26th International Symposium on Spin Physics

A Century of Spin

Exploring Sivers Effects in SIDIS Vector Meson Production

Ya-jin Zhou (Shandong University)

Based on paper: Yongjie Deng, Tianbo Liu and Ya-jin Zhou,

Chinese Physics Letters 42, 061301 (2025) （Editors Suggestion）

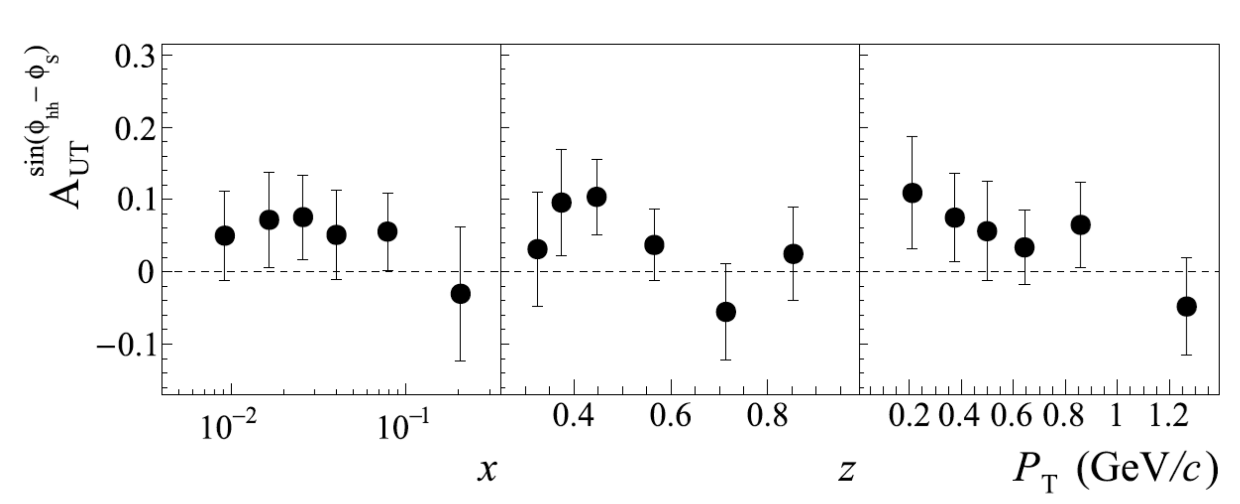
, arXiv:2412.05782

Motivations

- SIDIS process: one of the key processes for probing 3D structure of the nucleon, using TMD PDFs and TMD FFs.
- Sivers effect: correlation between parton transverse momentum and nucleon spin, extensively studied but still need to be explored.
- First measurement of Sivers asymmetry for ρ^0 production in SIDIS was released by COMPASS recently.
- Future EIC and EicC high-statistic data requires further theoretical study.

Motivations

"The COMPASS collaboration has performed the first measurement of the Collins and Sivers asymmetries for inclusively produced ρ^0 mesons"



The COMPASS collaboration, Phys.Lett.B 843 (2023) 137950

Motivations

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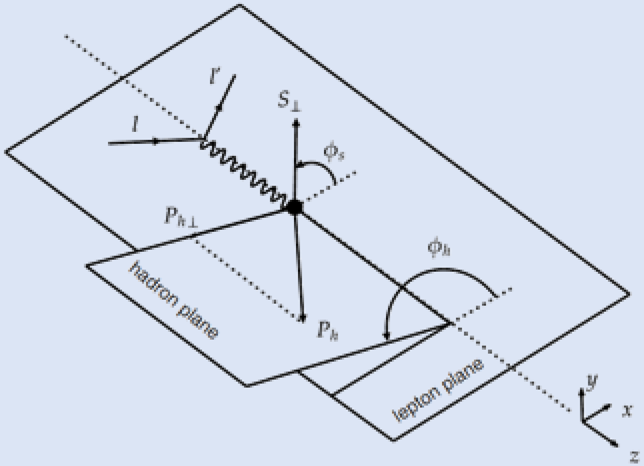
Bernd Surrow's talk on Friday morning　　*Jiancheng Yang's talk on Friday morning*

Theoretical framework

The Sivers asymmetry in SIDIS process

$$l(\ell) + N(P, S_\perp) \longrightarrow l(\ell') + h(P_h) + X$$



The cross section

$$\frac{d\sigma}{dx_B\, dy\, dz_h\, dP_{h\perp}^2\, d\phi_h\, d\phi_S} = \frac{\alpha^2}{x_B y Q^2} \frac{y^2}{2(1-\epsilon)} \left(1 + \frac{\gamma^2}{2x_B}\right) \left[F_{UU}(x_B, z_h, P_{h\perp}, Q^2) + |S_\perp| \sin(\phi_h - \phi_S)\, F_{UT}^{\sin(\phi_h - \phi_S)}(x_B, z_h, P_{h\perp}, Q^2) + \ldots\right]$$

The Sivers asymmetry

$$A_{UT}^{\sin(\phi_h-\phi_S)}(x_B, z_h, P_{h\perp}, Q^2) \equiv \frac{2\int d\phi_h d\phi_S \sin(\phi_h - \phi_S) \frac{d\sigma}{dx_B\, dy\, dz_h\, dP_{h\perp}^2\, d\phi_h\, d\phi_S}}{\int d\phi_h d\phi_S \frac{d\sigma}{dx_B\, dy\, dz_h\, dP_{h\perp}^2\, d\phi_h\, d\phi_S}} = \frac{F_{UT}^{\sin(\phi_h-\phi_S)}(x_B, z_h, P_{h\perp}, Q^2)}{F_{UU}(x_B, z_h, P_{h\perp}, Q^2)}$$

TMD factorization

$$= \frac{\sum_q e_q^2 \mathcal{C}\left[\frac{k_\perp \cdot P_{h\perp}}{M P_{h\perp}} f_{1T}^{\perp q} D_{1q}\right]}{\sum_q e_q^2 \mathcal{C}\left[f_1^q\ D_{1q}\right]}$$

TMD evolution

- TMD Evolution: matching TMD PDFs/FFs to the process energy scale

Collins-Soper equation

$$\zeta \frac{d\widetilde{F}(x,b;\mu,\zeta)}{d\zeta} = -\mathcal{D}(\mu,b)\widetilde{F}(x,b;\mu,\zeta),$$

Remornalization group equation

$$\mu^2 \frac{d\widetilde{F}(x,b,\mu,\zeta)}{d\mu^2} = \frac{\gamma_F(\mu,\zeta)}{2}\widetilde{F}(x,b,\mu,\zeta),$$

⇩

Solution

$$\widetilde{F}(x,b;\mu_f,\zeta_f) = \exp\left[\int_P \left(\gamma_F(\mu,\zeta)\frac{d\mu}{\mu} - \mathcal{D}(\mu,b)\frac{d\zeta}{\zeta}\right)\right]\widetilde{F}(x,b;\mu_i,\zeta_i)$$

$$\equiv \underline{R[b;(\mu_i,\zeta_i),(\mu_f,\zeta_f)]}\,\widetilde{F}(x,b;\mu_i,\zeta_i).$$

$$\zeta\frac{d}{d\zeta}\gamma_F(\mu,\zeta) = -\mu\frac{d}{d\mu}\mathcal{D}(\mu,b),$$

Evolution factor, in principal path independent, but in practical path dependent due to truncation.

We follow 'ζ-prescription' to choose the path.

J.C.Collins and D.E.Soper, Nucl.Phys.B 193 (1981) 381

I. Scimemi, A. Vladimirov, JHEP 08 (2018) 003

TMD evolution

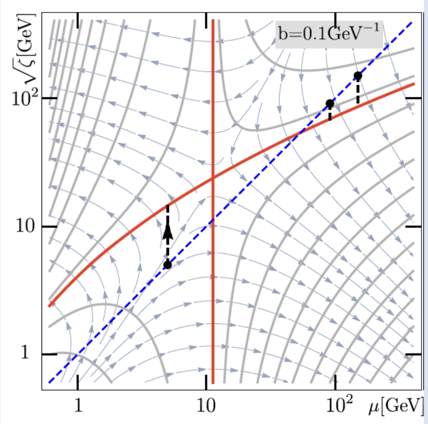
ζ-prescription

Initial scale: $\mu_i \sim \frac{1}{b}$, $\zeta_i = \zeta_Q(b)$ (optimal TMD distribution)

Final scale: $(\mu_f, \zeta_f) = (Q, Q^2)$

see also Valentin Moos' talk on Tuesday

Path choice:



$$R[b;(\mu_i,\zeta_i),(\mu_f,\zeta_f)] = \left(\frac{\zeta_f}{\zeta_{\mu_f}(\mu_i,\zeta_i)}\right)^{-\mathcal{D}(\mu_f,b)}$$

$$\mathcal{D}(\mu,b) = \mathcal{D}_{\text{resum}}(b_*,\mu) + d_{\text{NP}}(b), \quad d_{\text{NP}}(b) = c_0 b b_*,$$

$$\zeta_\mu(b) = \zeta_\mu^{\text{pert}}(b) e^{-b^2/B_{\text{NP}}^2} + \zeta_\mu^{\text{exact}}(b)\left(1 - e^{-b^2/B_{\text{NP}}^2}\right)$$

I. Scimemi, A. Vladimirov, JHEP 08 (2018) 003 and 06 (2020) 137

Sivers asymmetry

Structure functions in b-space

$$\widetilde{F}_{UU}(x_B, z_h, b, Q) = H(\mu, Q) \sum_q e_q^2 \widetilde{f}_{1,q/p}(x_B, b, \mu, \zeta_1)\, \widetilde{D}_{1,h/q}(z_h, b, \mu, \zeta_2)$$

$$\widetilde{F}^{\alpha}_{\text{Sivers}}(x_B, z_h, b, Q) = H(\mu, Q) \sum_q e_q^2 (-iMb^{\alpha})\, \widetilde{f}^{\perp}_{1T,q/p}(x_B, b, \mu, \zeta_1)\, \widetilde{D}_{1,h/q}(z_h, b, \mu, \zeta_2)$$

Sivers asymmetry in TMD factorization

Sivers function

Unpolarized TMD FF

$$A_{UT}^{\sin(\phi_h - \phi_S)}(x_B, z_h, P_{h\perp}, Q^2) = \frac{-M \sum_q e_q^2 \int_0^\infty \frac{\mathrm{d}b}{2\pi} b^2 J_1\left(\frac{bP_{h\perp}}{z_h}\right) \left(\frac{Q^2}{\zeta_Q(b)}\right)^{-2\mathcal{D}(b,Q)} \widetilde{f}^{\perp}_{1T,q/p}(x_B, b)\, \widetilde{D}_{1,h/q}(z_h, b)}{\sum_q e_q^2 \int_0^\infty \frac{\mathrm{d}b}{2\pi} b J_0\left(\frac{bP_{h\perp}}{z_h}\right) \left(\frac{Q^2}{\zeta_Q(b)}\right)^{-2\mathcal{D}(b,Q)} \widetilde{f}_{1,q/p}(x_B, b)\, \widetilde{D}_{1,h/q}(z_h, b)}$$

Evolution factor

Unpolarized TMD PDF

Numerical calculation

Inputs: TMD PDFs and FFs

phenomenological ansatzes for TMD distributions

$$f_{1,f\leftarrow h}(x,b) = \int_x^1 \frac{dy}{y} \sum_{f'} C_{f\leftarrow f'}\left(y, \mathbf{L}_{\mu_{\rm OPE}}, a_s(\mu_{\rm OPE})\right) f_{1,f'\leftarrow h}\left(\frac{x}{y}, \mu_{\rm OPE}\right) f_{\rm NP}(x,b)$$

$$D_{1,f\to h}(z,b) = \frac{1}{z^2}\int_z^1 \frac{dy}{y} \sum_{f'} y^2 \mathbb{C}_{f\to f'}\left(y, \mathbf{L}_{\mu_{\rm OPE}}, a_s(\mu_{\rm OPE})\right) d_{1,f'\to h}\left(\frac{z}{y}, \mu_{\rm OPE}\right) D_{\rm NP}(z,b)$$

Inputs: TMD PDFs and FFs

Inputs

- **Unpolarized TMD PDF:**
  - SV19 parametrization for the NP part

    I. Scimemi, A. Vladimirov, JHEP 06 (2020) 137
- **Unpolarized TMD FF:**
  - Collinear part: for ρ^0, global fit; for K*, follow

    K.Chen, Z.Liang,Y.Song,S.Wei, PRD102((2020))034001
  - NP part, same parametrization form as π, SV19
- **Sivers function**
  - Two parametrizations, denoted as BPV20 and ZLSZ (from pion/kaon data)

    M.Bury, A.Prokudin, A.Vladimirov, JHEP05(2021)151

    C. Zeng, T.Liu, P.Sun, Y.Zhao, PRD 106 (2022) 9, 094039

Unpolarized collinear FF for ρ^0

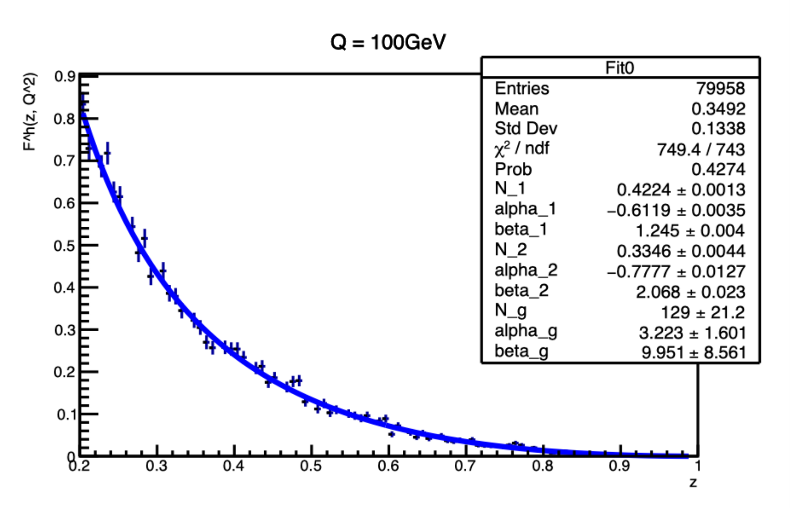
global fit of ρ^0 production data from Pythia.

Observable:

$$F^h\left(z, Q^2\right) = \frac{1}{\sigma_{\text{tot}}} \frac{d\sigma\left(e^+e^- \to hX\right)}{dz} \frac{1}{\sum_q \hat{e}_q^2}\left[2F_1^h\left(z, Q^2\right) + F_L^h\left(z, Q^2\right)\right]$$

Parametrization form:

$$D_{h/i}\left(z, Q_0^2\right) = N_i^h z^{\alpha_i^h}(1-z)^{\beta_i^h}, \quad \left(i = u, d, s, g, \bar{u}, \bar{d}, \bar{s}\right)$$

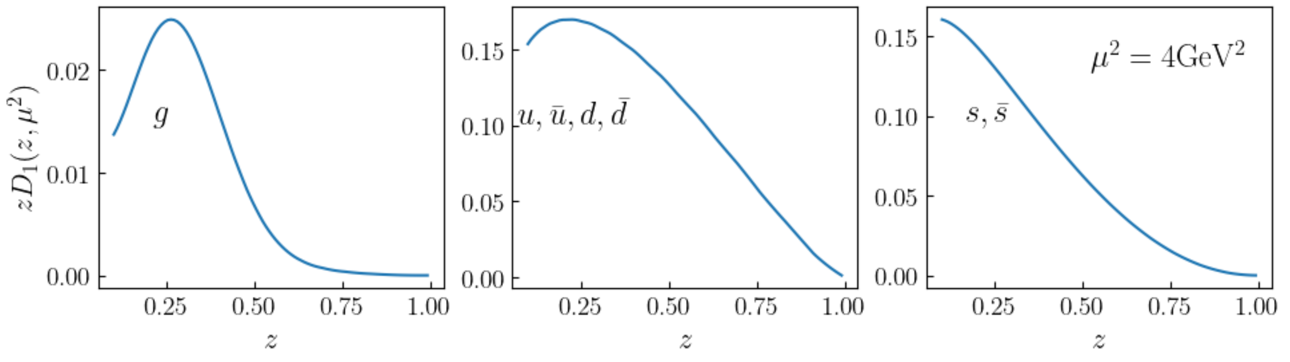


Unpolarized collinear FF for ρ^0

fitting result:

TABLE II. Parameters determined for ρ^0.

$\chi^2/d.o.f. = 749/743$			
function	N	α	β
$D_{\rho^0/u}$	0.4224 ± 0.0013	-0.6119 ± 0.0035	1.2448 ± 0.0037
$D_{\rho^0/s}$	0.3346 ± 0.0044	-0.7777 ± 0.0127	2.0681 ± 0.0229
$D_{\rho^0/g}$	129.04 ± 21.159	3.2234 ± 1.6011	9.9508 ± 8.5609



Unpolarized TMD FF for ρ^0 and K*, NP part

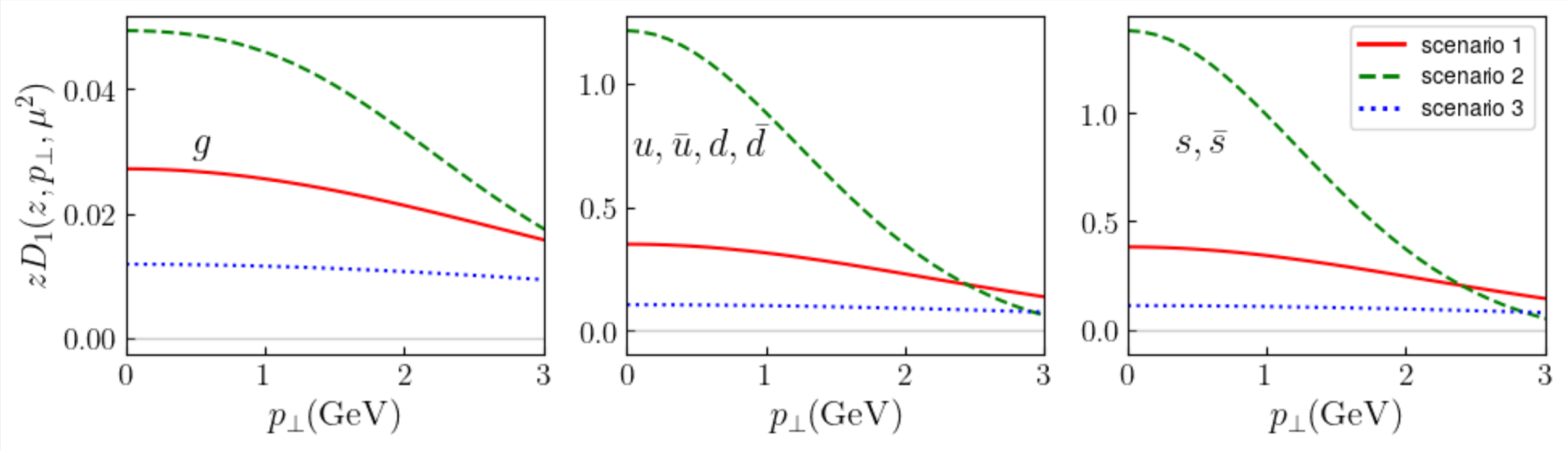
NP part, SV19 parametrization:

$$D_{NP}(x,b) = \exp\left(-\frac{\eta_1 z + \eta_2(1-z)}{\sqrt{1+\eta_3(\boldsymbol{b}/z)^2}}\frac{\boldsymbol{b}^2}{z^2}\right)\left(1+\eta_4\frac{\boldsymbol{b}^2}{z^2}\right)$$

Scenarios	η_1	η_2	η_3	η_4
Scenario 1	0.260	0.476	0.478	0.483
Scenario 2	0.078	0.143	0.143	0.145
Scenario 3	0.78	1.428	1.434	1.449

Unpolarized TMD FF for ρ^0

$z = 0.1,\ \mu^2 = 4\text{GeV}^2$

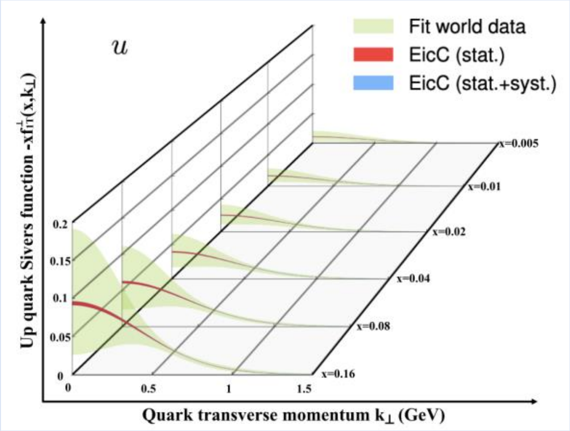


Sivers function

- ZLSZ parametrization

$$f_{1T;q\leftarrow p}^{\perp}(x,b) = N_q \frac{(1-x)^{\alpha_q} x^{\beta_q}(1+\epsilon_q x)}{n(\beta_q,\epsilon_q,\alpha_q)} \exp(-r_q b^2)$$

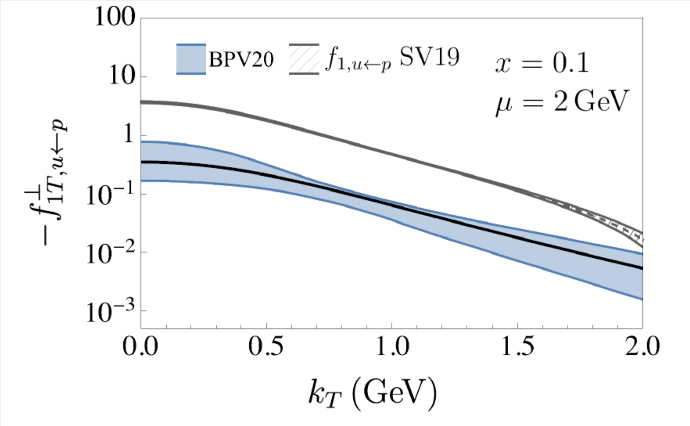
C. Zeng, T.Liu, P.Sun, Y.Zhao, PRD 106 (2022) 9, 094039



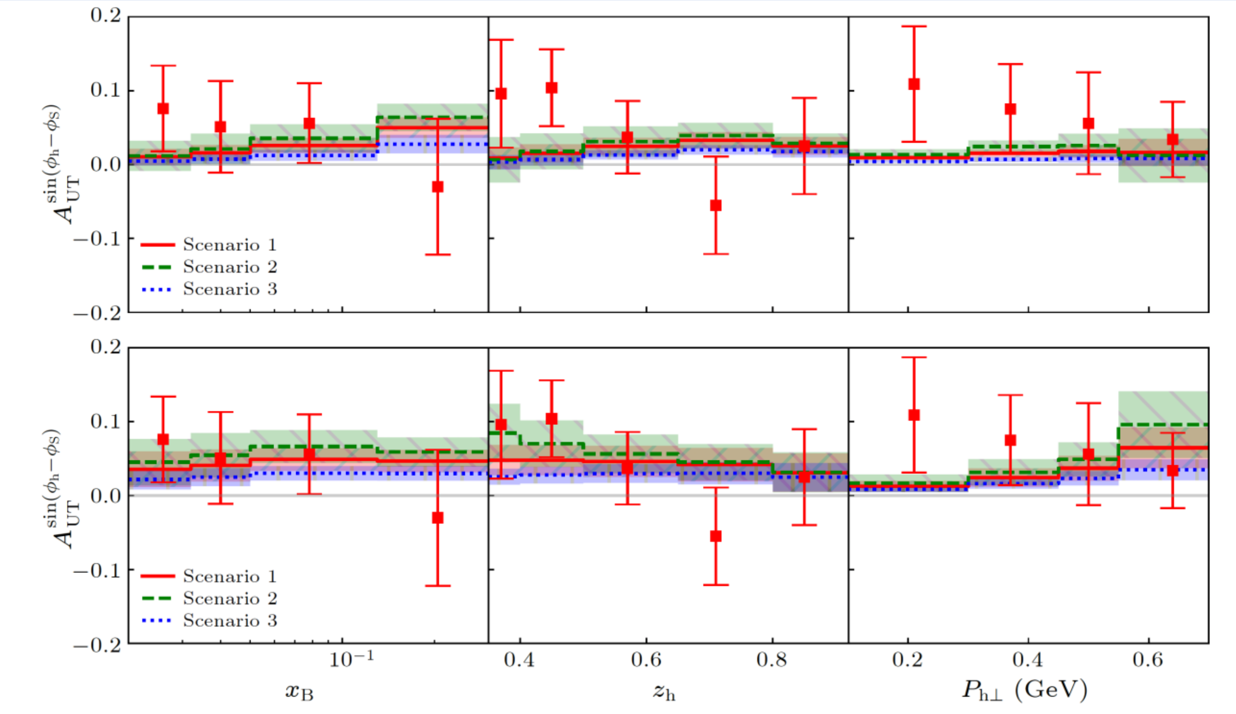
- BPV20 parametrization

$$f_{1T;q\leftarrow h}^{\perp}(x,b) = N_q \frac{(1-x)x^{\beta_q}(1+\epsilon_q x)}{n(\beta_q,\epsilon_q)} \exp\left(-\frac{r_0 + x r_1}{\sqrt{1+r_2 x^2 b^2}} b^2\right)$$

M.Bury, A.Prokudin, A.Vladimirov, JHEP05(2021)151



Sivers effect results for ρ^0, compared with COMPASS data



ZLSZ parametrization for Sivers function

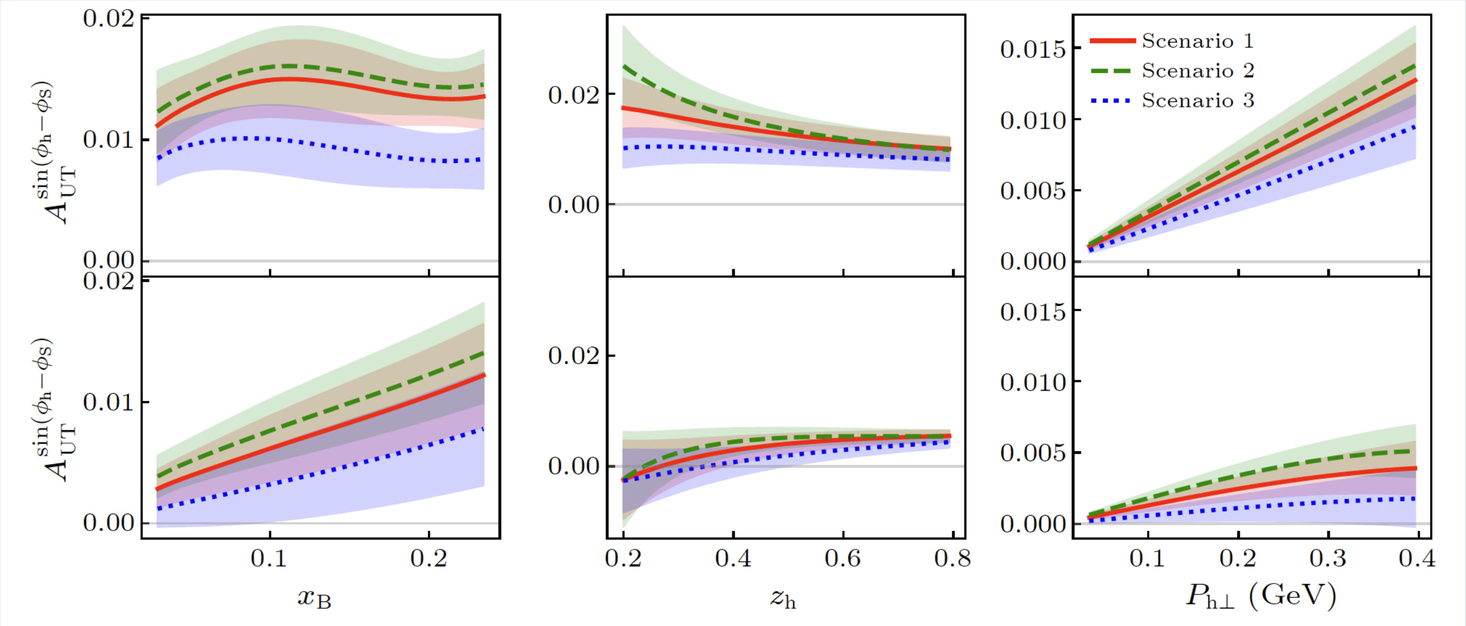
C. Zeng, T.Liu, P.Sun, Y.Zhao, PRD 106 (2022) 9, 094039

BPV20 parametrization for Sivers function

M.Bury, A.Prokudin, A.Vladimirov, JHEP05(2021)151

Sivers effect results for ρ^0, at EIC

$\sqrt{s} = 100$ GeV

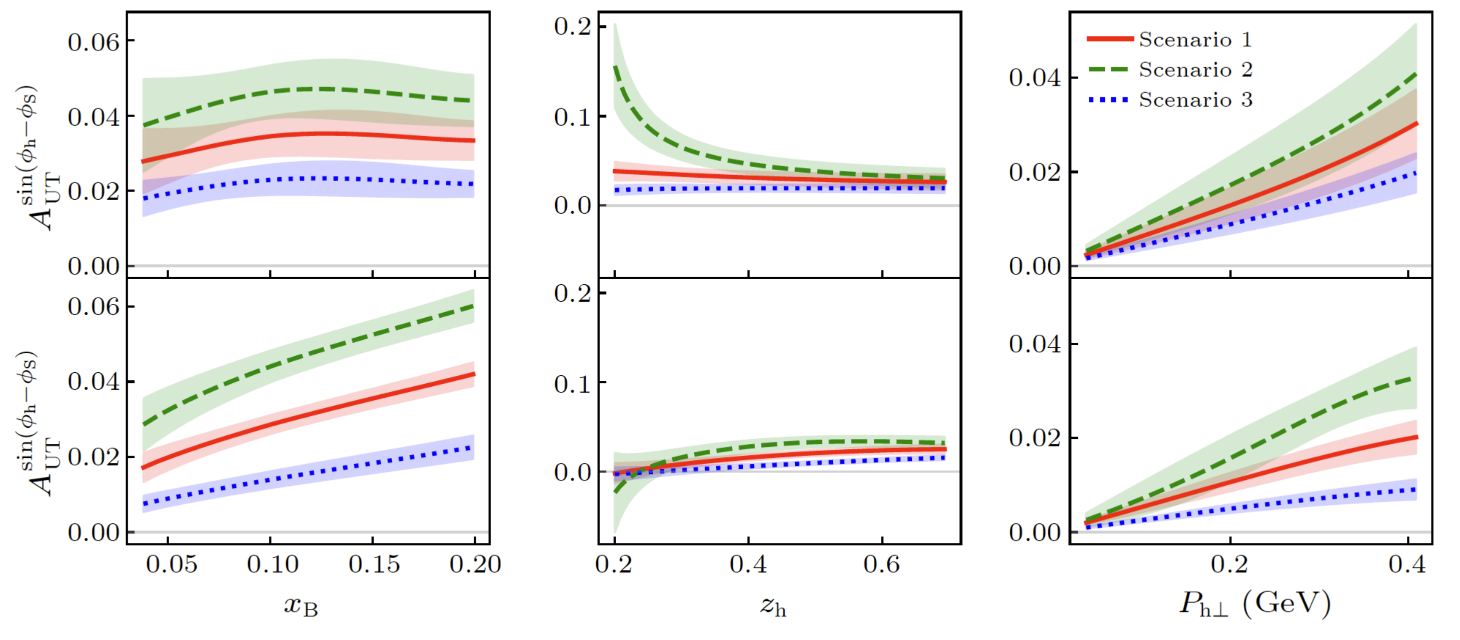


BPV20

ZLSZ

Sivers effect results for ρ^0, at EicC

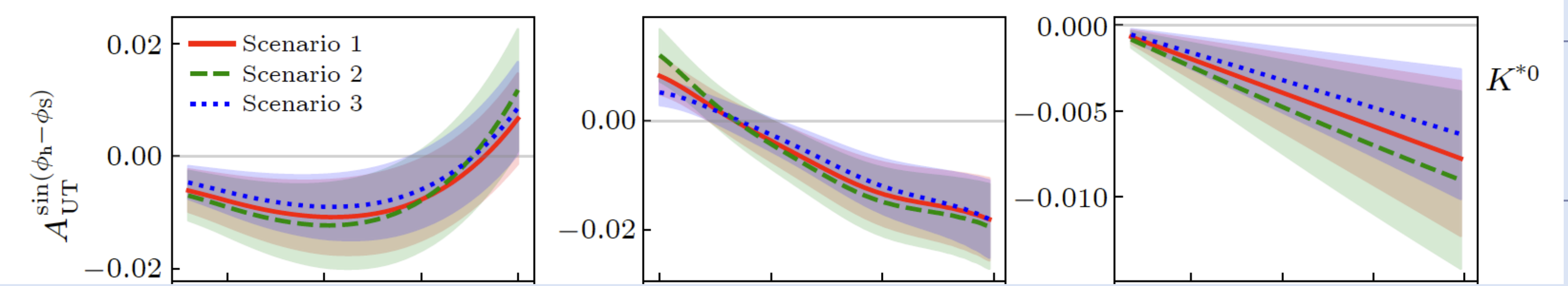
$\sqrt{s} = 16.7$ GeV



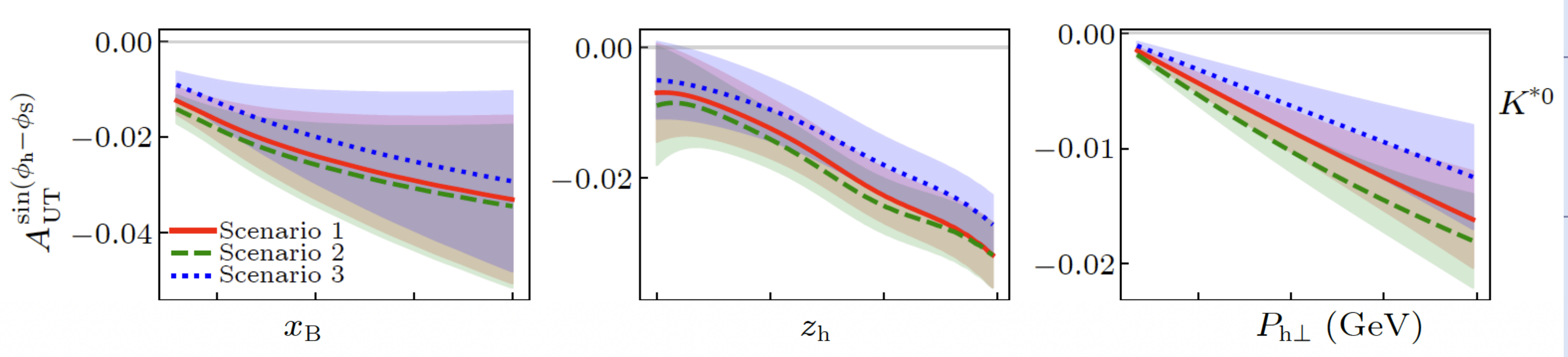
BPV20

ZLSZ

Sivers effect results for K*, at EIC

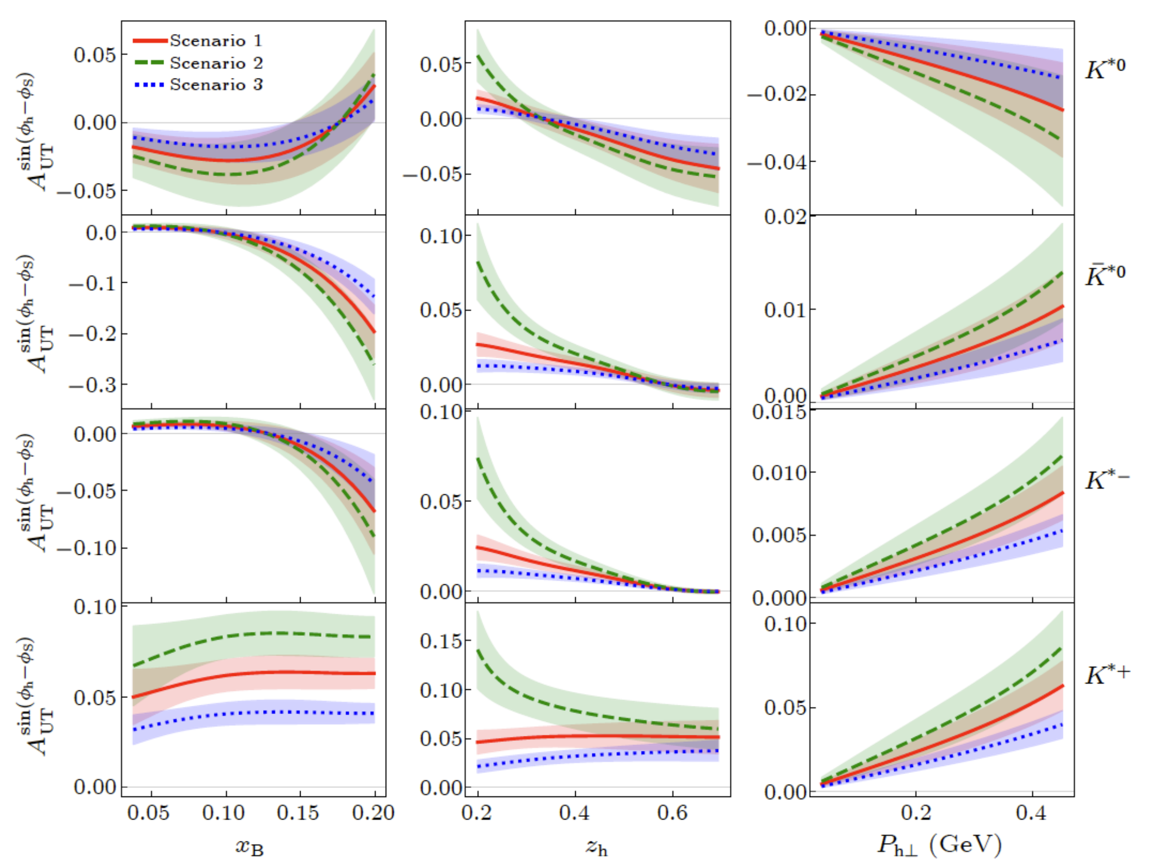


BPV20



ZLSZ

Sivers effect results for K*, at EicC



BPV20

Summary

- Calculations consistent with COMPASS data; Supports Sivers function universality.
- Different FF scenarios affect magnitude; Concentrated distributions enhance asymmetry.
- BPV20 and ZLSZ describe data equally but differ in EIC/EicC predictions.
- Future EIC/EicC data will constrain Sivers function further.

Thanks!

backups

The rapidity anomalous dimension and the rapidity scale

$$\mathcal{D}(\mu, b) = \mathcal{D}_{\text{resum}}(b_*, \mu) + d_{\text{NP}}(b), \quad d_{\text{NP}}(b) = c_0 b b_*,$$

$$b_* = \frac{b}{\sqrt{1 + \frac{b^2}{B_{\text{NP}}^2}}}, \quad B_{\text{NP}} = 1.93\,\text{GeV}^{-1} \quad c_0 = 0.0391\text{GeV}^2$$

$$\begin{aligned}
\mathcal{D}_{\text{resum}}(\mu, b) = &-\frac{\Gamma_0}{2\beta_0}\ln(1-X) + \frac{a_s}{2\beta_0(1-X)}\left[-\frac{\beta_1\Gamma_0}{\beta_0}(\ln(1-X)+X) + \Gamma_1 X\right] \\
&+ \frac{a_s^2}{(1-X)^2}\left[\frac{\Gamma_0\beta_1^2}{4\beta_0^3}\left(\ln^2(1-X) - X^2\right) + \frac{\beta_1\Gamma_1}{4\beta_0^2}\left(X^2 - 2X - 2\ln(1-X)\right)\right. \\
&\left. + \frac{\Gamma_0\beta_2}{4\beta_0^2}X^2 - \frac{\Gamma_2}{4\beta_0}X(X-2) + C_F C_A\left(\frac{404}{27} - 14\zeta_3\right) - \frac{112}{27}T_R N_f C_F\right].
\end{aligned}$$

The rapidity anomalous dimension and the rapidity scale

$$\zeta_\mu(\mu, b) = \zeta_\mu^{\text{pert}}(\mu, b) e^{-b^2/B_{\text{NP}}^2} + \zeta_\mu^{\text{exact}}(\mu, b) \left(1 - e^{-b^2/B_{\text{NP}}^2}\right)$$

$$\zeta_\mu^{\text{exact}}(\mu, b) = \mu^2 e^{-g(\mu,b)/\mathcal{D}(\mu,b)},$$

where the expression of $g(\mu, b)$ up to two-loop order can be written as

$$g(\mu, b) = \frac{1}{a_s} \frac{\Gamma_0}{2\beta_0^2} \left\{ e^{-p} - 1 + p + a_s \left[\frac{\beta_1}{\beta_0} \left(e^{-p} - 1 + p - \frac{p^2}{2} \right) - \frac{\Gamma_1}{\Gamma_0} \left(e^{-p} - 1 + p \right) + \frac{\beta_0 \gamma_1}{\Gamma_0} p \right] \right.$$
$$\left. + a_s^2 \left[\left(\frac{\Gamma_1^2}{\Gamma_0^2} - \frac{\Gamma_2}{\Gamma_0} \right) (\cosh p - 1) + \left(\frac{\beta_1 \Gamma_1}{\beta_0 \Gamma_0} - \frac{\beta_2}{\beta_0} \right) (\sinh p - p) + \left(\frac{\beta_0 \gamma_2}{\Gamma_0} - \frac{\beta_0 \gamma_1 \Gamma_1}{\Gamma_0^2} \right) (e^p - 1) \right] \right\},$$

$$\zeta_\mu^{\text{pert}}(\mu, b) = \frac{2\mu e^{-\gamma_E}}{b} e^{-v(\mu,b)},$$

$$v(\mu, b) = \frac{\gamma_1}{\Gamma_0} + a_s \left[\frac{\beta_0}{12} \mathbf{L}_\mu^2 + \frac{\gamma_2 + d_2(0)}{\Gamma_0} - \frac{\gamma_1 \Gamma_1}{\Gamma_0^2} \right]$$

Unpolarized TMD PDF, NP part

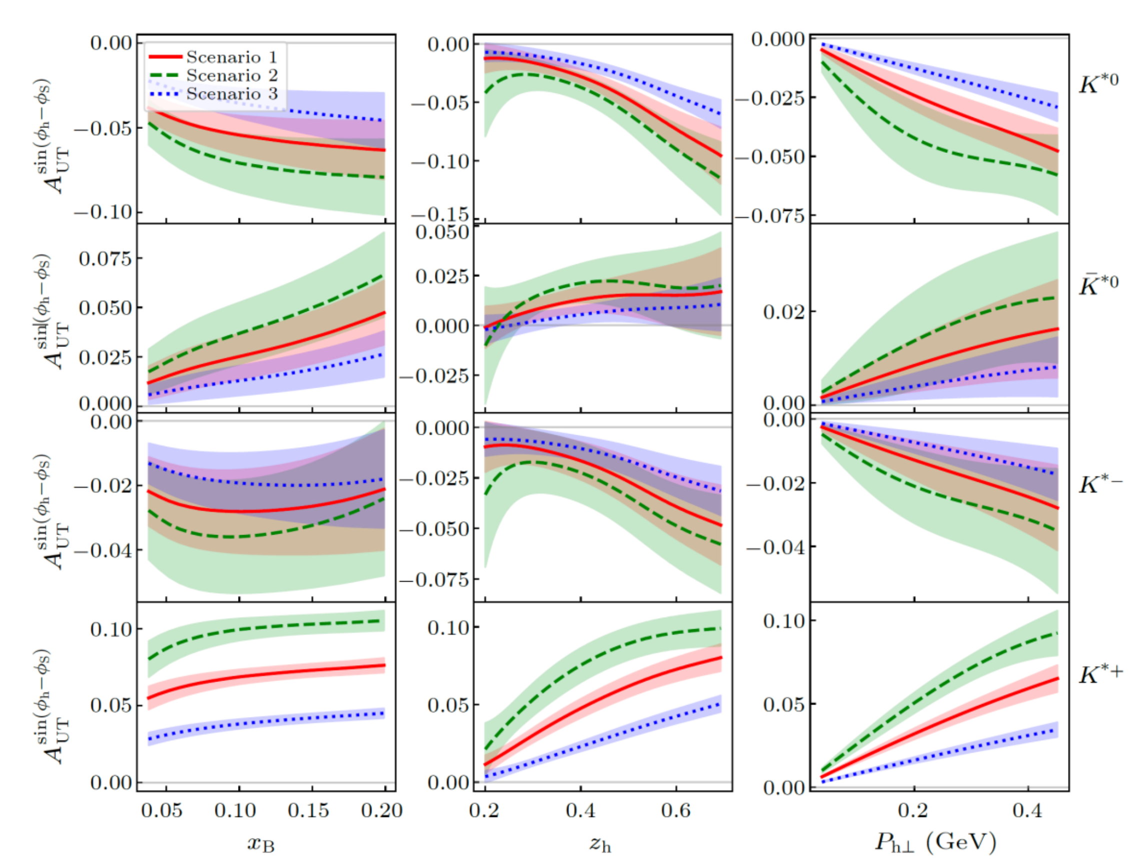
SV19:

$$f_{NP}(x,b) = \exp\left(-\frac{\lambda_1(1-x)+\lambda_2 x + x(1-x)\lambda_5}{\sqrt{1+\lambda_3 x^{\lambda_4}\boldsymbol{b}^2}}\boldsymbol{b}^2\right)$$

λ_1	λ_2	λ_3	λ_4	λ_5
0.198	9.30	431	2.12	-4.44

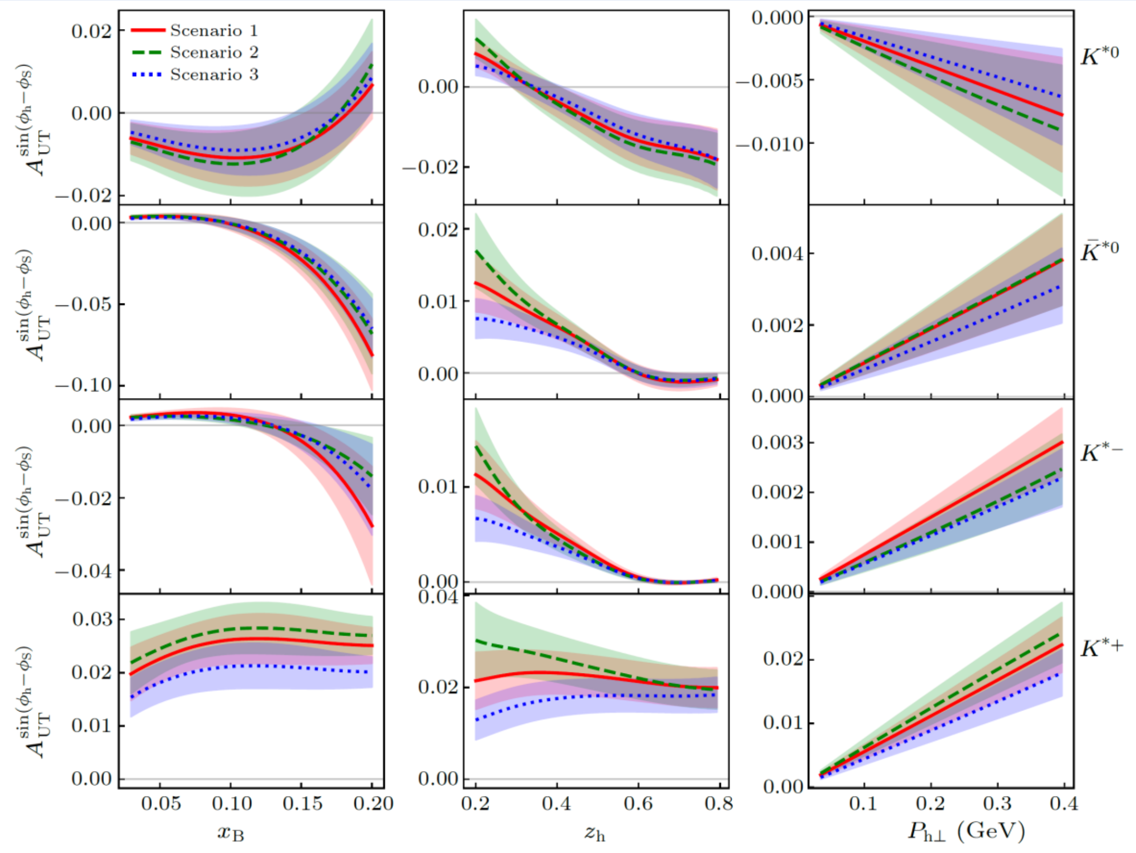
I. Scimemi, A. Vladimirov, JHEP 06 (2020) 137

Sivers effect results for K*, at EicC



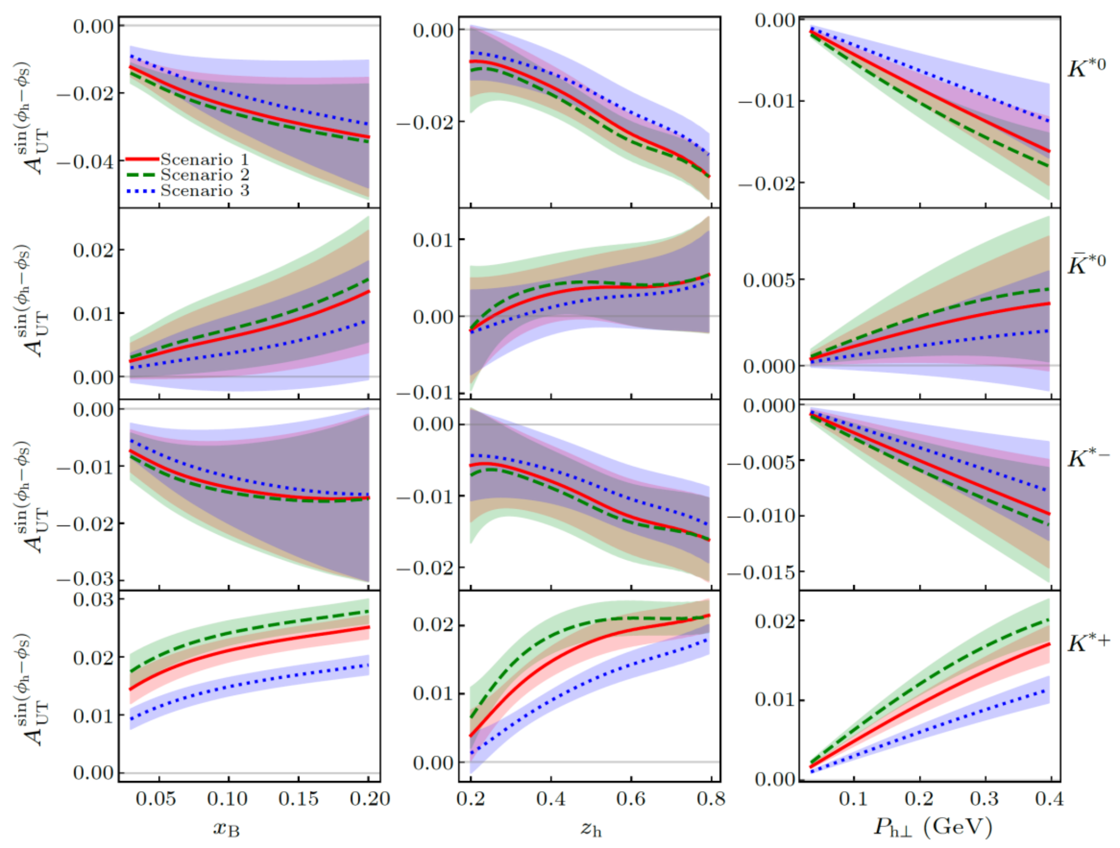
ZLSZ

Sivers effect results for K*, at EIC



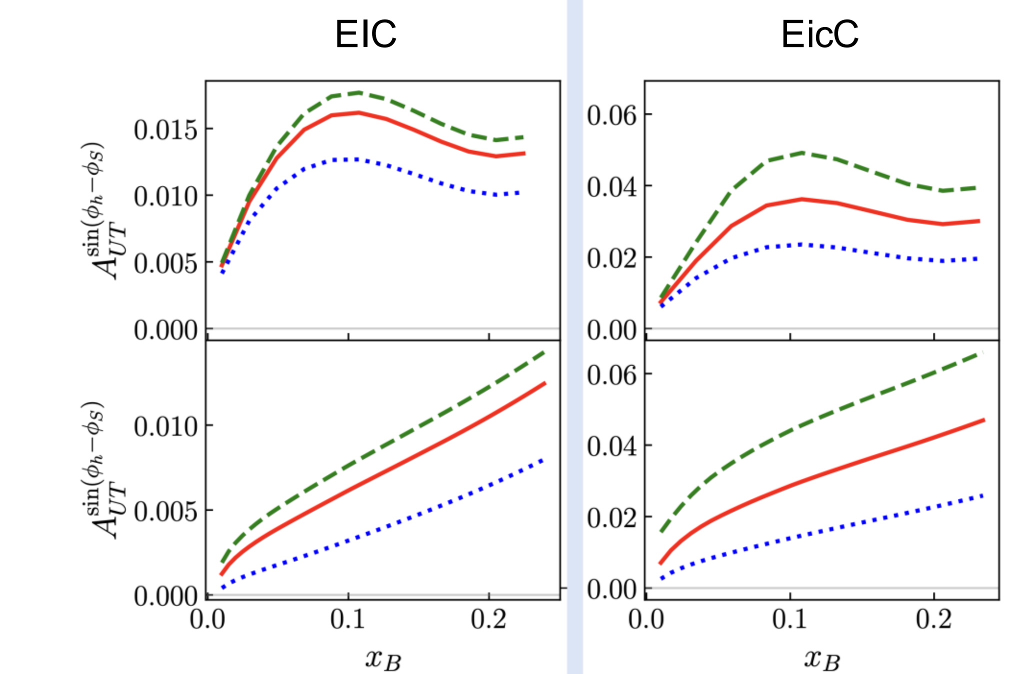
BPV20

Sivers effect results for K*, at EIC



ZLSZ

Comparison between EIC and EicC



BPV20

ZLSZ