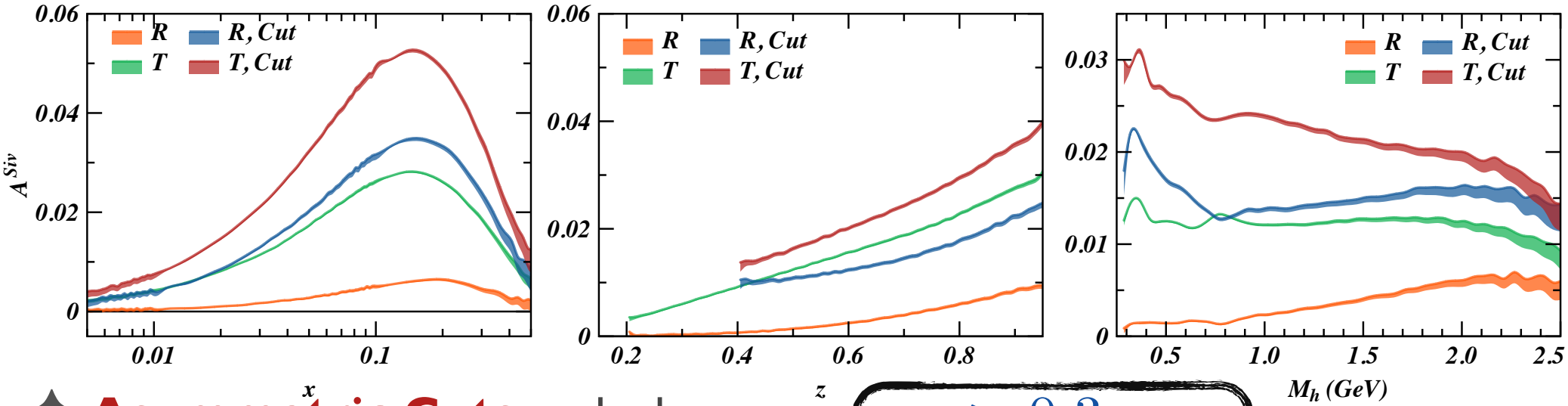


DIHADRON SIVERS USING **MLEPTO** MC

✦COMPASS Results in **One** Hadron Sivers and **mLEPTO** MC



✦ **mLEPTO** Predictions for DiHadron Sivers in COMPASS kinematics



✦ **Asymmetric Cuts** on hadron pair momenta enhances the signal !

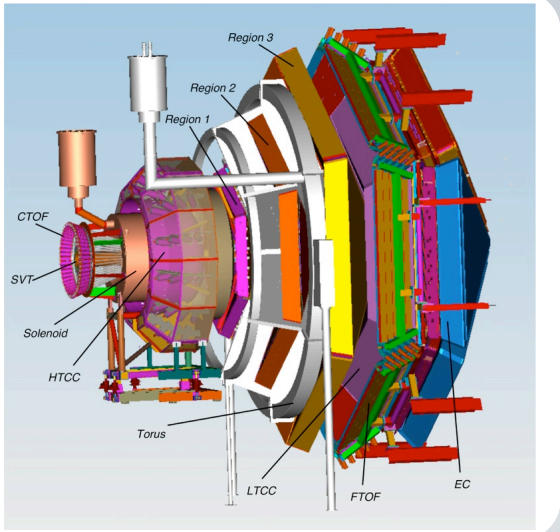
$$z_1 > 0.3$$
$$P_{1T} > 0.3 \text{ GeV}$$

mPYTHIA 6.4

Simulations for CLAS12 and EIC

in collaboration with E.-C. Aschenauer and H. Avakian

CLAS12 @ JLAB 12GeV



- Upcoming SIDIS experiment, 1H and 2H
- 11 GeV electron off polarized proton target.
- Access to large x region of nucleon structure.
- We use mPYTHIA for SIDIS predictions.

- Include the kinematical cuts on $x, Q^2, W, \theta_{e'}, \theta_h, M_{Mis}, z, \ldots$

$0.075 \leq x \leq 0.532$

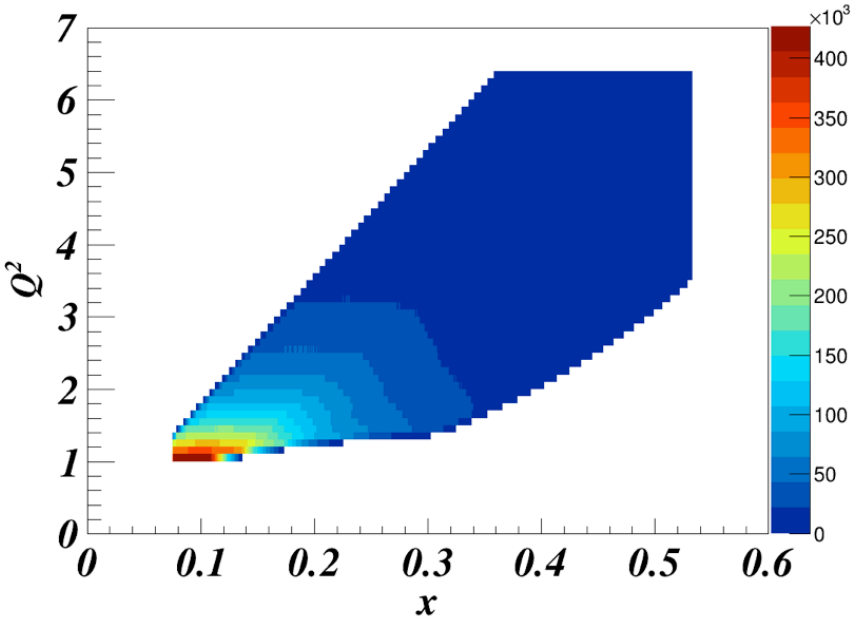
$1\ \text{GeV} \leq Q^2 \leq 6.3\ \text{GeV}$

$W \geq 2\ \text{GeV}$

$MMis_{(ep)-(e'hX)} \geq 1.5\ \text{GeV}$

$MMis_{(ep)-(e'h_1h_2X)} \geq 1.5\ \text{GeV}$

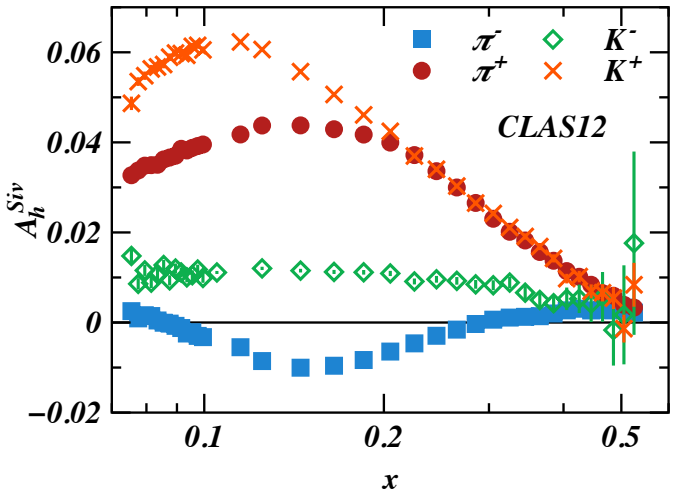
DIS kinematics

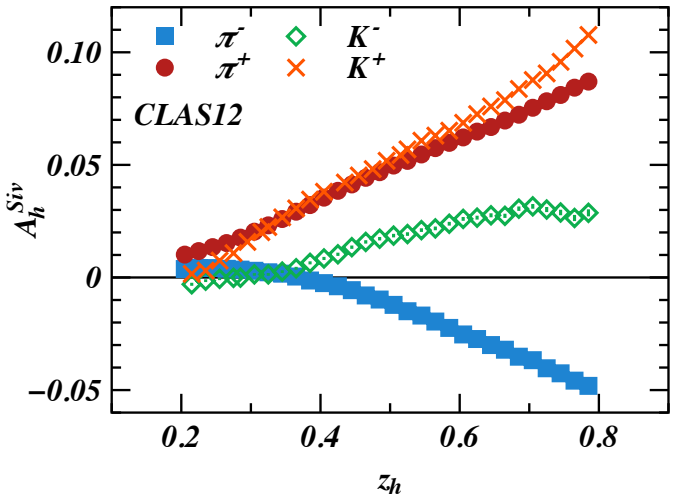


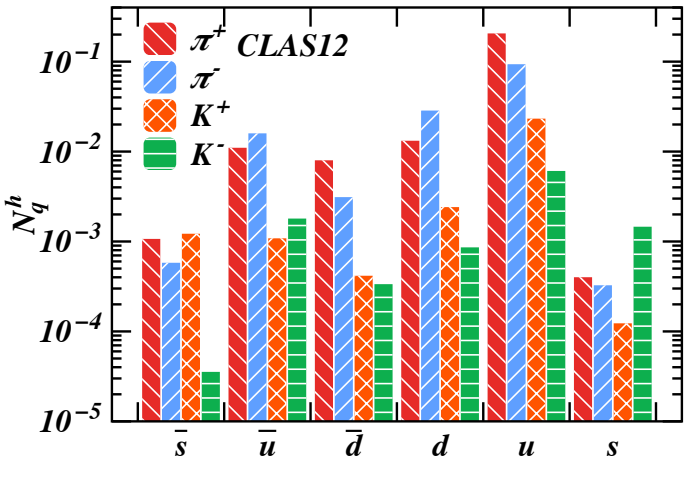
Sivers SSAs at CLAS12

❖ ***Exploring the large x (HiX) region.***

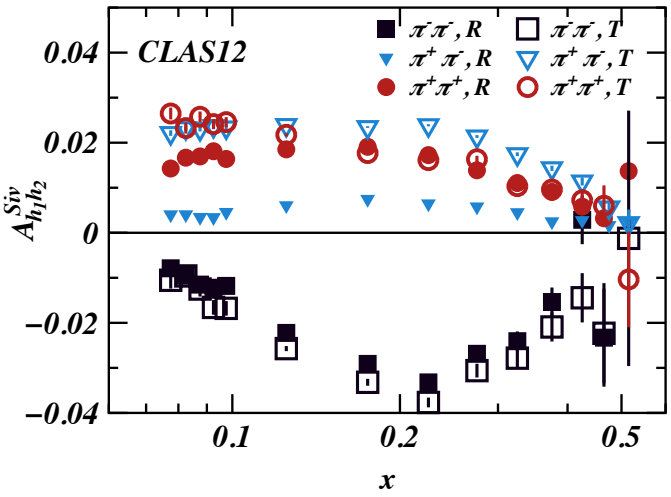
✦ **Single hadron** SSAs.

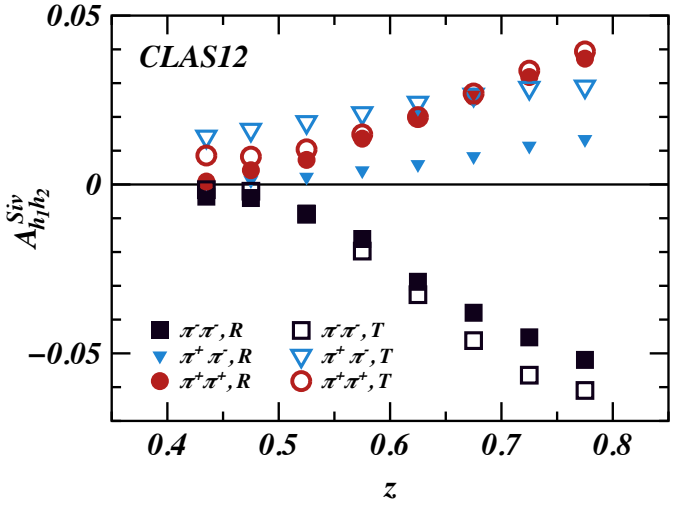


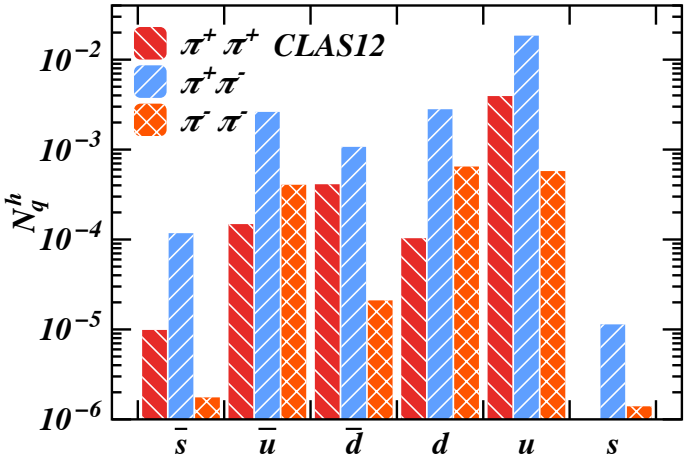




✦ **Dihadron** SSAs for pion pairs: identical pairs via z-ordering $z_1 \geq z_2$

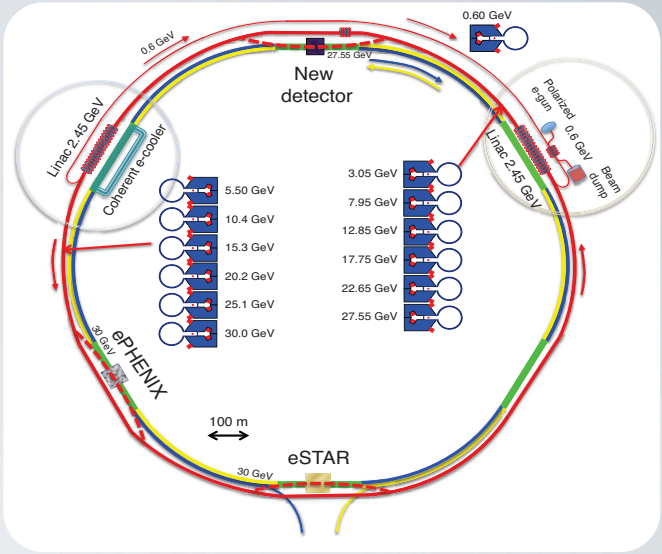






✦ Both Single and Dihadron SSAs are comparable in size!

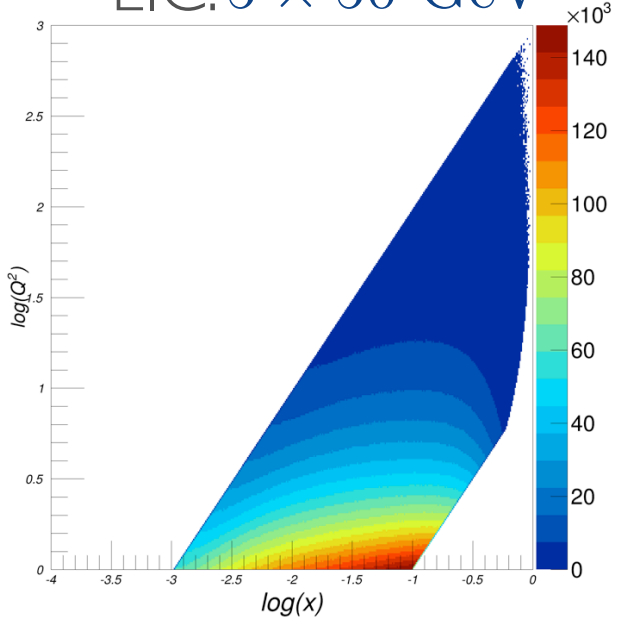
EIC: eRHIC



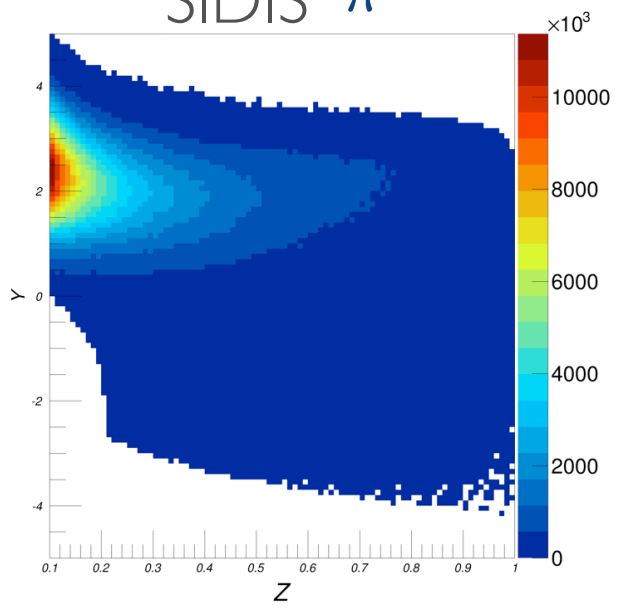
White Paper -- Accardi et. al. : 1212.1701(2012).

- EIC using RHIC + electron ring.
- Various proposed beam momenta: $l_e \times P_N$
- We use mPYTHIA for SIDIS predictions.

EIC: 5×50 GeV



SIDIS π^+

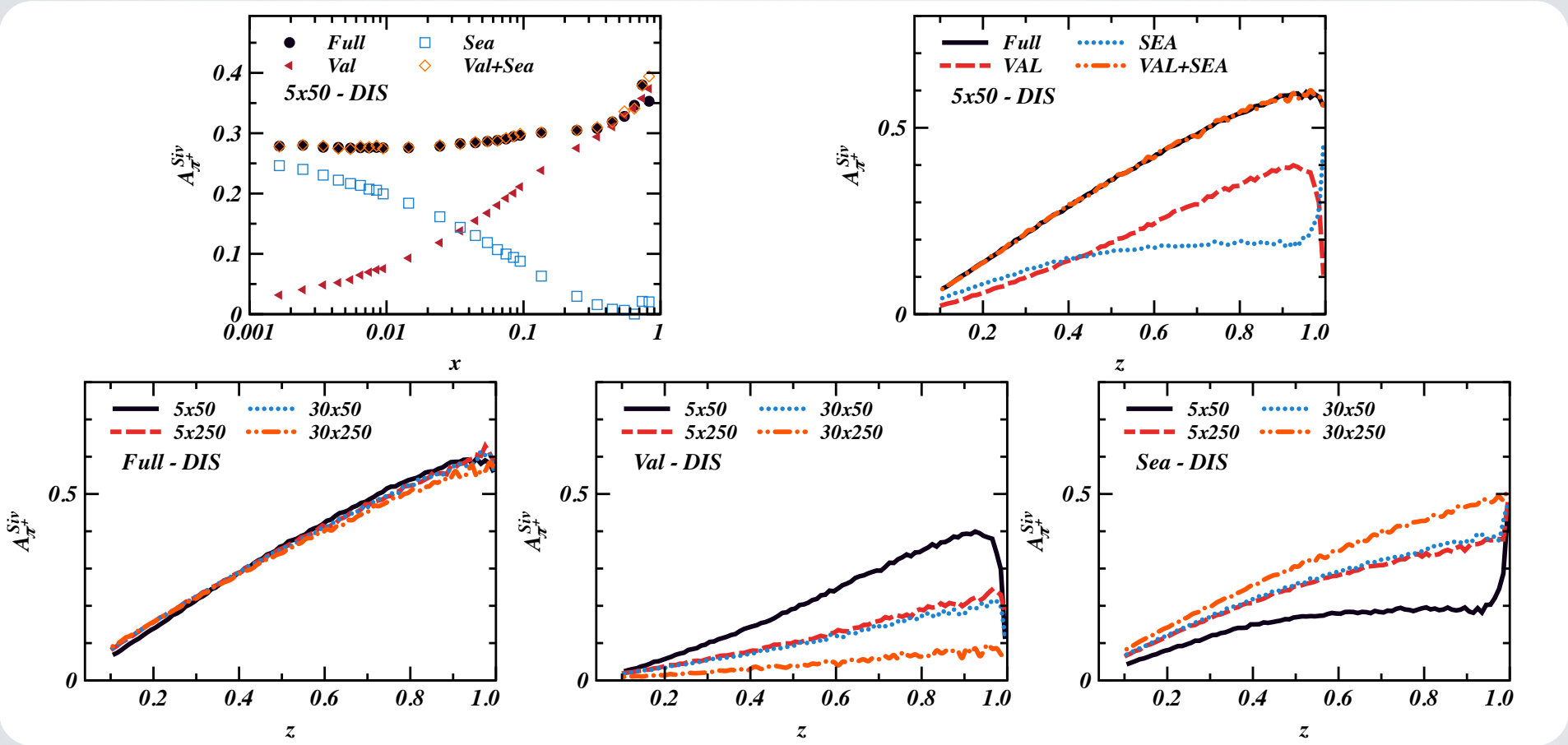


EIC TOY MODEL STUDIES

- What can we learn about Sivers PDF at EIC?
- Use a TOY model for Sivers PDF to explore.

$$f_{\uparrow}^{q,Toy}(x, \boldsymbol{k}_T) = f_1^q(x, k_T)[1 + 0.9\sin(\varphi_q - \varphi_S)]$$

- ***Interplay of valence and sea quarks, at different CM energies.***



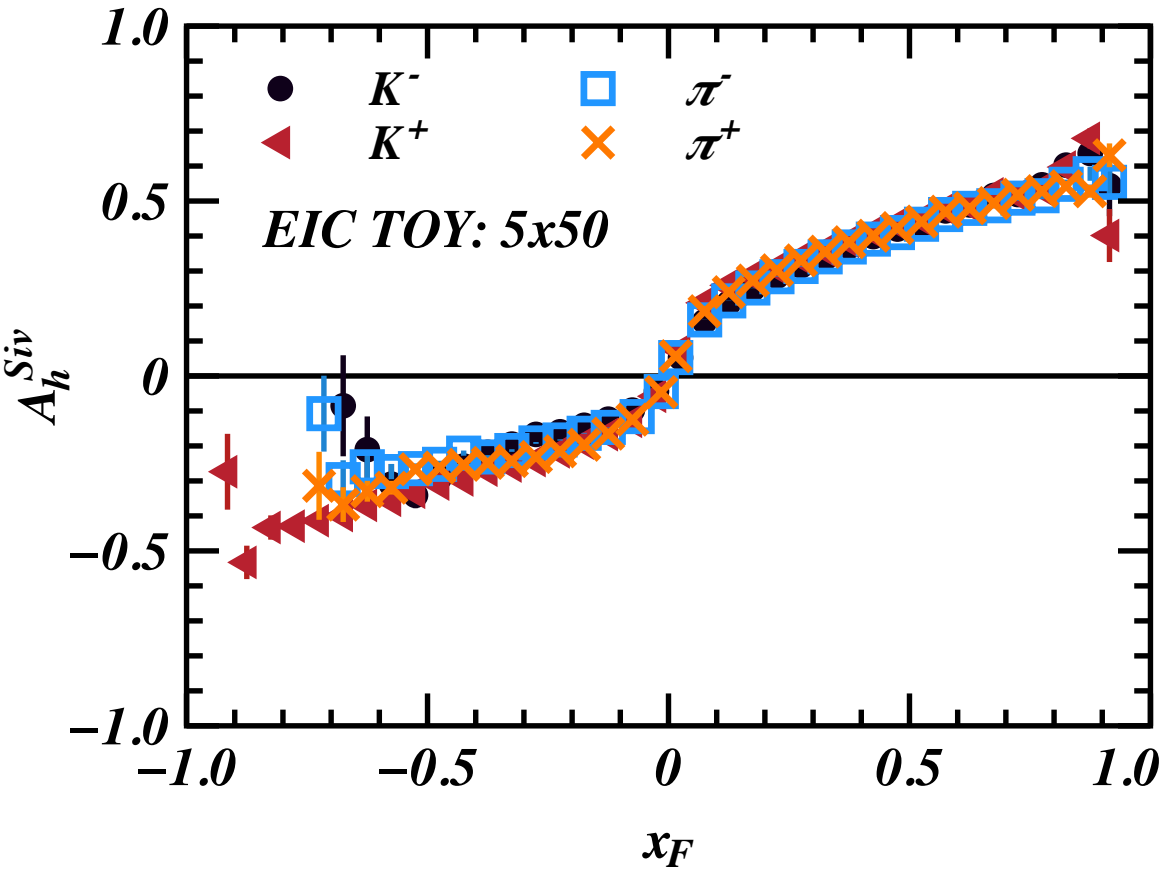
- Access Sivers PDF at small x, and for sea quarks.

TOY MODEL : TARGET FRAGMENTATION

- What can we learn about Sivers PDF at EIC?
- Use a TOY model for Sivers PDF to explore.

$$f_{\uparrow}^{q,Toy}(x, \boldsymbol{k}_T) = f_1^q(x, k_T)[1 + 0.9\sin(\varphi_q - \varphi_S)]$$

- ***Explore Target Fragmentation Regions*** $x_F < 0$.



- Sivers SSA changes sign, fragmentation of nucleon remnant!

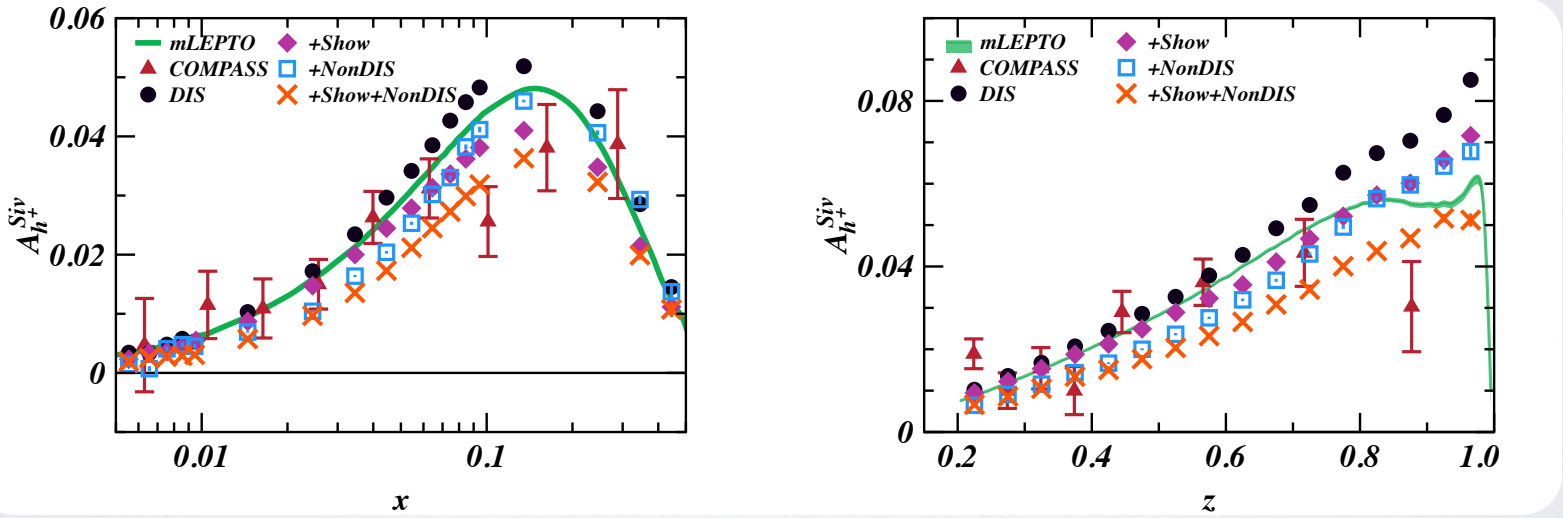
LO APPROXIMATION FOR SSA

- Fits for *Sivers PDF* from HERMES and COMPASS data utilize *LO DIS-only* expressions for *SSAs*.

M. Anselmino et. al.: PRD 86, 014028 (2012).

$$A_{UT}^{\sin(\phi_h-\phi_S)} = \frac{\sum_q \int d\phi_S d\phi_h d^2\boldsymbol{k}_\perp \Delta^N \hat{f}_{q/p^\uparrow}(x, k_\perp, Q) \sin(\varphi - \phi_S) \frac{d\hat{\sigma}^{\ell q\to\ell q}}{dQ^2} \hat{D}_q^h(z, p_\perp, Q) \sin(\phi_h - \phi_S)}{\sum_q \int d\phi_S d\phi_h d^2\boldsymbol{k}_\perp \hat{f}_{q/p}(x, k_\perp, Q) \frac{d\hat{\sigma}^{\ell q\to\ell q}}{dQ^2} \hat{D}_q^h(z, p_\perp, Q)}.$$

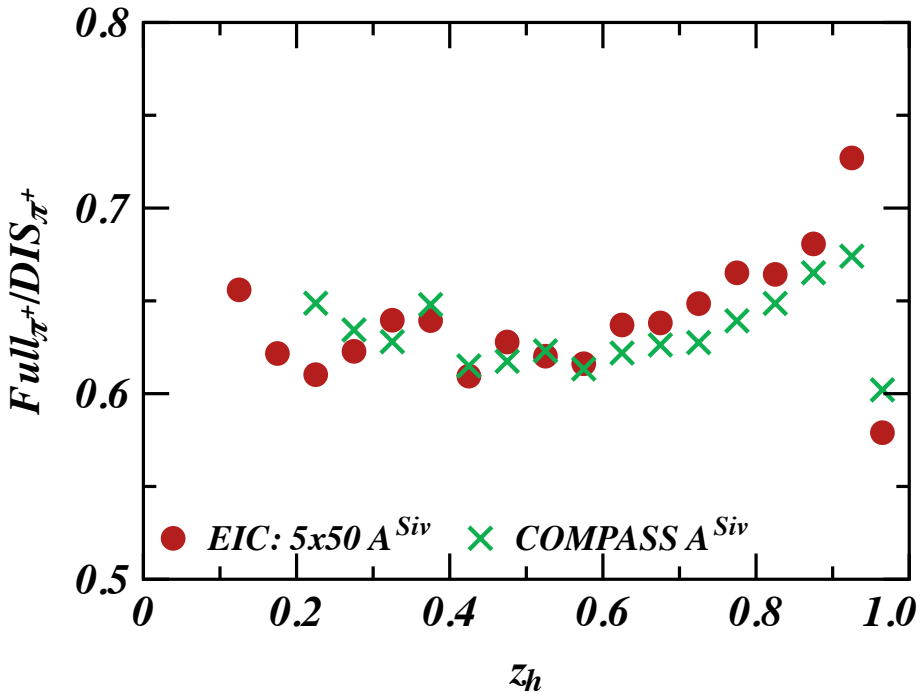
- **Is this justified at COMPASS energies?**
- ***Test using mPYTHIA: turn on non-DIS effects (VMD, GVMD, "direct") and parton showering (QCD+QED).***

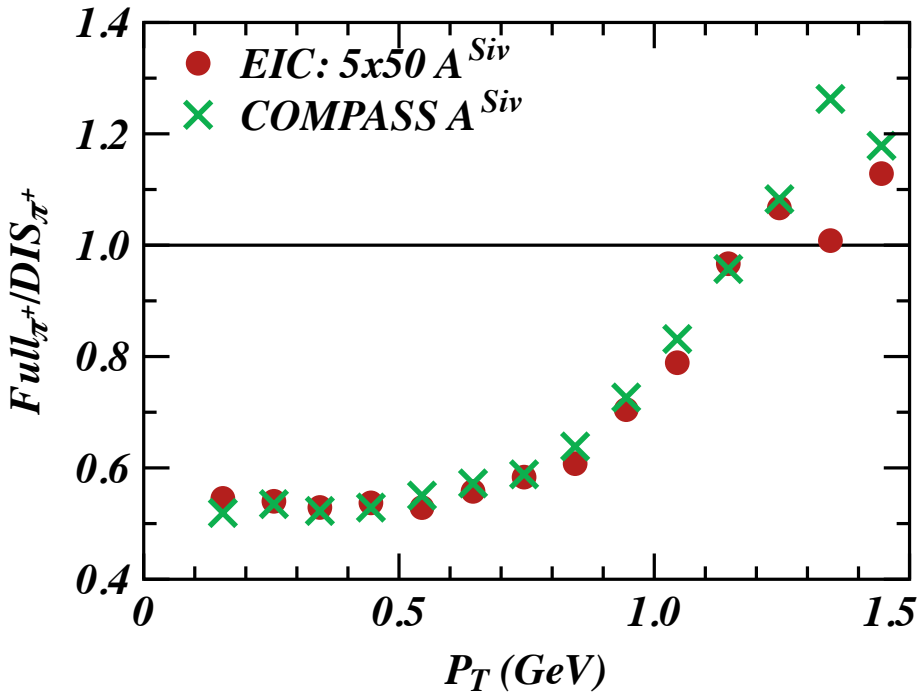


- **Significant** effects, but still agrees with data**!**
- Current Sivers PDF extractions *may* be underestimated.

HOW ABOUT EIC?

- Ratios of full(+nonDIS+showers) to DIS-only *SSAs* for EIC and COMPASS.

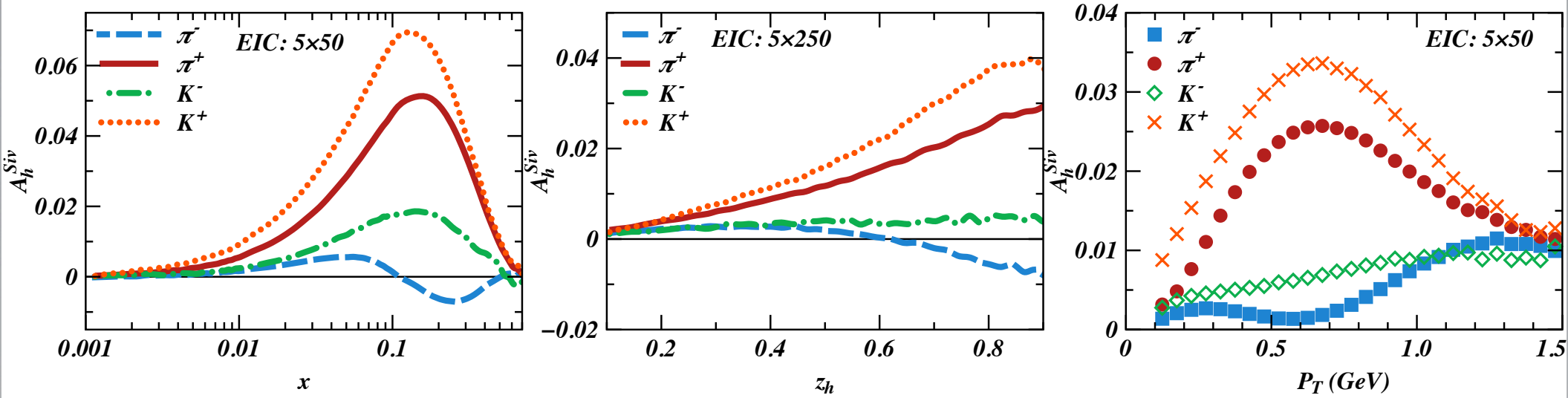




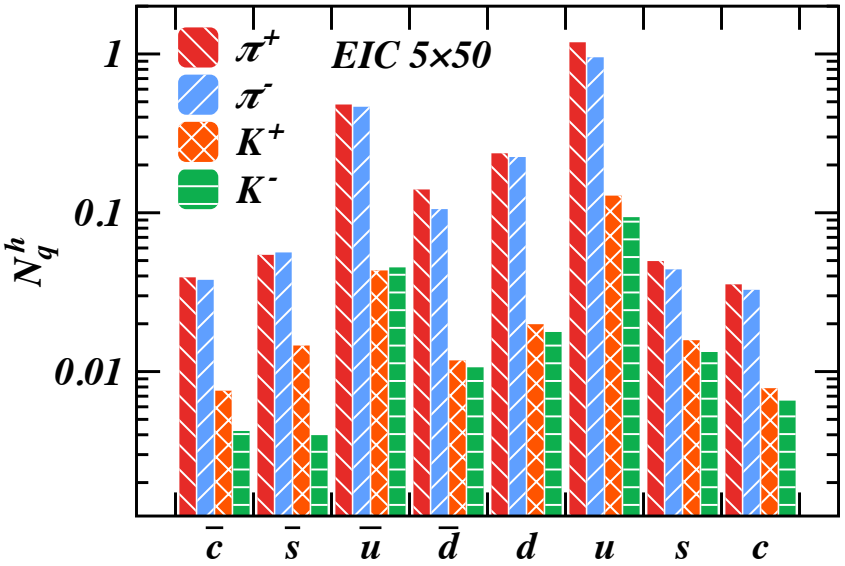
- Ratios are ***very similar:*** can use mPYTHIA with *DIS-only* channel ***to predict*** EIC SSAs.

mPYTHIA RESULTS FOR EIC: ONE H

- SSAs for charged pions and kaons from ***proton*** target.



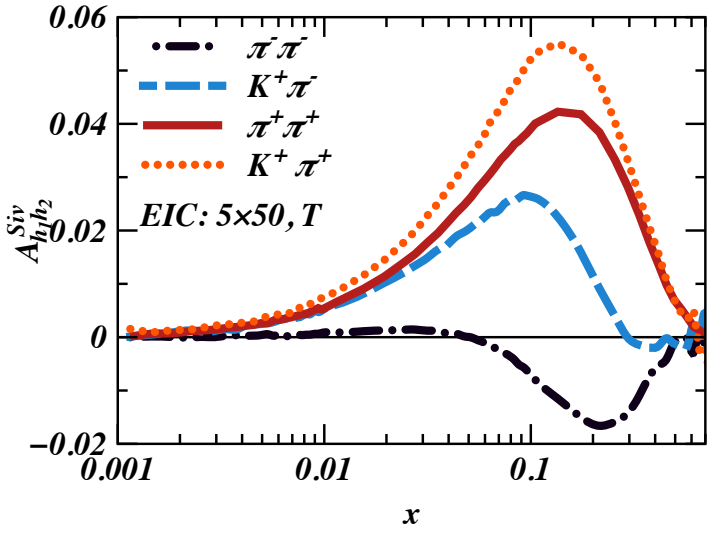
- **Average** number of hadrons by struck quark flavor.

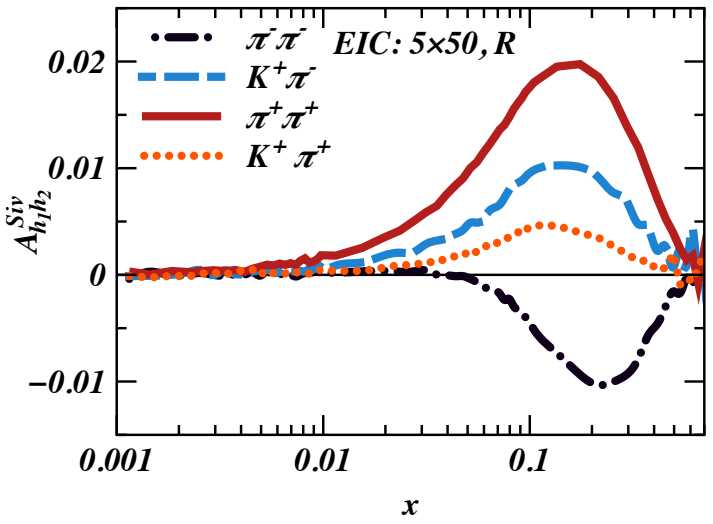


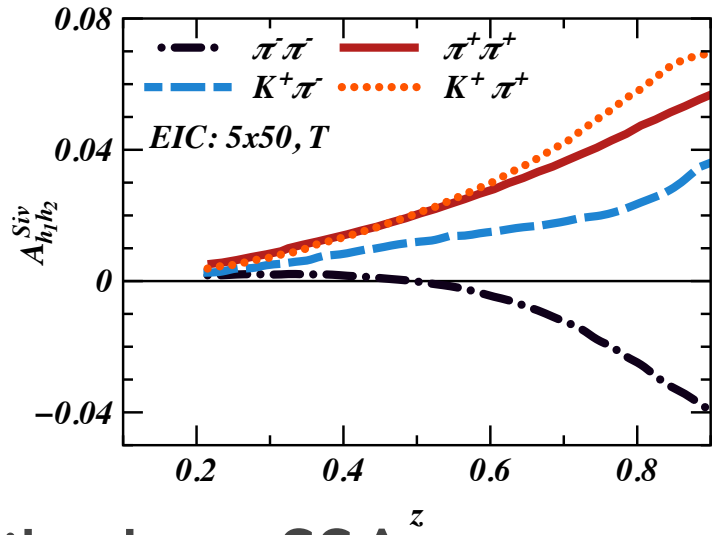
- π^+ multiplicities larger than K^+, but kaon SSAs are larger. Up quark dominates the multiplicities.

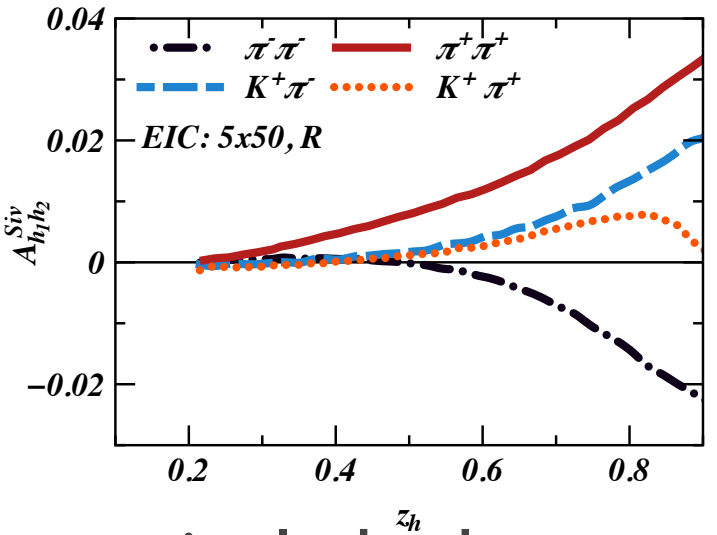
DIHADRON SIVERS FOR EIC

- Identical pairs via z-ordering: $z_1 \geq z_2$ (so $\sigma_R \neq 0$)









- Dihadron SSAs are *comparable* to single hadron ones!

(the one- and two-hadron FFs should mostly cancel in the ratios)

CONCLUSIONS - I

- ***Sivers Effect*** allows us to explore the momentum correlations of partons and the transverse spin of the nucleon.

- ***One-hadron SIDIS*** has long been one of the key processes to access Sivers PDF.

- ***Two-hadron SIDIS*** will provide complementary information and wider basis for extracting ***flavor*** and ***TM*** dependencies. (Together with one hadron SIDIS and Drell-Yan measurements at COMPASS). Can be extracted from the same data used for IFF analyses (different variables). Such analysis proposal *E12-10-006A* for IFF + 2H Sivers at ***SoLID*** has been approved.

CONCLUSIONS - II

- LEPTO and PYTHIA ***MC*** event generators have been modified to predict Sivers SSAs for both one and two hadrons:
  - mLEPTO for COMPASS: *dihadron SSA ≅ single hadron SSA*.
  - CLAS12 and SoLID predictions.
  - EIC: Measurable SSAs, *non-DIS processes and showers* should be considered in the extractions of the Sivers PDF .

- Future Plans:
  - Feasibility study for CLAS12 (with detector effects, integrated luminosity, etc).
  - Explore the target fragmentation.
  - Include TMD evolution (using TMDlib ?).

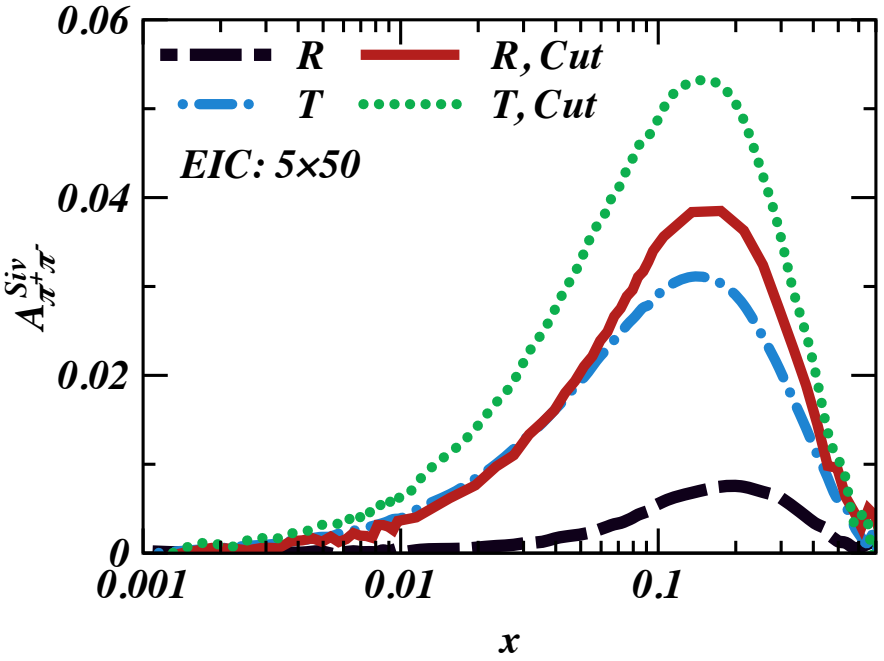

Thanks!
Photo by Jun Zhang

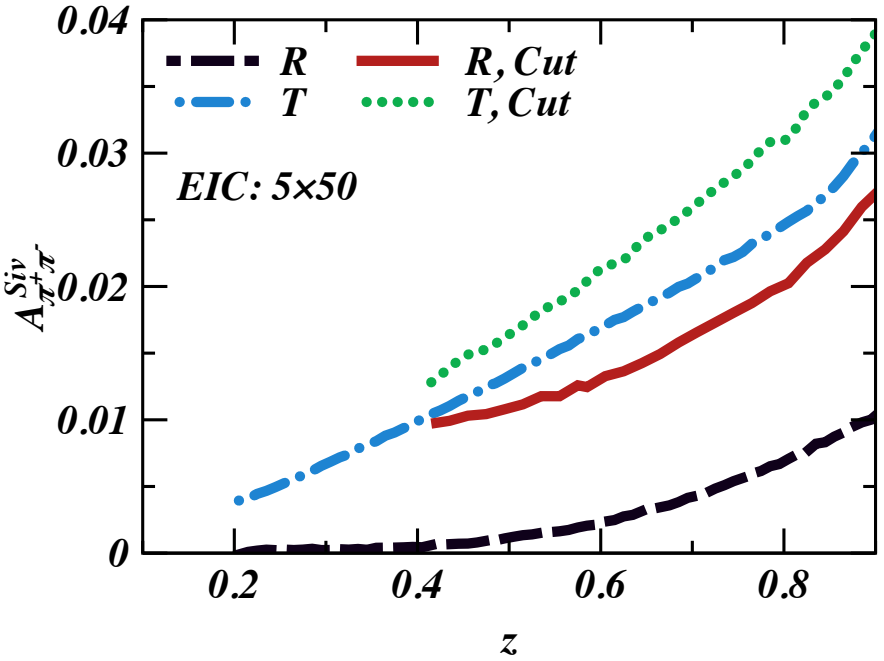
BACKUP SLIDES

ASYMMETRIC CUTS FOR HADRON PAIR

✦ **Asymmetric Cuts** on hadron pair momenta enhances the signal !

$$z_1 > 0.3$$
$$P_{1T} > 0.3 \text{ GeV}$$



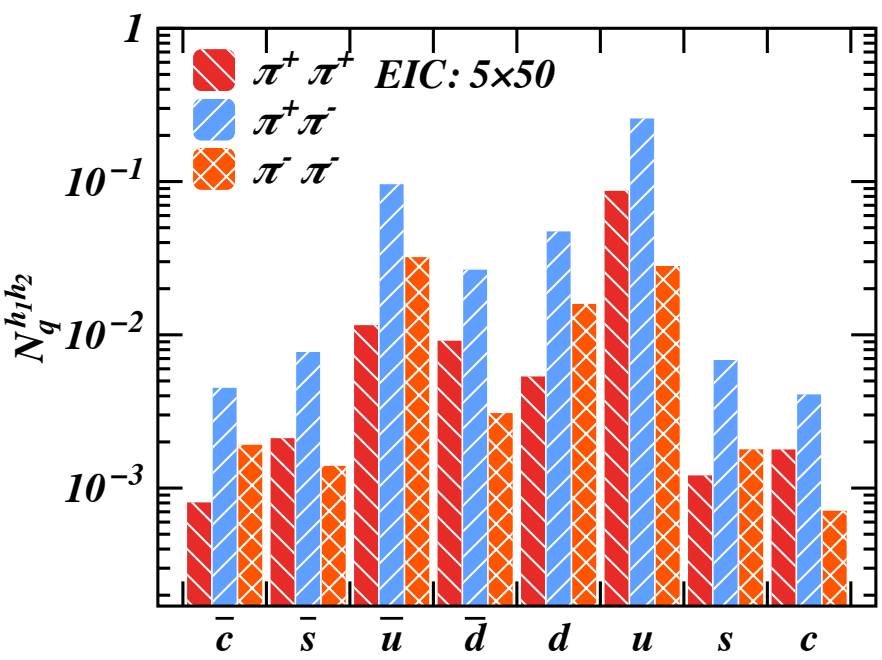


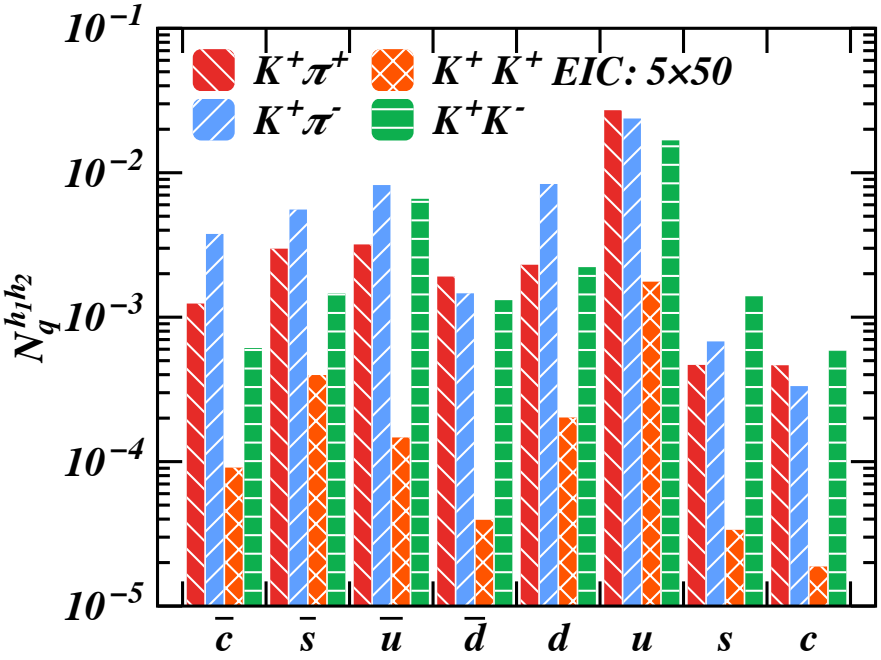
✦ ***Enhancement*** in SSA, but ***decrease*** of the average multiplicities. (especially R mods are enhanced, due to our choice of R)

✦ Should be chosen to ***maximize signal/noise*** for a specific experiment!

RATES FOR PAIR PRODUCTION AT EIC

✦ **Average** number of hadron pairs for given struck quark flavor.



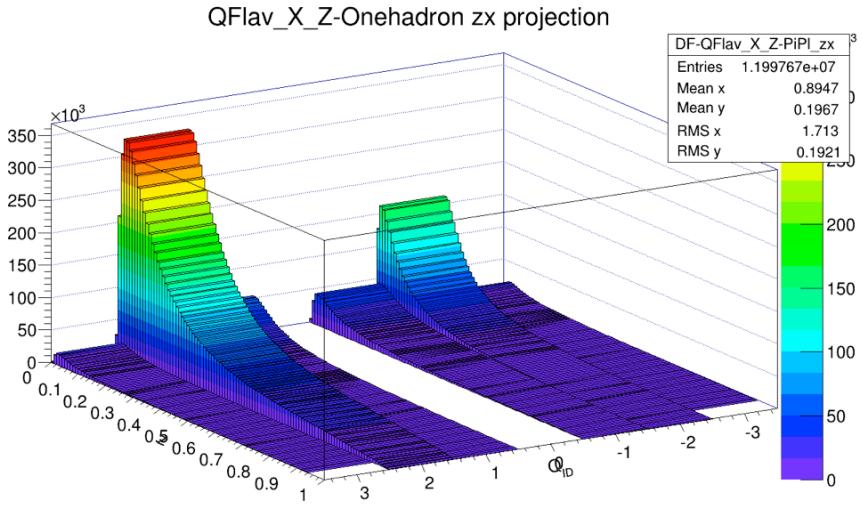


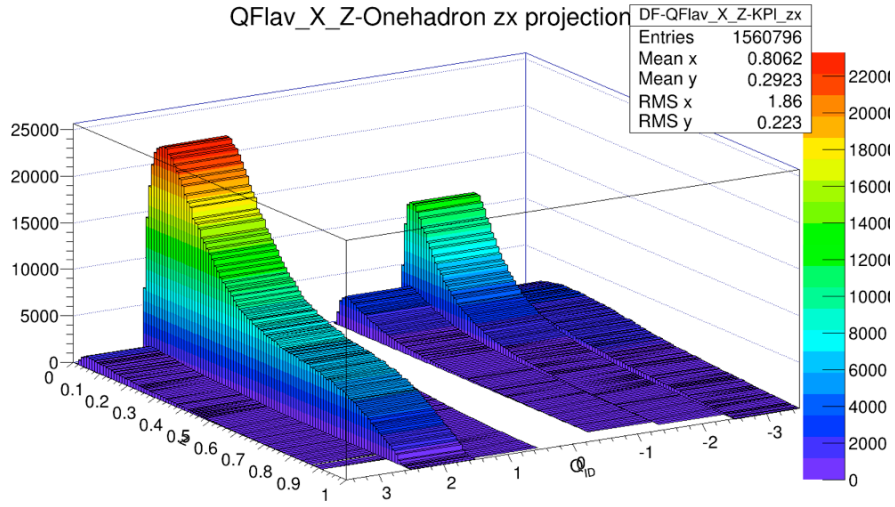
✦ Pure pion pairs dominate, but mixed pion-kaon pairs are also large enough.

✦ Different pairs allow to ***enhance*** the contributions of ***different quark flavors***! Needed for flavor decomposition.

K^+ Study at EIC

✦ Positive pion and kaon multiplicities by quark flavor .





✦ SSAs for positive pion and kaon with SSAs for various flavors turned off.