The Sivers asymmetry of vector meson production in SIDIS process

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Outline

1. Introduction

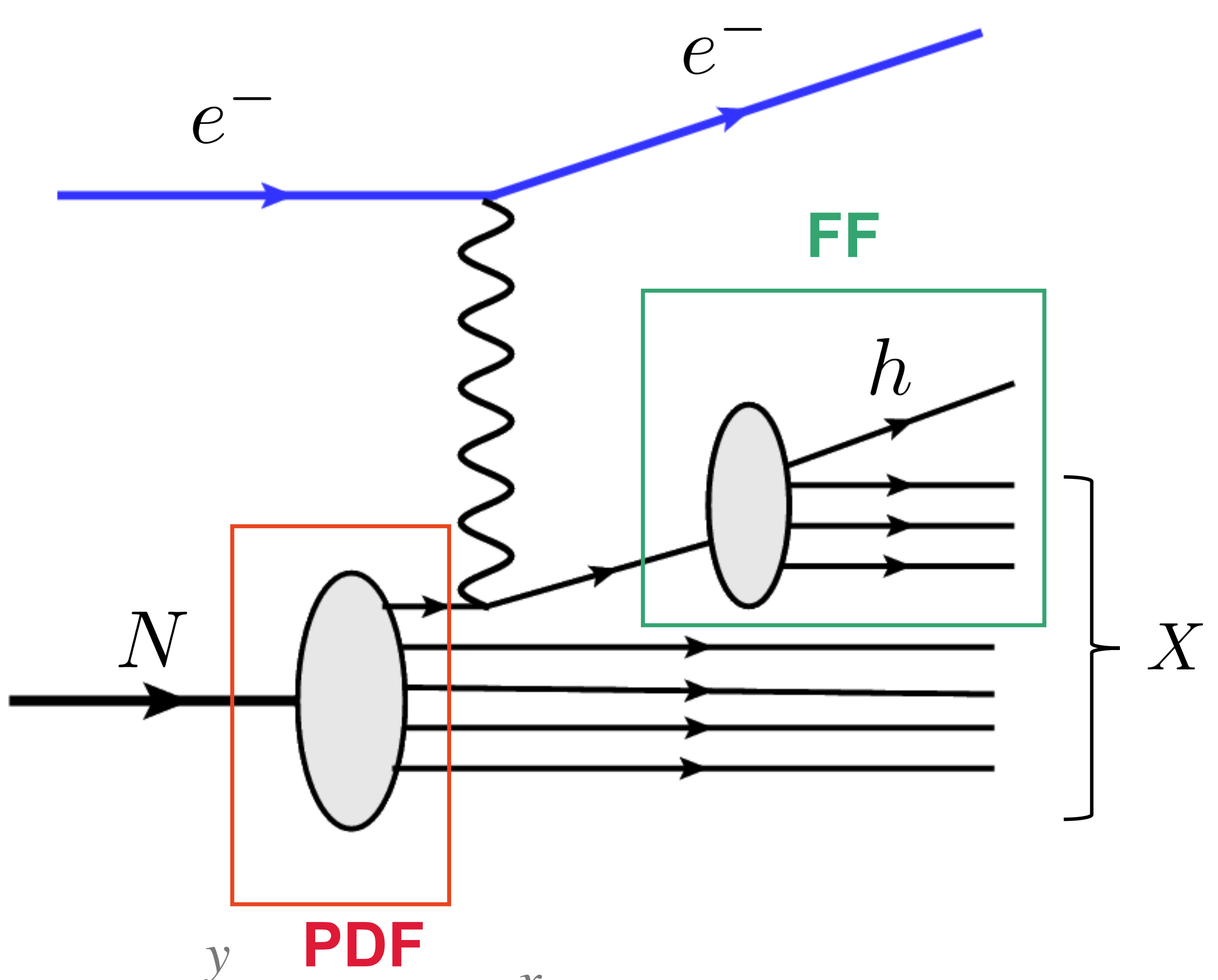
2. Framework

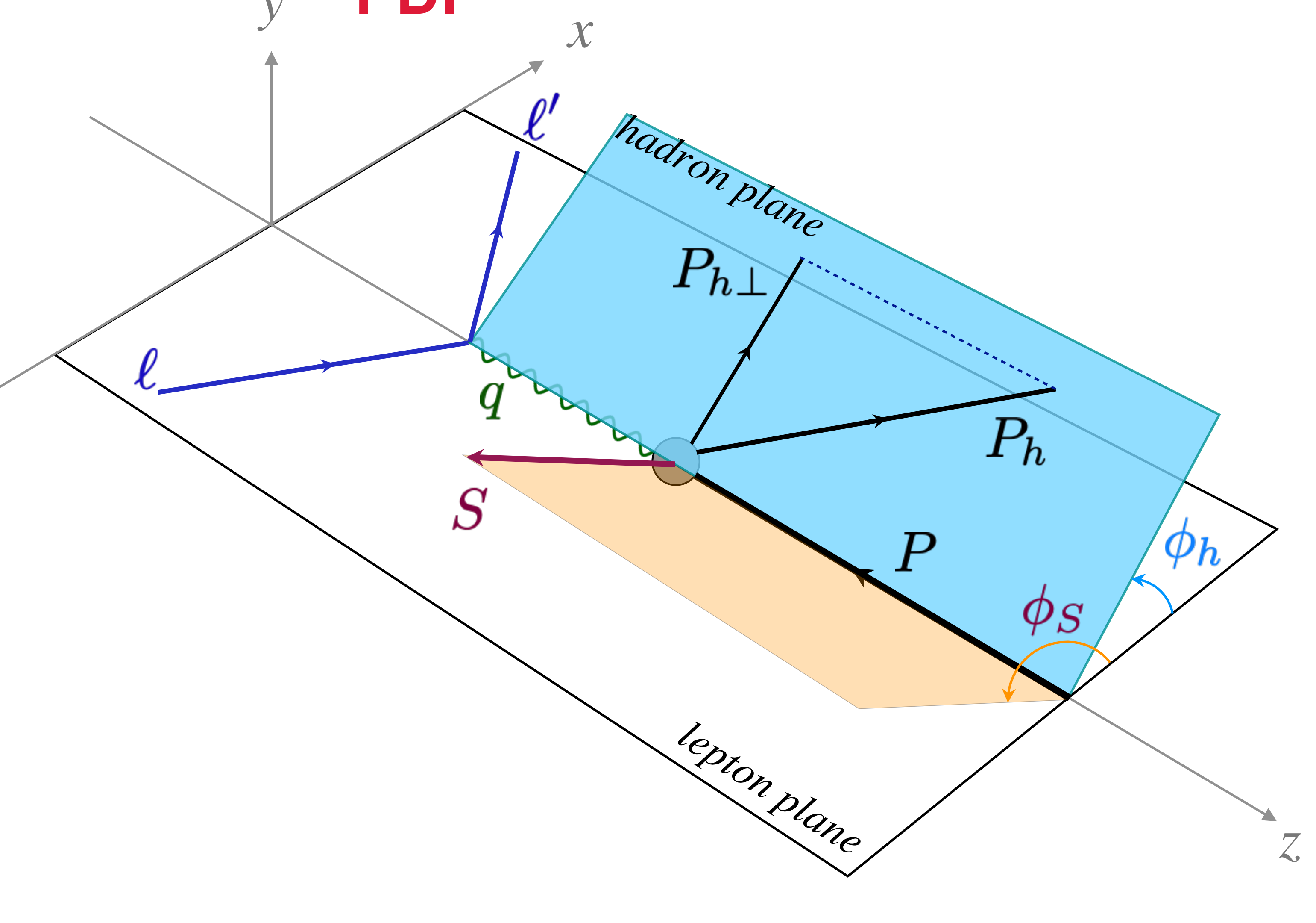
- TMD evolution
- The FFs of ρ^0 meson
- The calculation of Sivers asymmetry

3. Summary

Introduction

Semi-inclusive DIS (SIDIS)





Fragmentation function（TMD FF）

		Q		
		U	**L**	**T**
H	**U**	D_1		$H_1^\perp$

$$\textbf{Factorization:}\ \sigma^{ep\to ehX} = \sum_q PDF \otimes \sigma^{eq\to eq} \otimes FF$$

Parton distribution function（TMD PDF）

		Quark		
		U	**L**	**T**
H	**U**	f_1		$h_1^\perp$
	L		g_1	$h_{1L}^\perp$
	T	$f_{1T}^\perp$	$g_{1T}^\perp$	h_1 $h_{1T}^\perp$

U： Unpolarized
L： Longitudinal
T： Transversely

Introduction

$$\frac{d\sigma^h}{dx\,dy\,d\phi_S\,dz\,d\phi_h\,d\mathbf{P}_{h\perp}^2} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)$$

$$\times\Big\{ \quad \left[F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\varepsilon(1+\varepsilon)}\cos\phi_h F_{UU}^{\cos\phi_h} + \varepsilon\cos\left(2\phi_h\right)F_{UU}^{\cos 2\phi_h}\right]$$

$$+ \quad \lambda_l \quad \left[\sqrt{2\varepsilon(1-\varepsilon)}\sin\phi_h F_{LU}^{\sin\phi_h}\right]$$

$$+ \; S_L \quad \left[\sqrt{2\varepsilon(1+\varepsilon)}\sin\phi_h F_{UL}^{\sin\phi_h} + \varepsilon\sin\left(2\phi_h\right)F_{UL}^{\sin 2\phi_h}\right]$$

$$+ \; S_L\ \lambda_l \quad \left[\sqrt{1-\varepsilon^2}F_{LL} + \sqrt{2\varepsilon(1-\varepsilon)}\cos\phi_h F_{LL}^{\cos\phi_h}\right]$$

$$+ \; S_T \quad \Big[\sin\left(\phi_h-\phi_S\right)\left(F_{UT,T}^{\sin(\phi_h-\phi_S)} + \varepsilon F_{UT,L}^{\sin(\phi_h-\phi_S)}\right)$$

$$+\varepsilon\sin\left(\phi_h+\phi_S\right)F_{UT}^{\sin(\phi_h+\phi_S)} + \varepsilon\sin\left(3\phi_h-\phi_S\right)F_{UT}^{\sin(3\phi_h-\phi_S)}$$

$$+\sqrt{2\varepsilon(1+\varepsilon)}\sin\phi_S F_{UT}^{\sin\phi_S} + \sqrt{2\varepsilon(1+\varepsilon)}\sin\left(2\phi_h-\phi_S\right)F_{UT}^{\sin(2\phi_h-\phi_S)}\Big]$$

$$+ \; S_T\ \lambda_l \quad \Big[\sqrt{1-\varepsilon^2}\cos\left(\phi_h-\phi_S\right)F_{LT}^{\cos(\phi_h-\phi_S)} + \sqrt{2\varepsilon(1-\varepsilon)}\cos\phi_S F_{LT}^{\cos\phi_S}$$

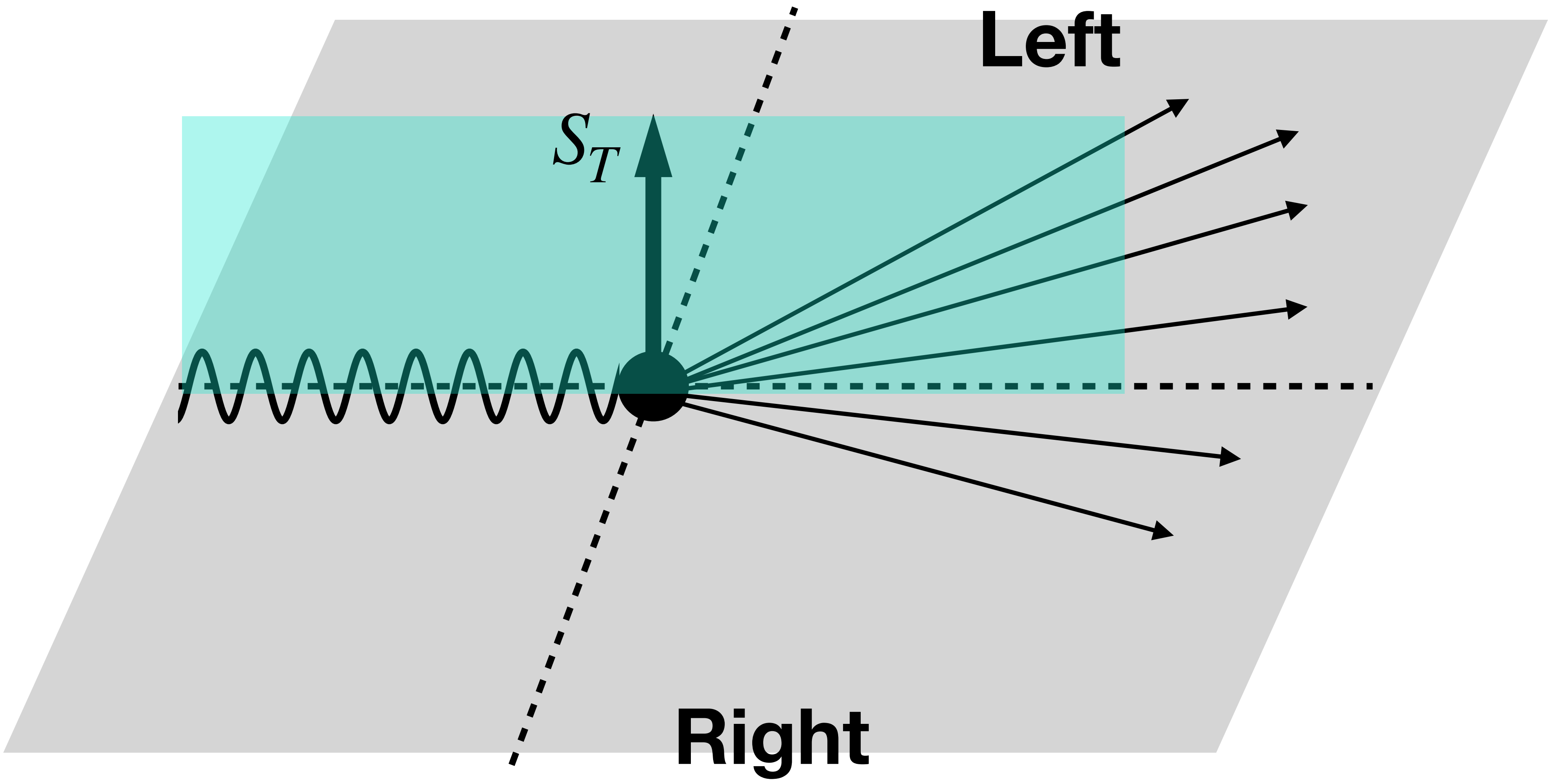
$$+\sqrt{2\varepsilon(1-\varepsilon)}\cos\left(2\phi_h-\phi_S\right)F_{LT}^{\cos(2\phi_h-\phi_S)}\Big]\Big\}$$

$F_{X\,Y,\,Z} \propto PDF \otimes FF$

X: Lepton polarization
Y: Target polarization
Z: γ^* polarization

Transversely single spin asymmetry (TSSA):

$$A_{UT} = \frac{\sigma\left(\vec{S}_T\right) - \sigma\left(-\vec{S}_T\right)}{\sigma\left(\vec{S}_T\right) + \sigma\left(-\vec{S}_T\right)}$$



Introduction

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$$+ \; S_L\;\lambda_l \left[\sqrt{1-\varepsilon^2}F_{LL} + \sqrt{2\varepsilon(1-\varepsilon)}\cos\phi_h F_{LL}^{\cos\phi_h}\right]$$

Contribute to TSSA

$$+ \; S_T \left[\sin\left(\phi_h-\phi_S\right)\left(F_{UT,T}^{\sin(\phi_h-\phi_S)} + \varepsilon F_{UT,L}^{\sin(\phi_h-\phi_S)}\right)\right.$$

$$+\varepsilon\sin\left(\phi_h+\phi_S\right) F_{UT}^{\sin(\phi_h+\phi_S)} + \varepsilon\sin\left(3\phi_h-\phi_S\right) F_{UT}^{\sin(3\phi_h-\phi_S)}$$

$$\left.+\sqrt{2\varepsilon(1+\varepsilon)}\sin\phi_S F_{UT}^{\sin\phi_S} + \sqrt{2\varepsilon(1+\varepsilon)}\sin\left(2\phi_h-\phi_S\right) F_{UT}^{\sin(2\phi_h-\phi_S)}\right]$$

$$+ \; S_T\;\lambda_l \left[\sqrt{1-\varepsilon^2}\cos\left(\phi_h-\phi_S\right) F_{LT}^{\cos(\phi_h-\phi_S)} + \sqrt{2\varepsilon(1-\varepsilon)}\cos\phi_S F_{LT}^{\cos\phi_S}\right.$$

$$\left.+\sqrt{2\varepsilon(1-\varepsilon)}\cos\left(2\phi_h-\phi_S\right) F_{LT}^{\cos(2\phi_h-\phi_S)}\right]\Big\}$$

$F_{X\,Y,\,Z} \propto PDF \otimes FF$

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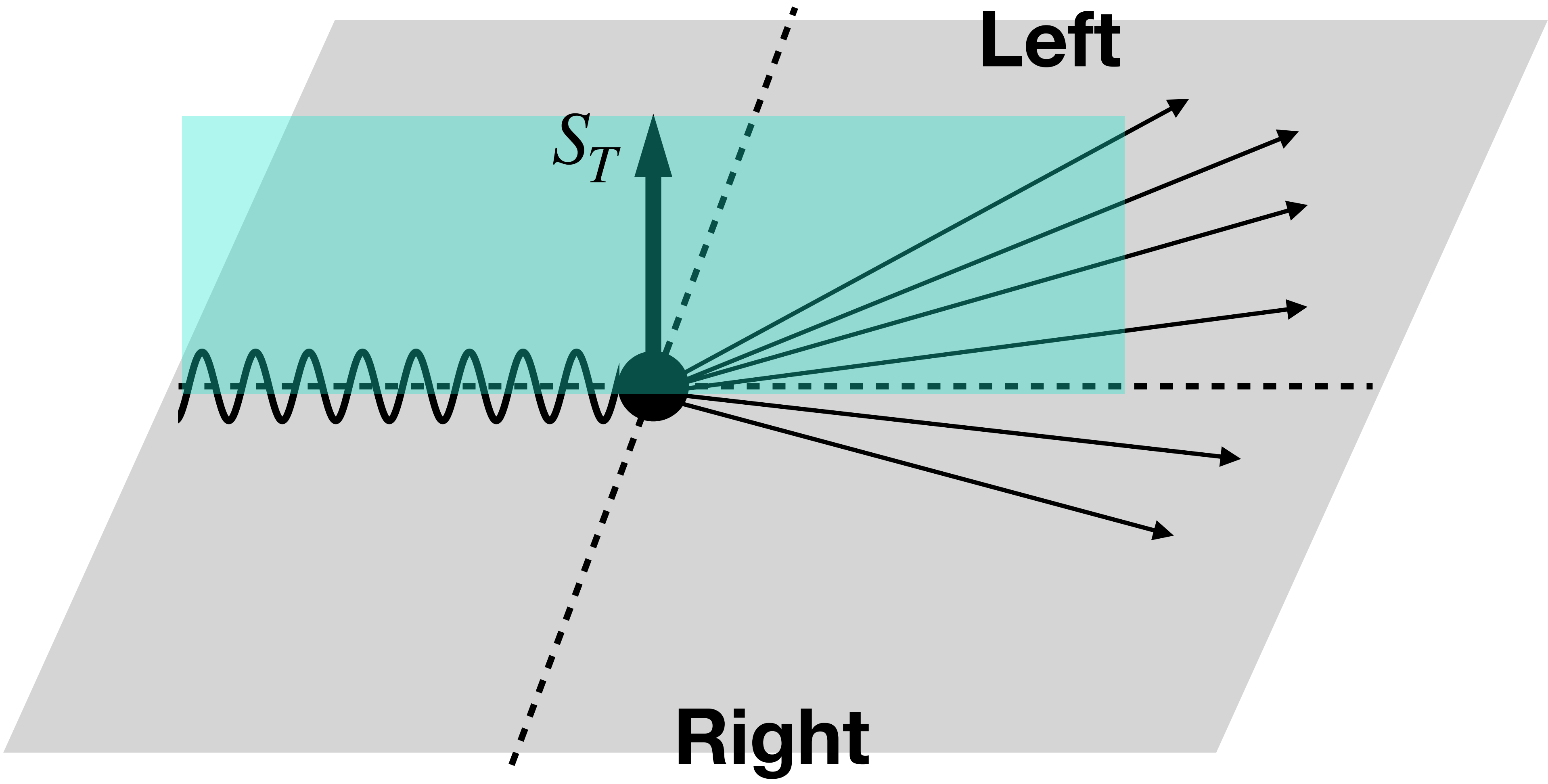

Introduction

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Contribute to TSSA

$$+ S_T \Big[\sin(\phi_h-\phi_S)\left(F_{UT,T}^{\sin(\phi_h-\phi_S)} + \varepsilon F_{UT,L}^{\sin(\phi_h-\phi_S)}\right)$$

$$+\varepsilon\sin(\phi_h+\phi_S)\,F_{UT}^{\sin(\phi_h+\phi_S)} + \varepsilon\sin(3\phi_h-\phi_S)\,F_{UT}^{\sin(3\phi_h-\phi_S)}$$

$$+\sqrt{2\varepsilon(1+\varepsilon)}\sin\phi_S F_{UT}^{\sin\phi_S} + \sqrt{2\varepsilon(1+\varepsilon)}\sin(2\phi_h-\phi_S)\,F_{UT}^{\sin(2\phi_h-\phi_S)}\Big]$$

$$+ S_T\,\lambda_l \Big[\sqrt{1-\varepsilon^2}\cos(\phi_h-\phi_S)\,F_{LT}^{\cos(\phi_h-\phi_S)} + \sqrt{2\varepsilon(1-\varepsilon)}\cos\phi_S F_{LT}^{\cos\phi_S}$$

$$+\sqrt{2\varepsilon(1-\varepsilon)}\cos(2\phi_h-\phi_S)\,F_{LT}^{\cos(2\phi_h-\phi_S)}\Big]\Big\}$$

$F_{X\,Y,\,Z} \propto PDF \otimes FF$

X: Lepton polarization
Y: Target polarization
Z: γ^* polarization

Sivers function

$$F_{UT,T}^{\sin(\phi_h-\phi_S)} = \mathcal{C}\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M}\,f_{1T}^{\perp}\;D_1\right]$$

Unpolarized TMD FF

Sivers asymmetry:

$$A_{UT}^{\sin(\phi_h-\phi_s)} = \frac{F_{UT}^{\sin(\phi_h-\phi_S)}}{F_{UU}}$$

Introduction

Collins and Sivers transverse-spin asymmetries in inclusive muoproduction of ρ^0 mesons

The COMPASS Collaboration

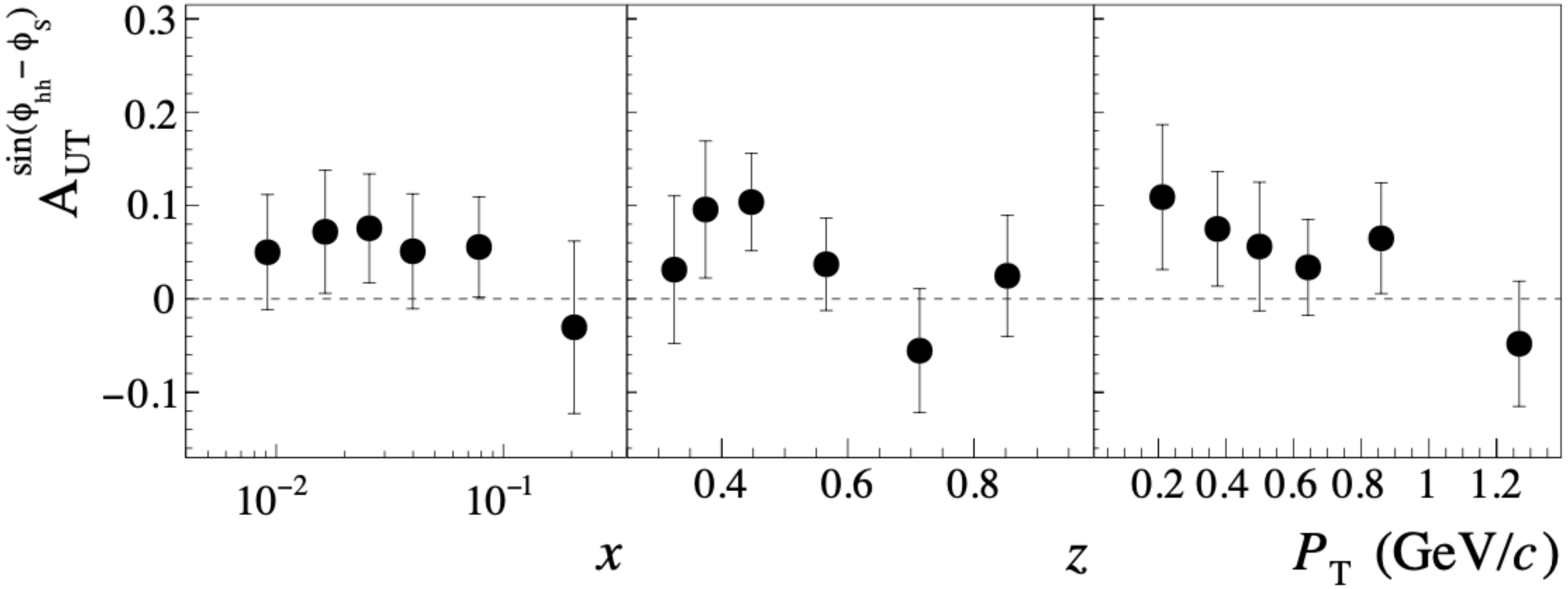
Abstract

The production of vector mesons in deep inelastic scattering is an interesting yet scarsely explored channel to study the transverse spin structure of the nucleon and the related phenomena. The COMPASS collaboration has performed the first measurement of the Collins and Sivers asymmetries for inclusively produced ρ^0 mesons. The analysis is based on the data set collected in deep inelastic scattering in 2010 using a 160 GeV/c μ^+ beam impinging on a transversely polarized NH_3 target. The ρ^0 mesons are selected from oppositely charged hadron pairs, and the asymmetries are extracted as a function of the Bjorken-x variable, the transverse momentum of the pair and the fraction of the energy z carried by the pair. Indications for positive Collins and Sivers asymmetries are observed.

The COMPASS, C. Alice, A. Amoroso, V. Andrieux et al., Phys.Lett.B 843 (2023) 137950

The Sivers asymmetry of ρ^0 meson in SIDIS process has been measured firstly.

Sivers asymmetry



Framework

TMD factorization and evolution:

$$A_{UT}^{\sin(\phi_h-\phi_S)} = \frac{F_{UT}^{\sin(\phi_h-\phi_S)}}{F_{UU}}$$

$$\sin(\phi_h - \phi_S)\, F_{UT}^{\sin(\phi_h-\phi_S)} = \varepsilon_{\perp\alpha\beta} S_\perp^\alpha F_{\text{Sivers}}^\beta$$

$$F_{\text{Sivers}}^\alpha(x_B, z_h, P_{h\perp}, Q) = \int \frac{d^2b}{(2\pi)^2} e^{i\vec{P}_{h\perp}\cdot\vec{b}/z_h} \widetilde{F}_{\text{Sivers}}^\alpha(x_B, z_h, b, Q) + Y_{\text{Sivers}}^\alpha(x_B, z_h, P_{h\perp}, Q)$$

Dominates in $P_{h\perp} \ll Q$ Dominates in $P_{h\perp} \gtrsim Q$

$$F_{UU}(x_B, z_h, P_{h\perp}, Q) = \int \frac{d^2b}{(2\pi)^2} e^{i\vec{P}_{h\perp}\cdot\vec{b}/z_h} \widetilde{F}_{UU}(x_B, z_h, b, Q) + Y_{UU}(x_B, z_h, P_{h\perp}, Q)$$

We focus on the region $P_{h\perp} \ll Q$, where the TMD factorization approximatively applies.

Framework

TMD Factorization

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

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

$$f_{1,q/p}(x, k_\perp^2, \mu, \zeta) = \frac{1}{2\pi} \int \mathrm{d}b\, bJ_0(bk_\perp) \widetilde{f}_{1,q/p}(x, b, \mu, \zeta)$$

$$D_{1,h/q}(z, p_\perp^2, \mu, \zeta) = \frac{1}{2\pi} \int \mathrm{d}b\, bJ_0\left(b\frac{p_\perp}{z}\right) \widetilde{D}_{1h/q}(z, b, \mu, \zeta)$$

$$\frac{k_\perp}{M} f^{\perp}_{1T}(x, k_\perp^2, \mu, \zeta) = \int_0^\infty \frac{dbb^2 M}{2\pi} J_1(bk_\perp) \widetilde{f}^{\perp}_{1T}(x, b, \mu, \zeta)$$

μ: the renormalization scale $\mu^2 = Q^2$

ζ: the rapidity scale $\zeta_1\zeta_2 = Q^4$ ➡ $\zeta_1 = \zeta_2 = Q^2$ symmetrical choice

Framework

TMD evolution

obtain the TMD functions with any scale.

$\tilde{F}$ stands for any TMD function.

TMDs evolution equations:

CS equation:

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

$\mathcal{D}$: the rapidity anomalous dimension

RG equation:

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

γ_F: the TMD anomalous dimension

The solution: $\widetilde{F}\left(x,b;\mu_f,\zeta_f\right) = R\left[b;\left(\mu_f,\zeta_f\right) \to \left(\mu_i,\zeta_i\right)\right] \widetilde{F}\left(x,b;\mu_i,\zeta_i\right)$

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

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

The finite-order perturbative calculation destroys the path independence property.

Framework

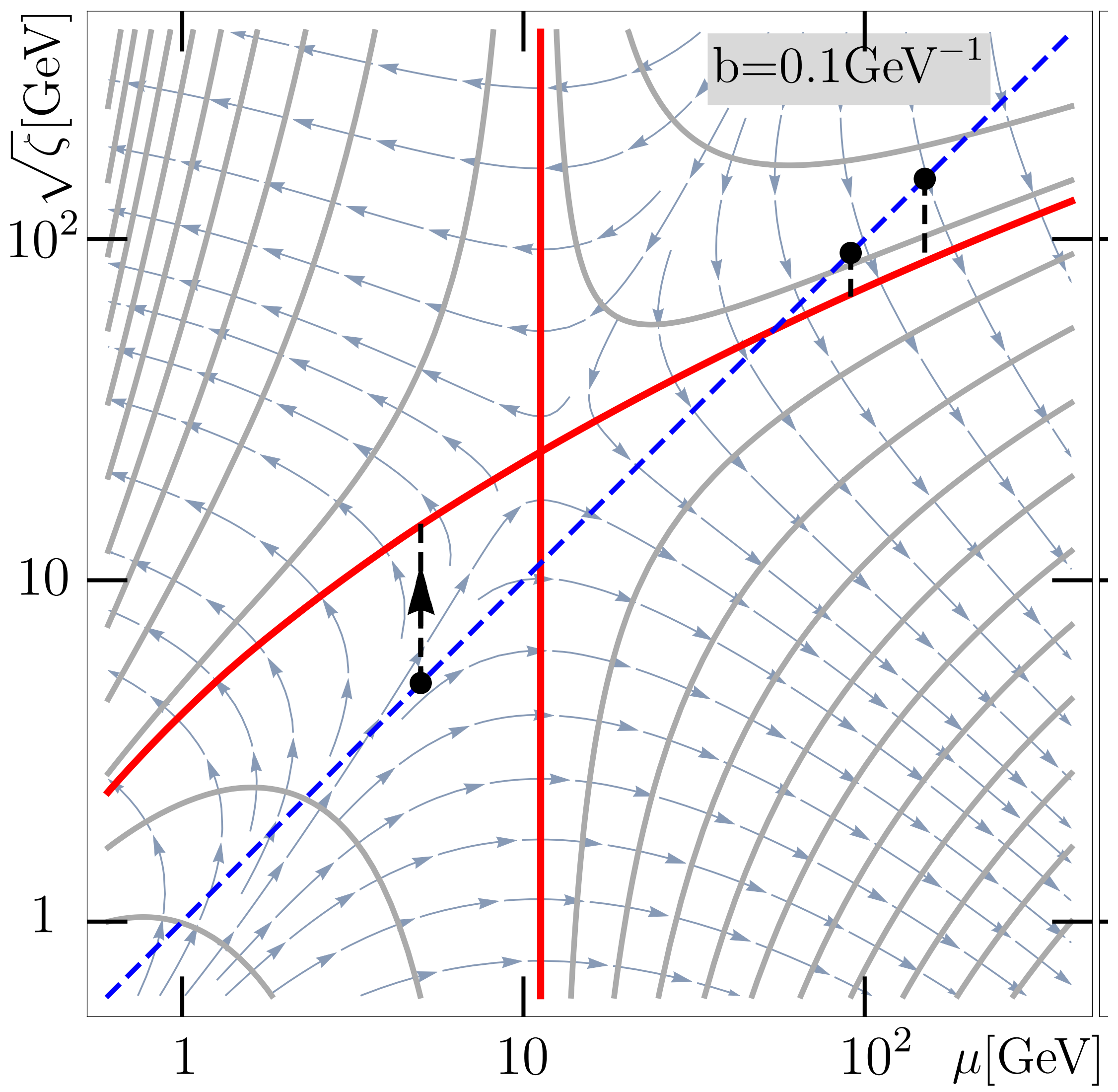
TMD evolution:

$$\frac{\partial \ln \tilde{F}(x,b,\mu,\zeta)}{\partial \ln \mu^2} = \frac{\gamma_F(\mu,\zeta)}{2}$$

$$\frac{\partial \ln \tilde{F}(x,b;\mu,\zeta)}{\partial \ln \zeta} = -\mathcal{D}(b,\mu)$$

$$\vec{E} = \left(\frac{\gamma_F(\mu,\zeta)}{2}, -\mathcal{D}(\mu,\zeta)\right)$$

Ignazio Scimemi, Alexey Vladimirov,
JHEP 06 (2020) 137



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

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

$$b_* = \frac{b}{\sqrt{1+\frac{b^2}{B_{NP}^2}}}$$

In the ζ-prescription, the initial scales μ and ζ belong to a null-evolution line, that is expressed as $\left(\mu, \zeta_\mu(b)\right)$

$$\widetilde{F}\left(x,b;Q,Q^2\right) = \exp\left[\int_P \left(\gamma_F(\mu,\zeta)\frac{d\mu}{\mu} - \mathcal{D}(\mu,b)\frac{d\zeta}{\zeta}\right)\right]\widetilde{F}(x,b)$$

$$= \left(\frac{Q^2}{\zeta_Q(b)}\right)^{-\mathcal{D}(b,Q)} \widetilde{F}(x,b)$$

Framework

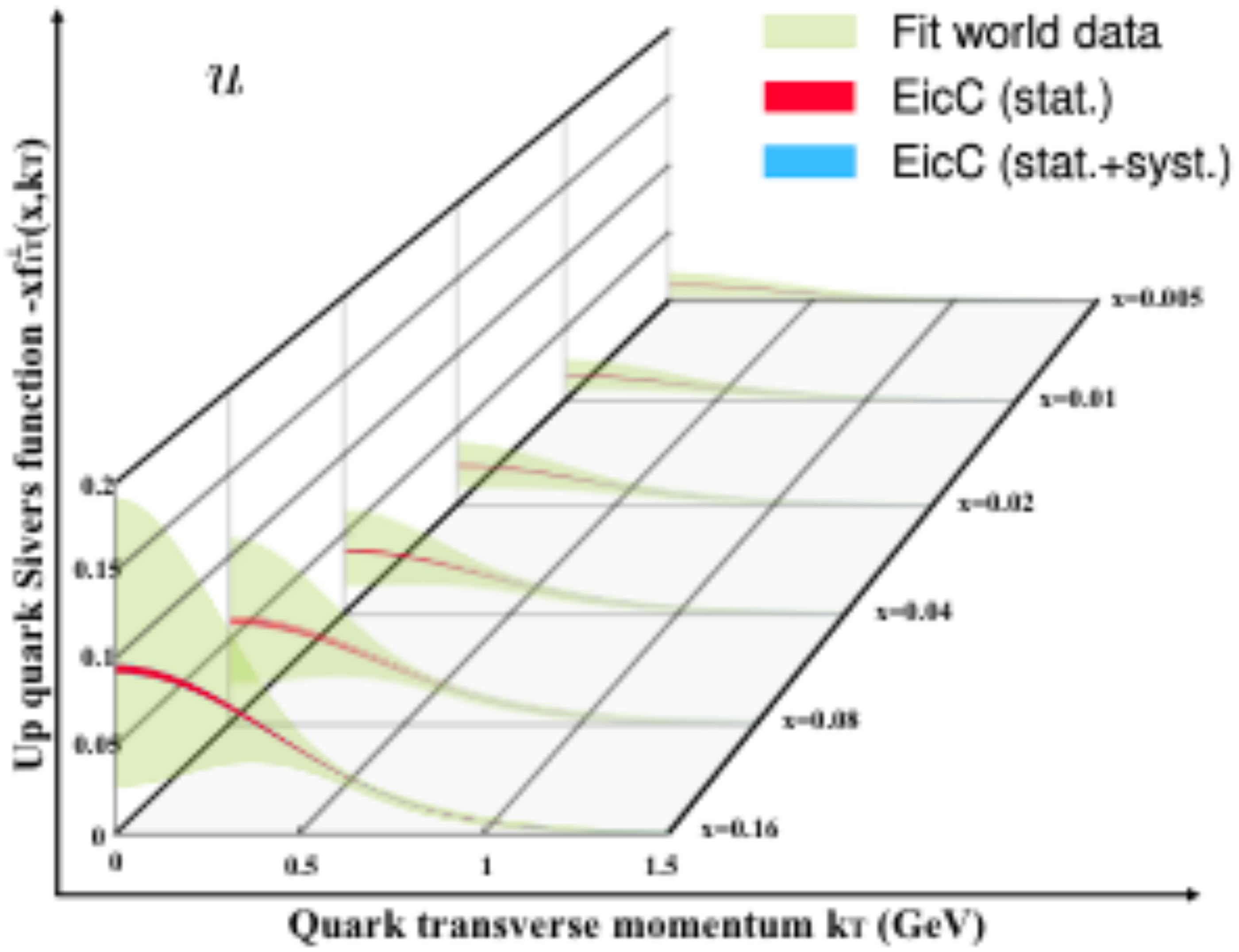
Within the TMD factorization and TMD evolution,
the Sivers asymmetry:

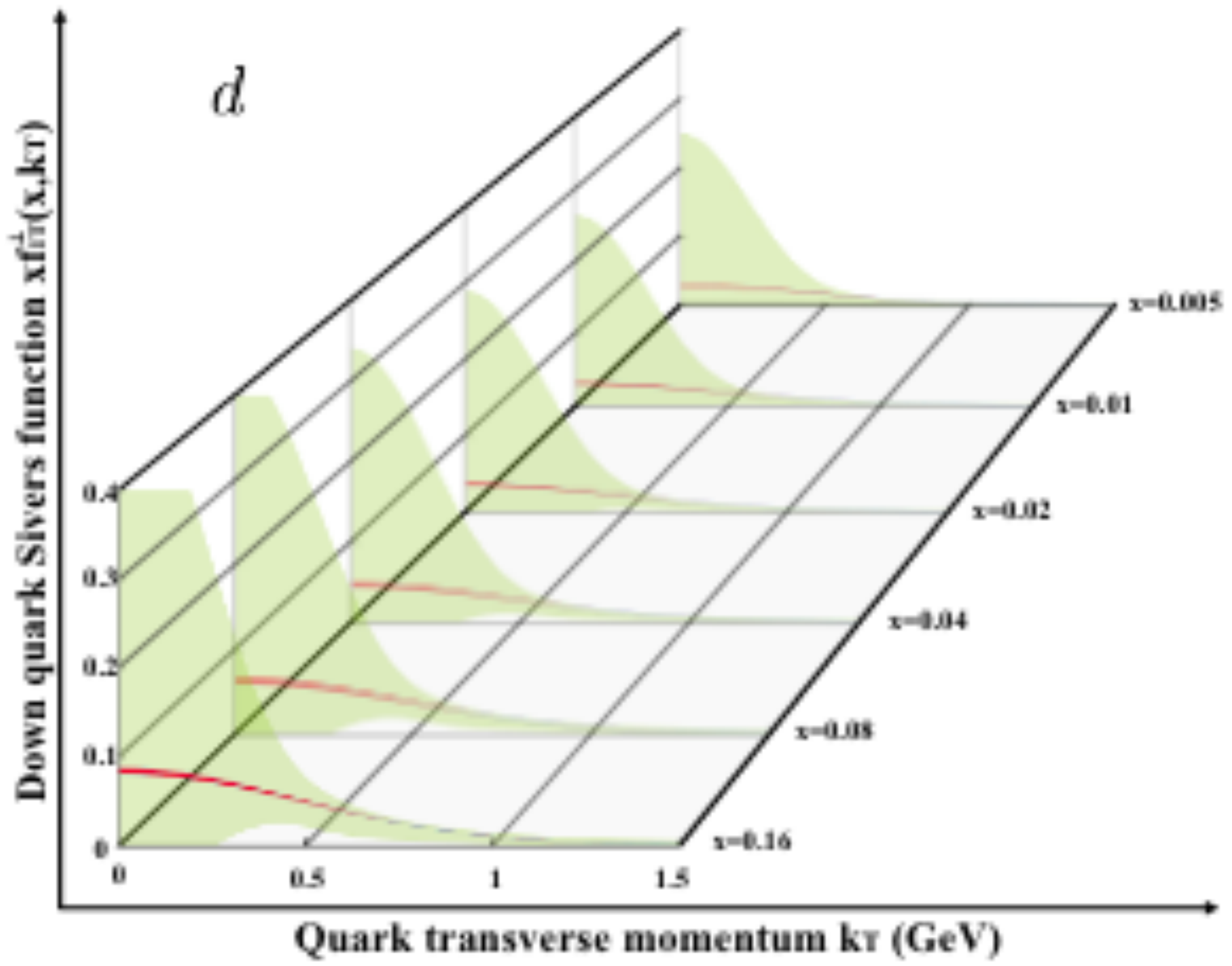
$$A_{UT}^{\sin(\phi_h-\phi_S)} = \frac{F_{UT}^{\sin(\phi_h-\phi_S)}}{F_{UU}}$$

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

$$F_{UU}\left(x_B, z_h, P_{h\perp}, Q\right) = H\left(\mu, Q\right) \sum_q e_q^2 \int_0^\infty \frac{\mathrm{d}b}{2\pi} b J_0\left(\frac{bP_{h\perp}}{z_h}\right)\left(\frac{Q^2}{\zeta_Q(b)}\right)^{-2\mathcal{D}(b,Q)} \times \widetilde{f}_{1,q/p}\left(x_B, b\right) \widetilde{D}_{1,h/q}\left(z_h, b\right)$$

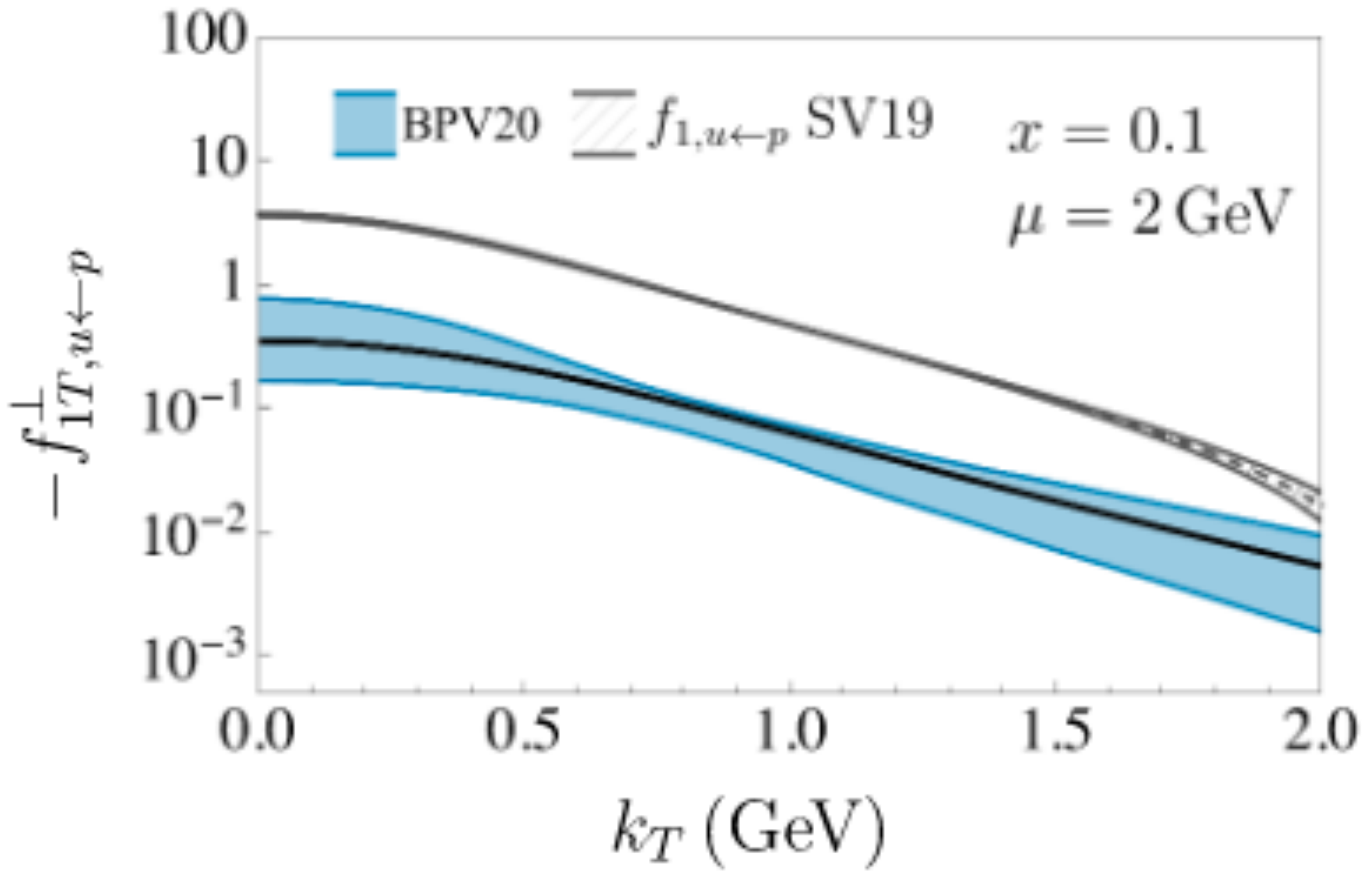
Framework

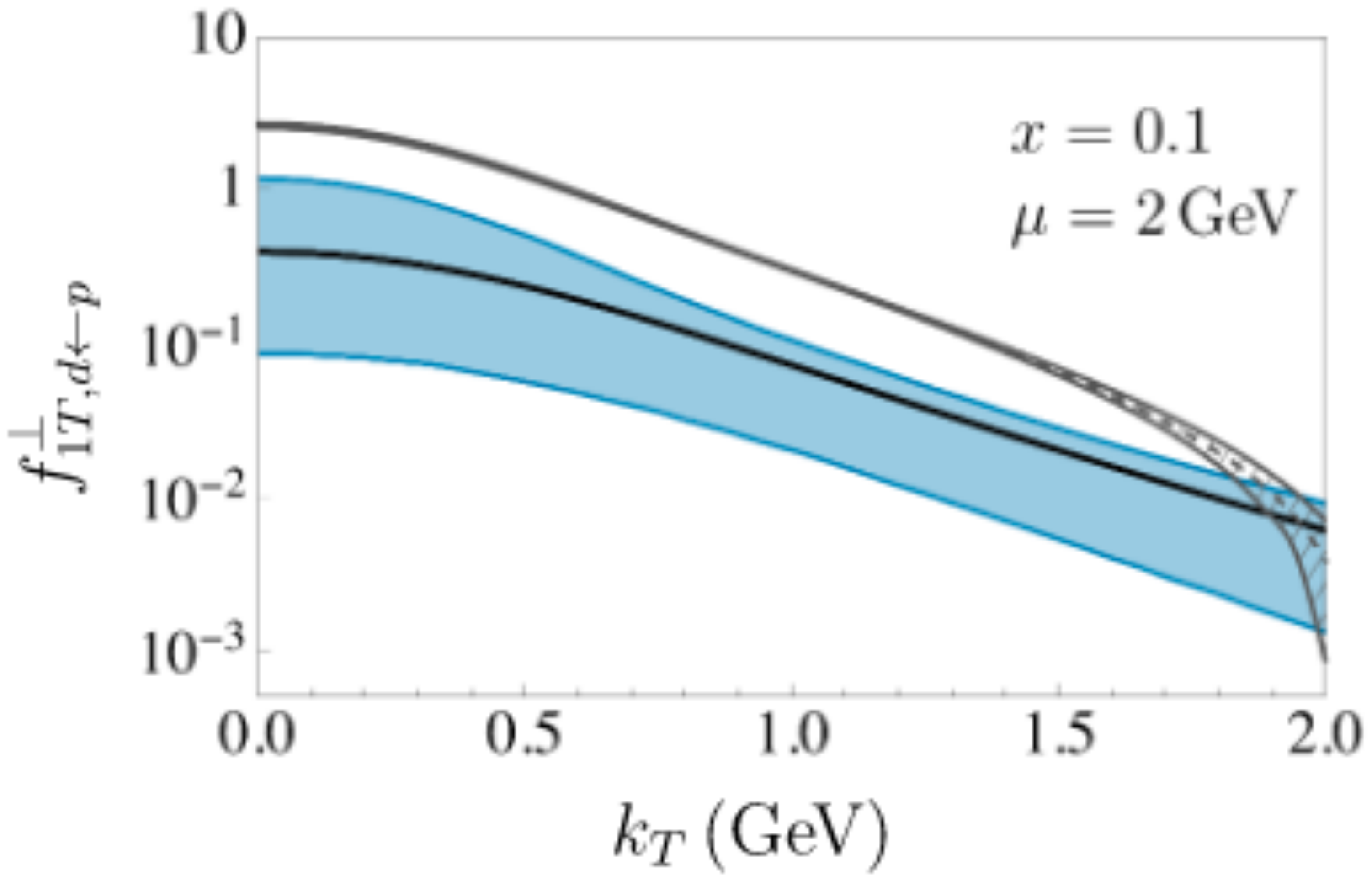




Sivers function parameterization: ZLSZ

Chunhua Zeng, Tianbo Liu, Peng Sun, Yuxiang Zhao, Phys.Rev.D 106 (2022) 9, 094039





Sivers function parameterization: BPV20

Marcin Bury, Alexei Prokudin, Alexey Vladimirov, JHEP 05 (2021) 151

Unpolarized FFs of ρ^0 meson

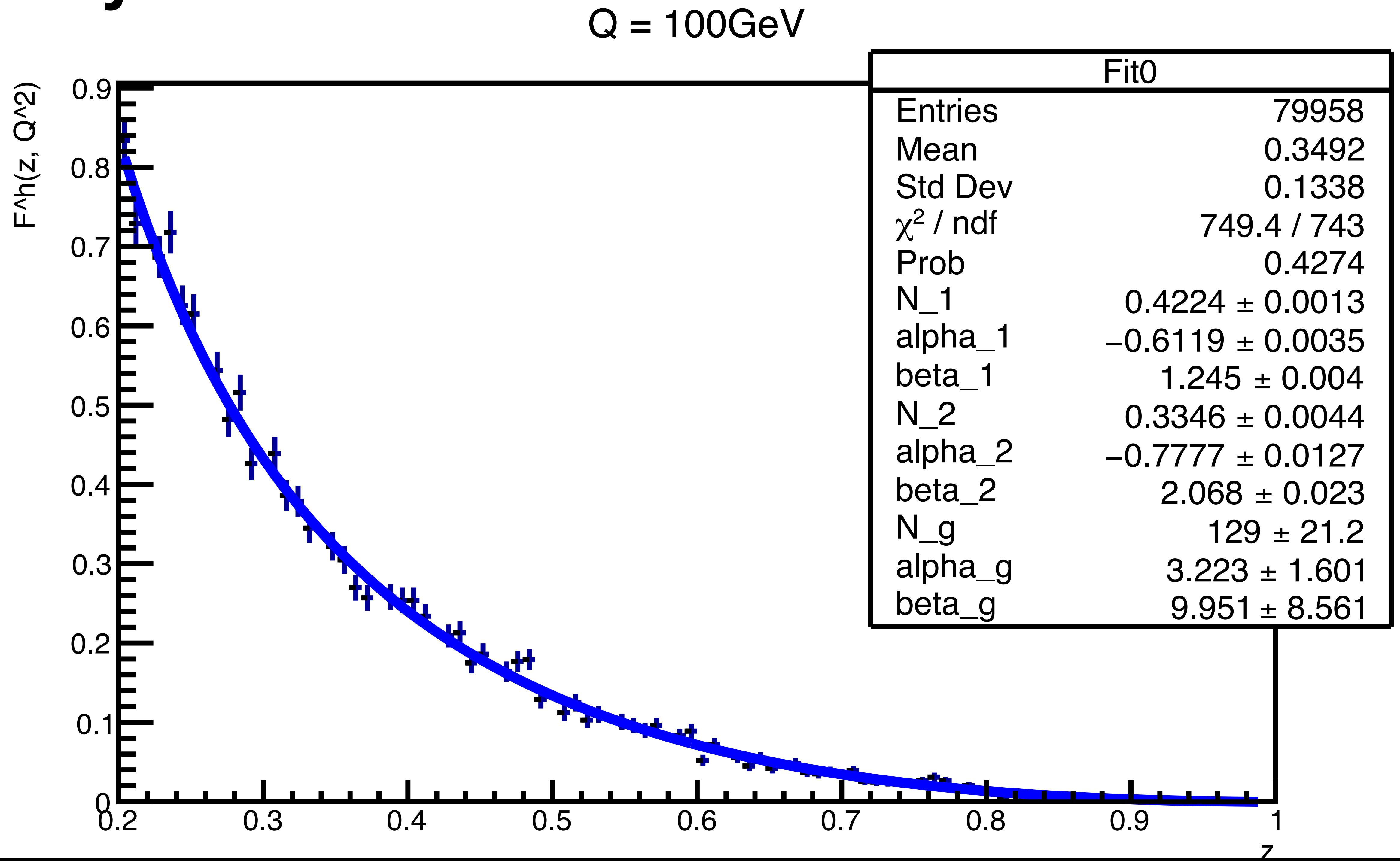
The unpolarized FFs of ρ^0 meson：

No appropriate parametrization for FFs of ρ^0 meson.

Approach： perform a global fit of Pythia's ρ^0 meson data.

$$F^{\rho^0}\left(z, Q^2\right) = \frac{1}{\sigma_{tot}} \frac{d\sigma\left(e^+e^- \to \rho^0 X\right)}{dz} = \frac{1}{N_{tot}} \frac{\Delta N\left(e^+e^- \to \rho^0 X\right)}{\Delta z}$$

Pythia data：



Charge conjugate symmetry, Isospin symmetry

the parameterization is chosen as：

$$D_{\rho^0/u}(z, \mu_0) = D_{\rho^0/d}(z, \mu_0) = D_{\rho^0/\bar{u}}(z, \mu_0)$$
$$= D_{\rho^0/\bar{d}}(z, \mu_0) = N_1 \times z^{\alpha_1} \times (1-z)^{\beta_1}$$

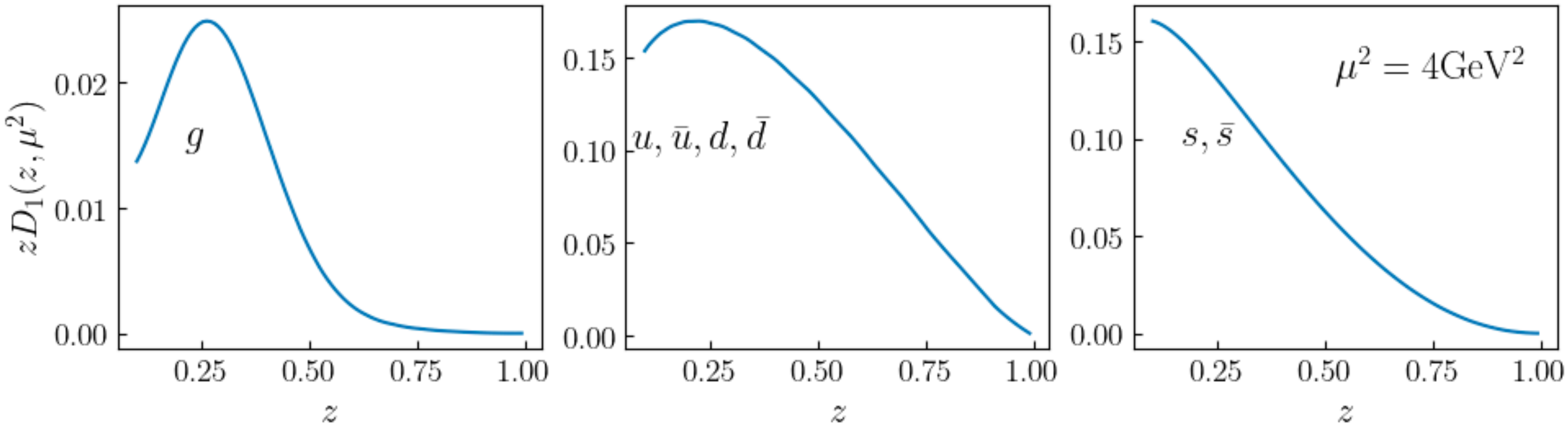
$$D_{\rho^0/s}(z, \mu_0) = D_{\rho^0/\bar{s}}(z, \mu_0) = N_2 \times z^{\alpha_2} \times (1-z)^{\beta_2}$$

$$D_{\rho^0/g}(z, \mu_0) = N_g \times z^{\alpha_g} \times (1-z)^{\beta_g} \qquad \mu_0^2 = 1.2GeV^2$$

Only take the gluon, $u, \bar{u}, d, \bar{d}, s, \bar{s}$ into account

Unpolarized FFs of ρ^0 meson

Result：



$\chi^2/d.o.f. = 749.4/743 = 1.0086$

function	N	α	β
$D_{\rho^0/u}$	0.4224 ± 0.0013	-0.6118 ± 0.0035	1.2448 ± 0.0037
$D_{\rho^0/s}$	0.3346 ± 0.0044	-0.7777 ± 0.0127	2.0681 ± 0.0229
$D_{\rho^0/g}$	129.038 ± 21.1586	3.2235 ± 1.6011	9.9509 ± 8.5609

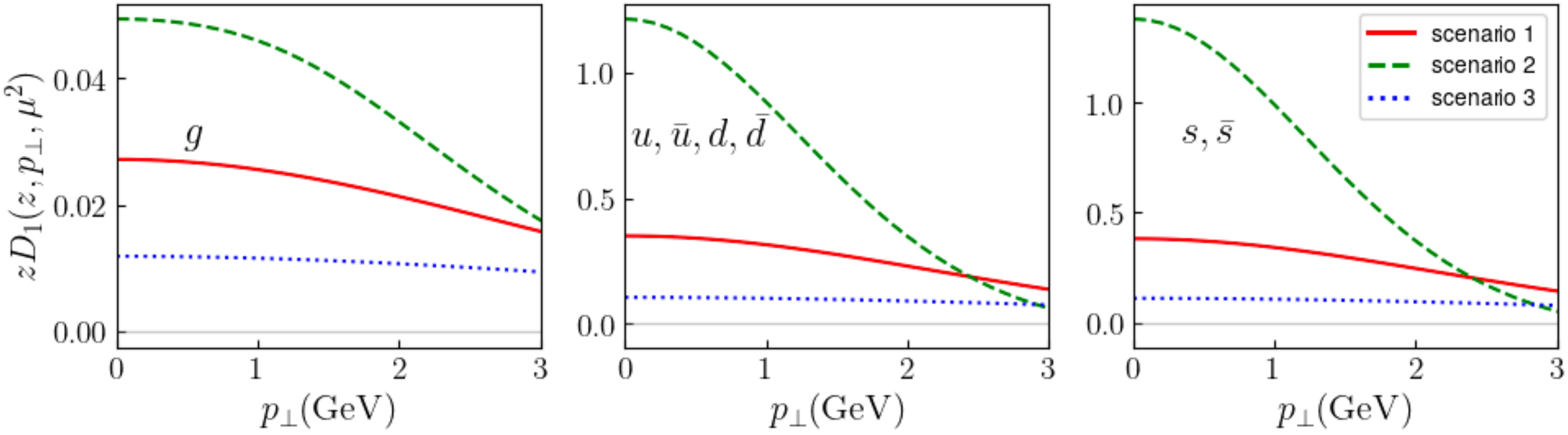
$$D_1\left(z,\mu_0^2\right) = N\, z^{\alpha}\ (1-z)^{\beta}$$

The TMD FFs

Obtain TMD FFs by collinear FFs：

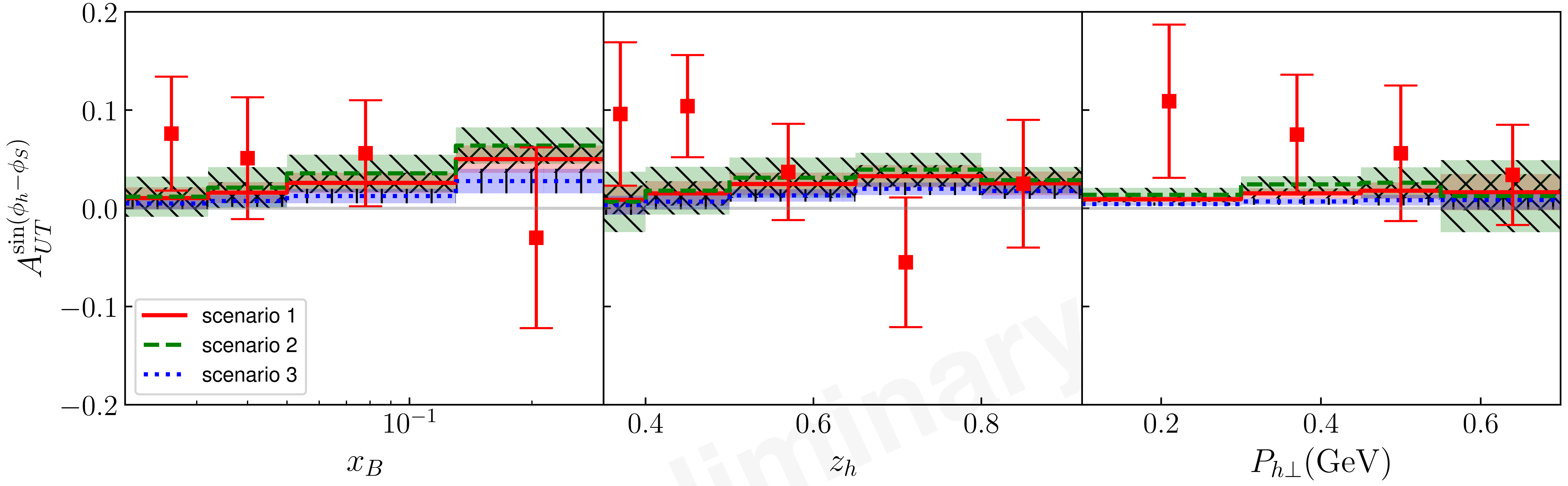
$$D_{1,h/f}(z,b) = \frac{1}{z^2}\sum_{f'}\int_z^1 \frac{\mathrm{d}y}{y} y^2 \mathbb{C}_{f\to f'}\left(y,b,\mu_{\mathrm{OPE}}^{\mathrm{FF}}\right) D_{1,h/f'}\left(\frac{z}{y},\mu_{\mathrm{OPE}}^{\mathrm{FF}}\right) D_{\mathrm{NP}}(z,b)$$

Three $p_\perp$ distributions $z = 0.1,\ \mu^2 = 4\mathrm{GeV}^2$

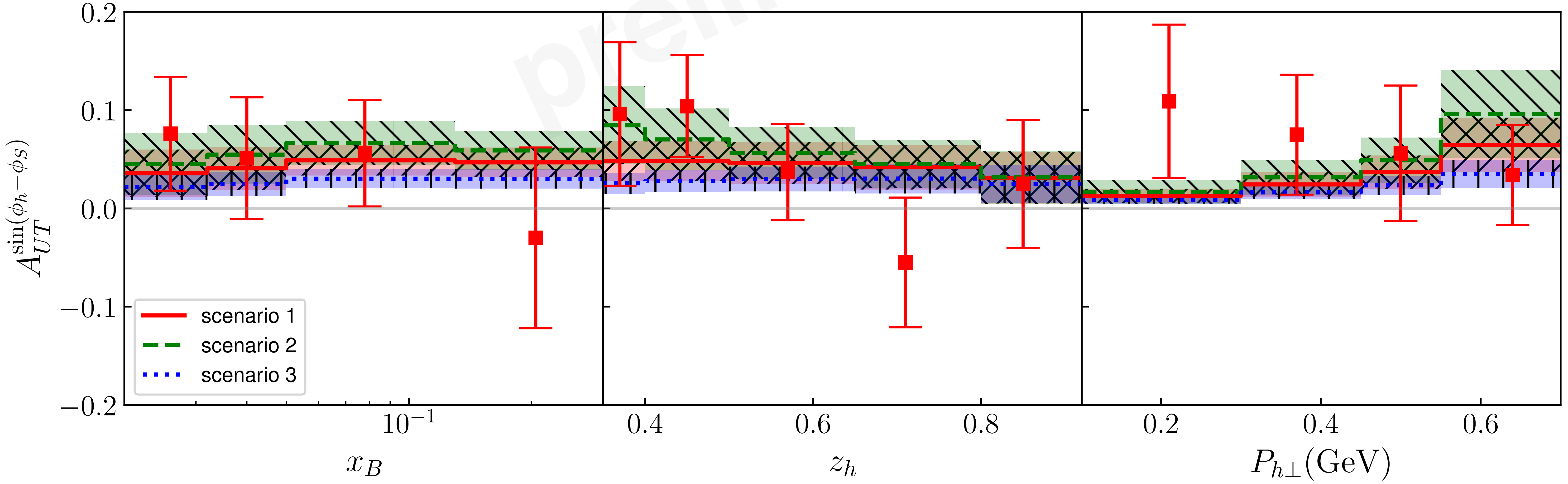


Numerical Result

The Sivers asymmetry of ρ^0 meson



Sivers function parameterization: ZLSZ



Sivers function parameterization: BPV20

Numerical Result

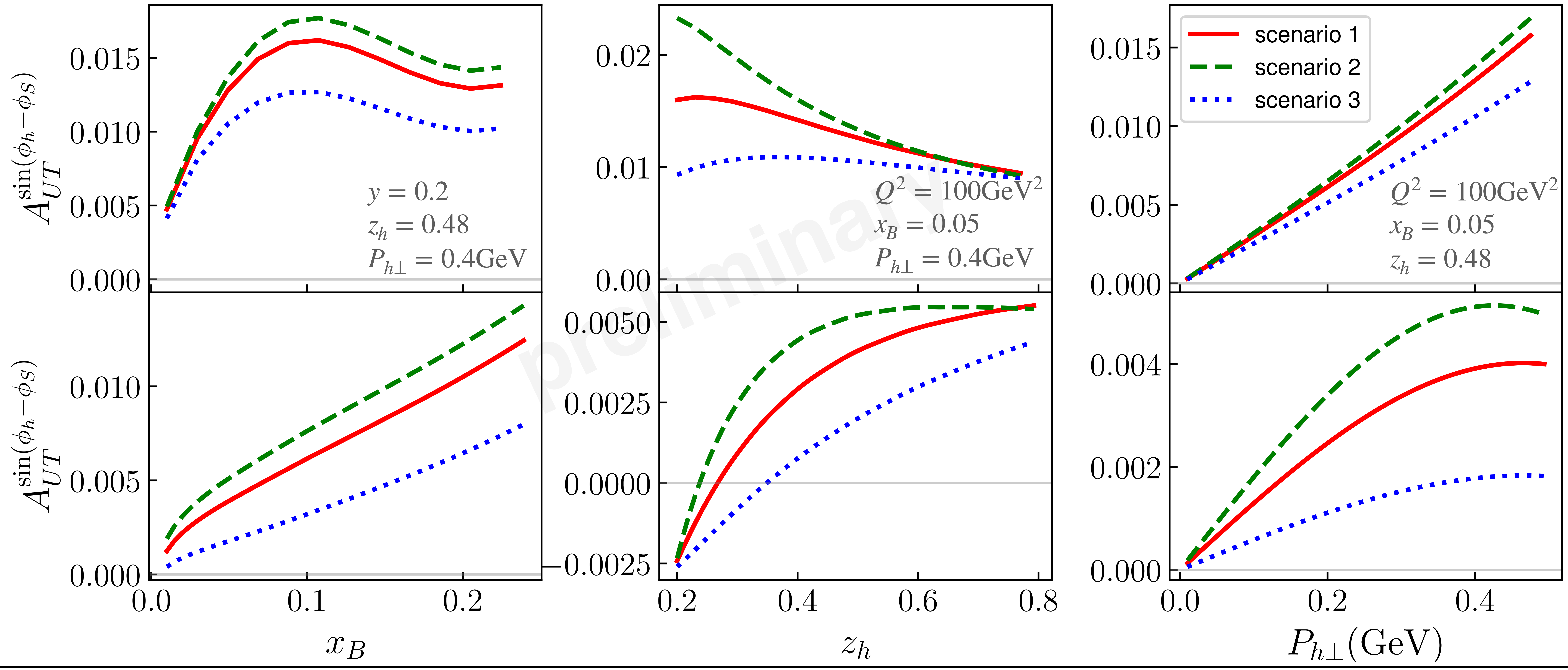
Sivers asymmetry at the EIC's kinematics

EIC

$\sqrt{s} = 100\text{GeV}$

BPV20

ZLSZ



Numerical Result

Sivers asymmetry at the EicC's kinematics

Numerical Result

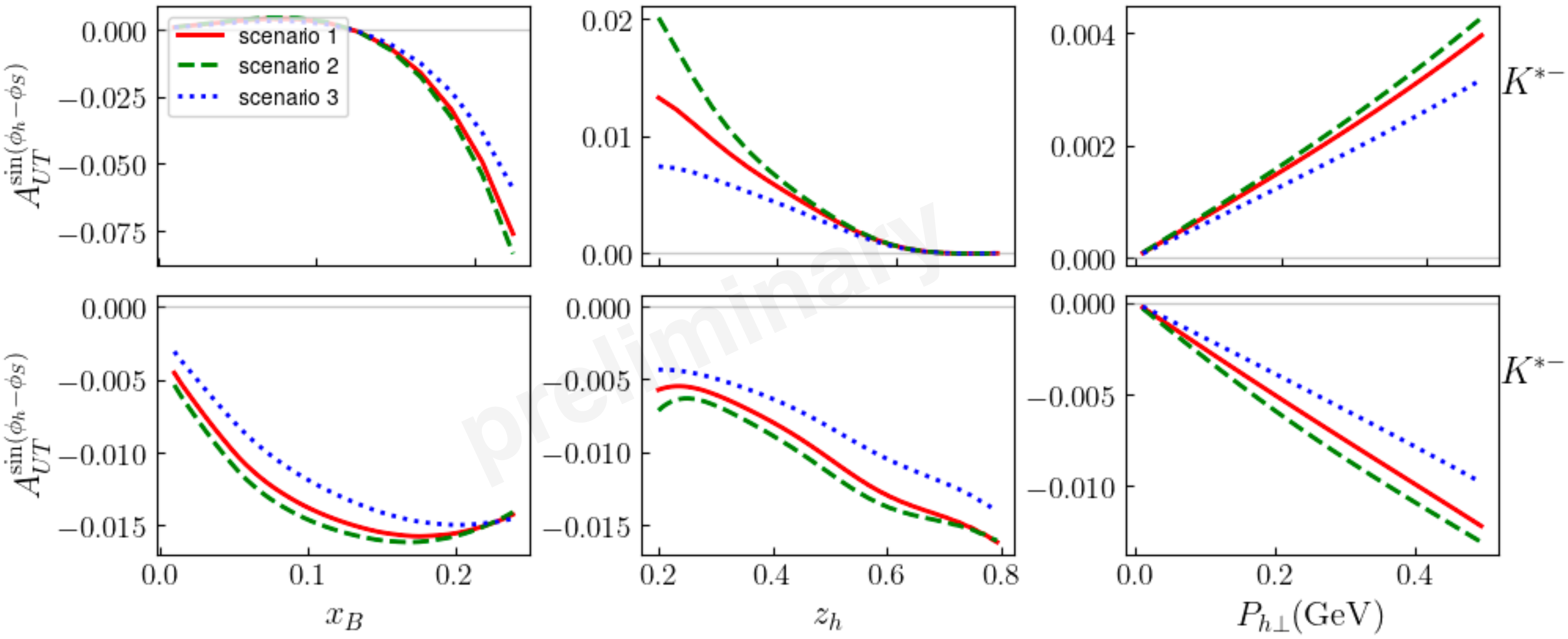
Sivers asymmetry of K^* mesons.

EIC

$\sqrt{s} = 100\text{GeV}$

BPV20

ZLSZ



$y = 0.2$
$z_h = 0.48$
$P_{h\perp} = 0.4\text{GeV}$

$Q^2 = 100\text{GeV}^2$
$x_B = 0.05$
$P_{h\perp} = 0.4\text{GeV}$

$Q^2 = 100\text{GeV}^2$
$x_B = 0.05$
$z_h = 0.48$

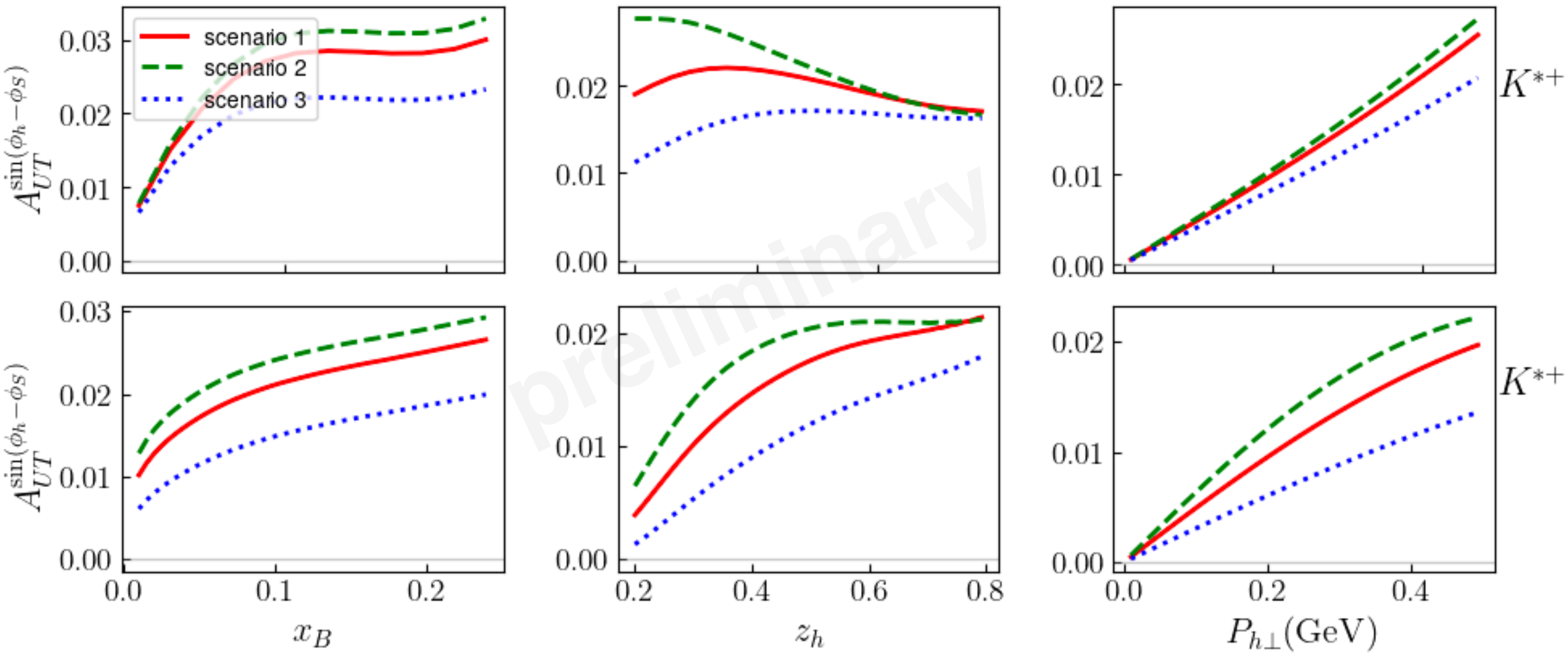
Numerical Result

Sivers asymmetry of $K*$ mesons.

EIC
$\sqrt{s} = 100\text{GeV}$

BPV20

ZLSZ



$y = 0.2$
$z_h = 0.48$
$P_{h\perp} = 0.4\text{GeV}$

$Q^2 = 100\text{GeV}^2$
$x_B = 0.05$
$P_{h\perp} = 0.4\text{GeV}$

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Numerical Result

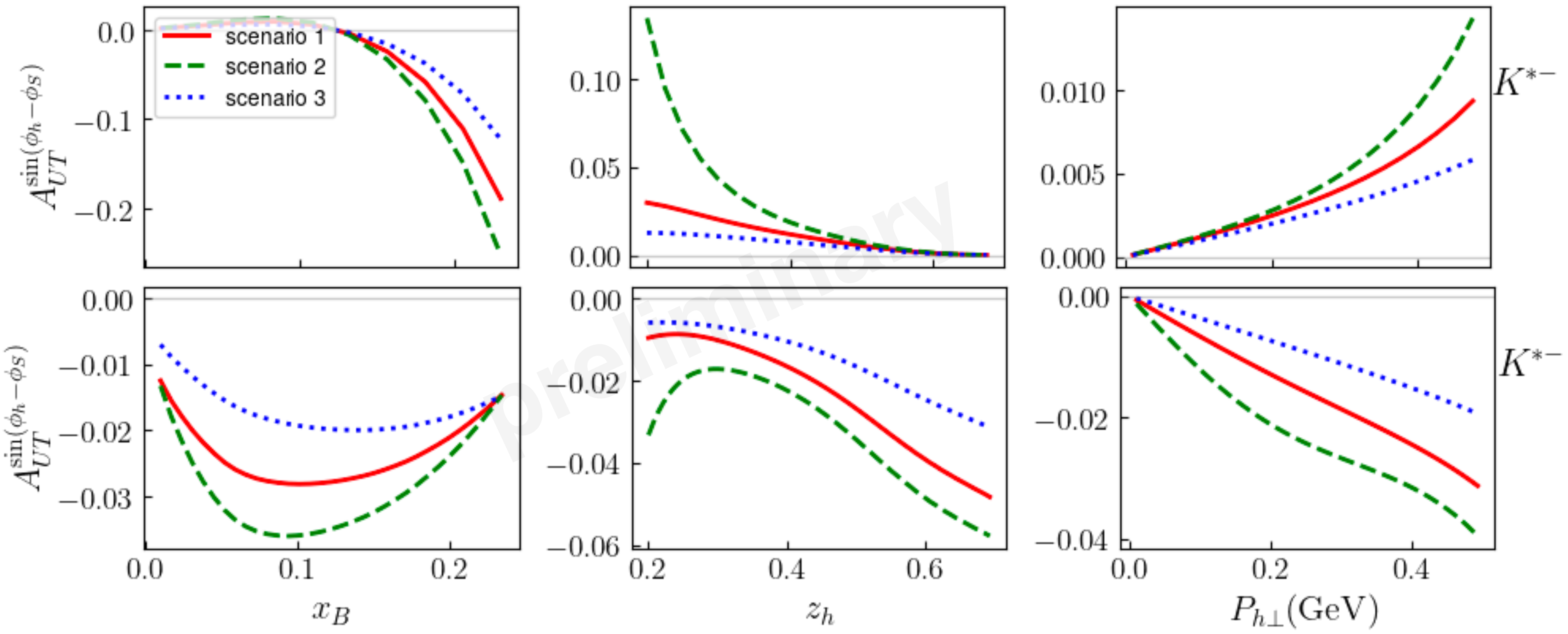
Sivers asymmetry of $K*$ mesons.

EicC

$\sqrt{s} = 16.7\text{GeV}$

BPV20

ZLSZ



$y = 0.2$
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$P_{h\perp} = 0.4\text{GeV}$

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$x_B = 0.05$
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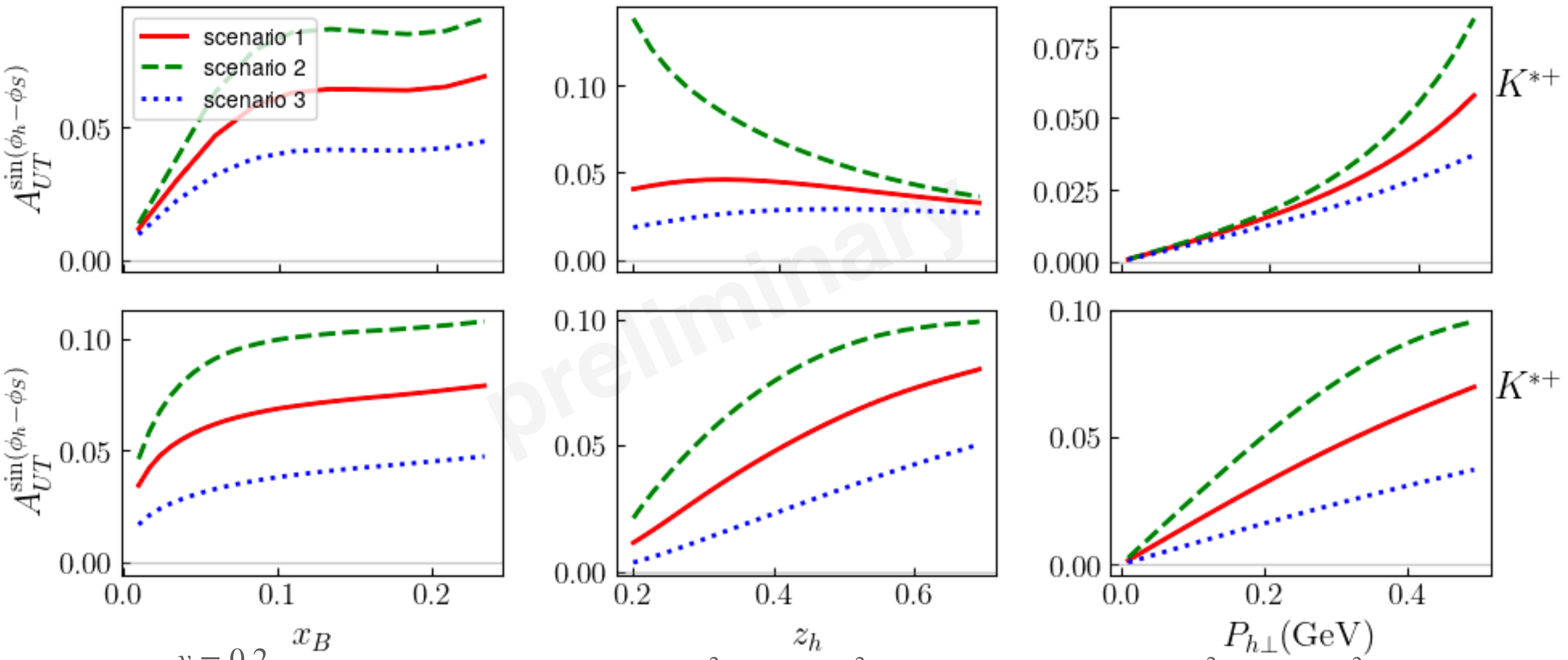

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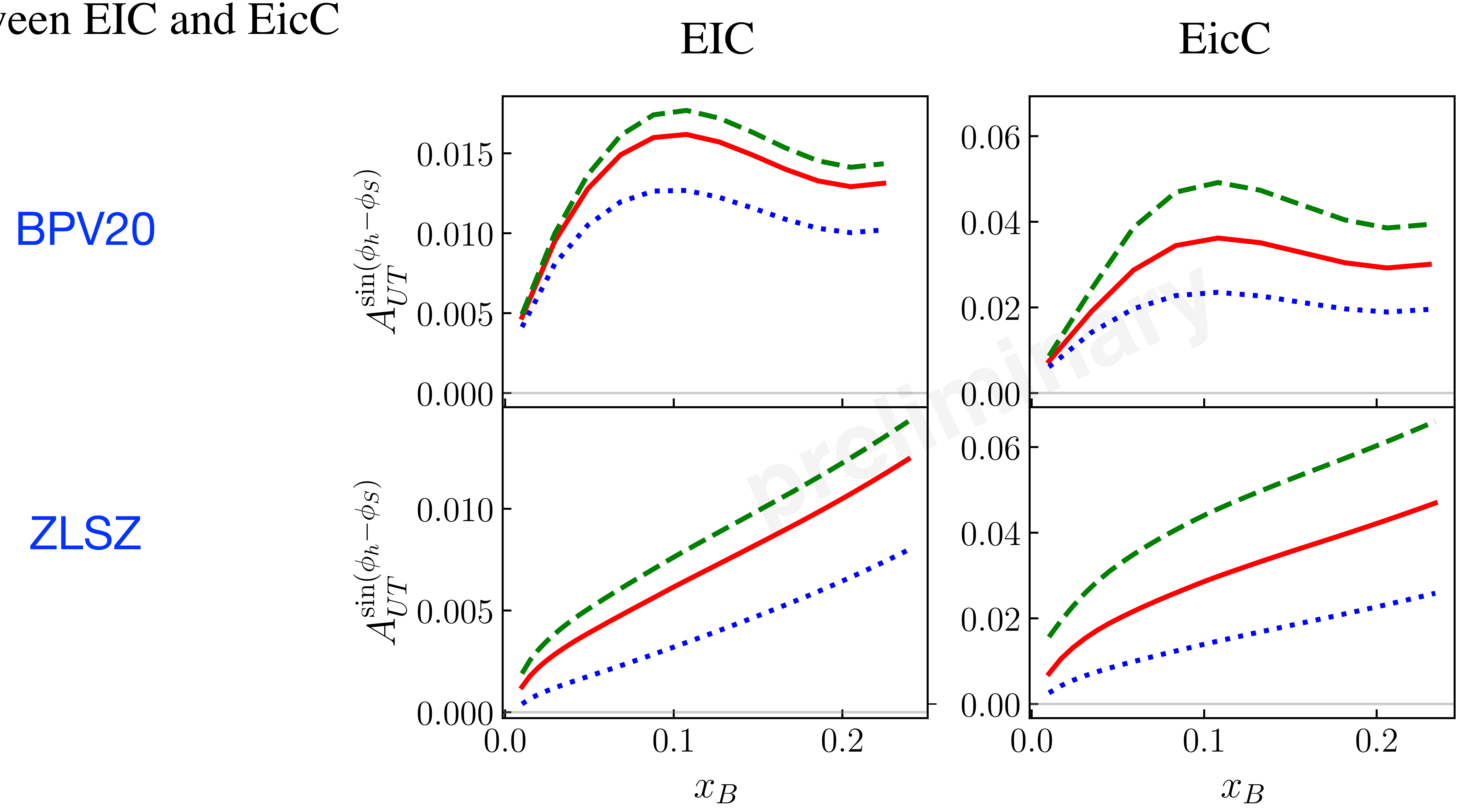
Numerical Result

Comparing the Sivers asymmetry between EIC and EicC



Summary

1. The Sivers function extracted from pion's and kaon's data can be well matched with ρ^0's data. The universality of Sivers function.

2. There is a large difference between ZLSZ parameterization and BPV20 parameterization. EIC and EicC can provide a test of the Sivers function's universality and constrain the extraction of the Sivers function.

Thanks!