

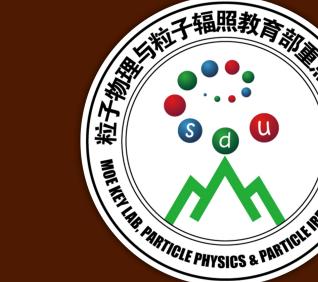
# The Sivers asymmetry of vector meson production in SIDIS process

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Collaborators: Tianbo Liu, Ya-jin Zhou



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粒子科学技术研究中心  
Research Center for Particle Science and Technology



# Outline

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## 1. Introduction

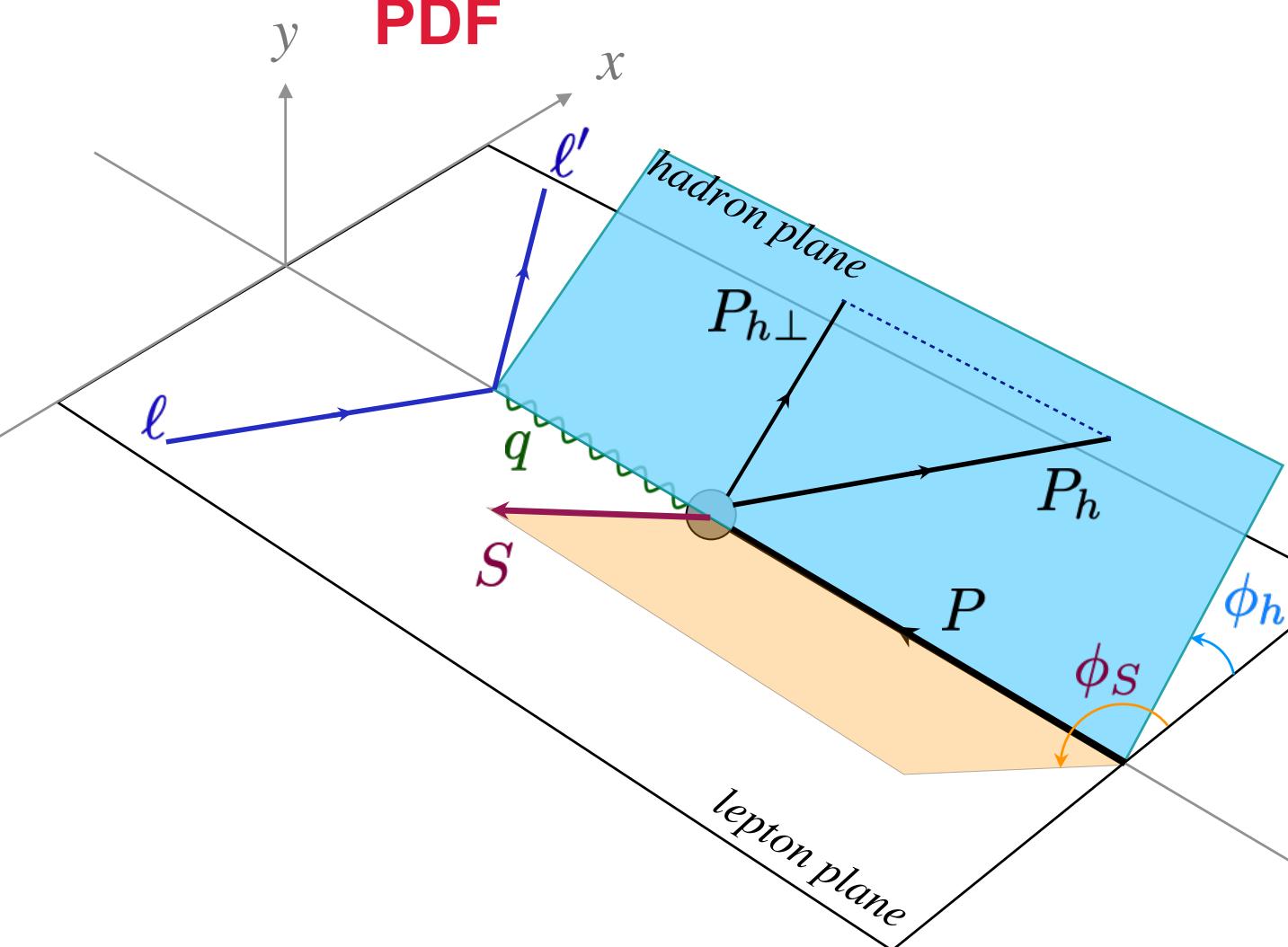
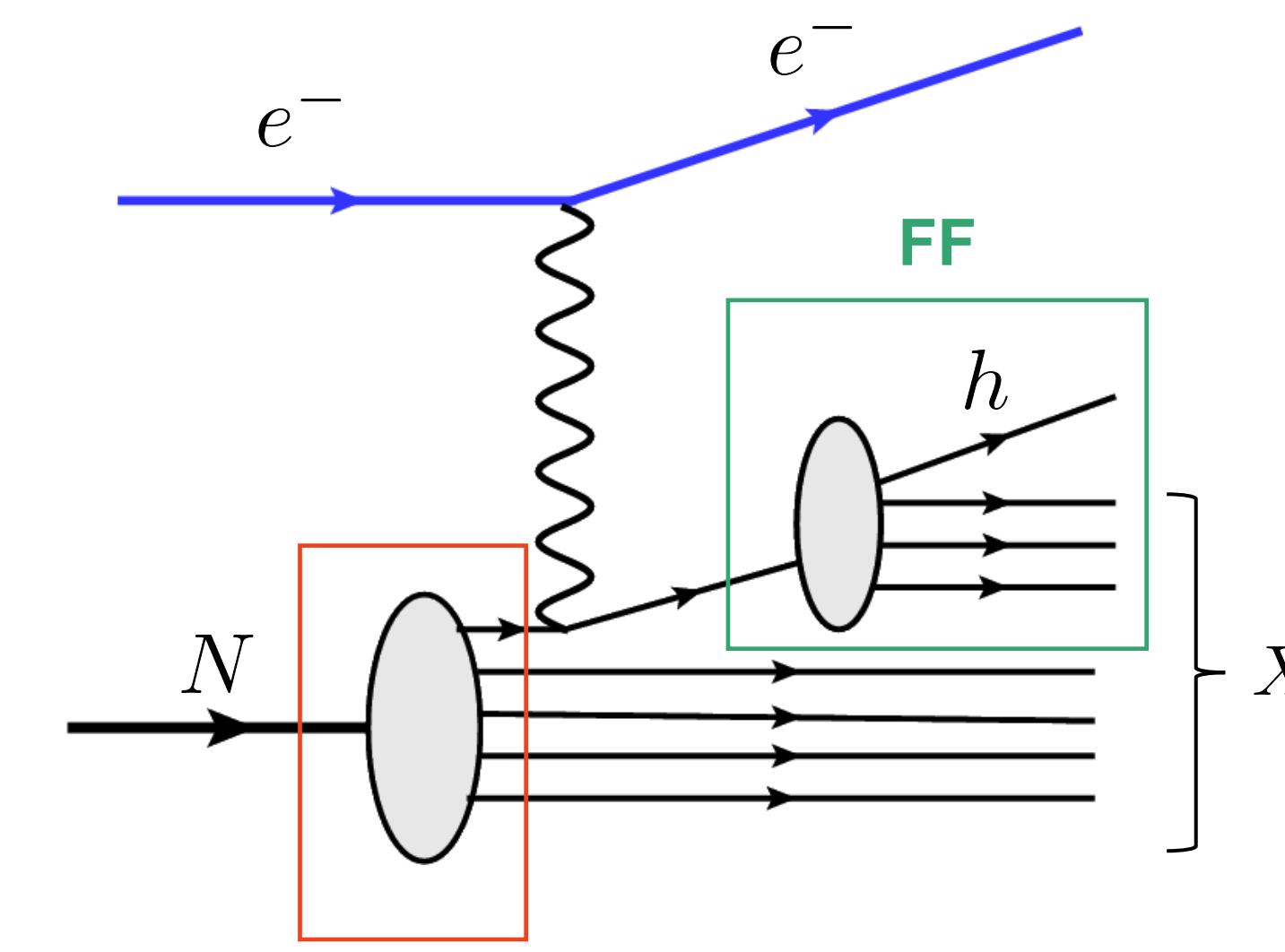
## 2. Framework

- TMD evolution
- The FFs of  $\rho^0$  meson
- The calculation of Sivers asymmetry

## 3. Summary

# Introduction

## Semi-inclusive DIS (SIDIS)



## Fragmentation function (TMD FF)

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

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

## 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

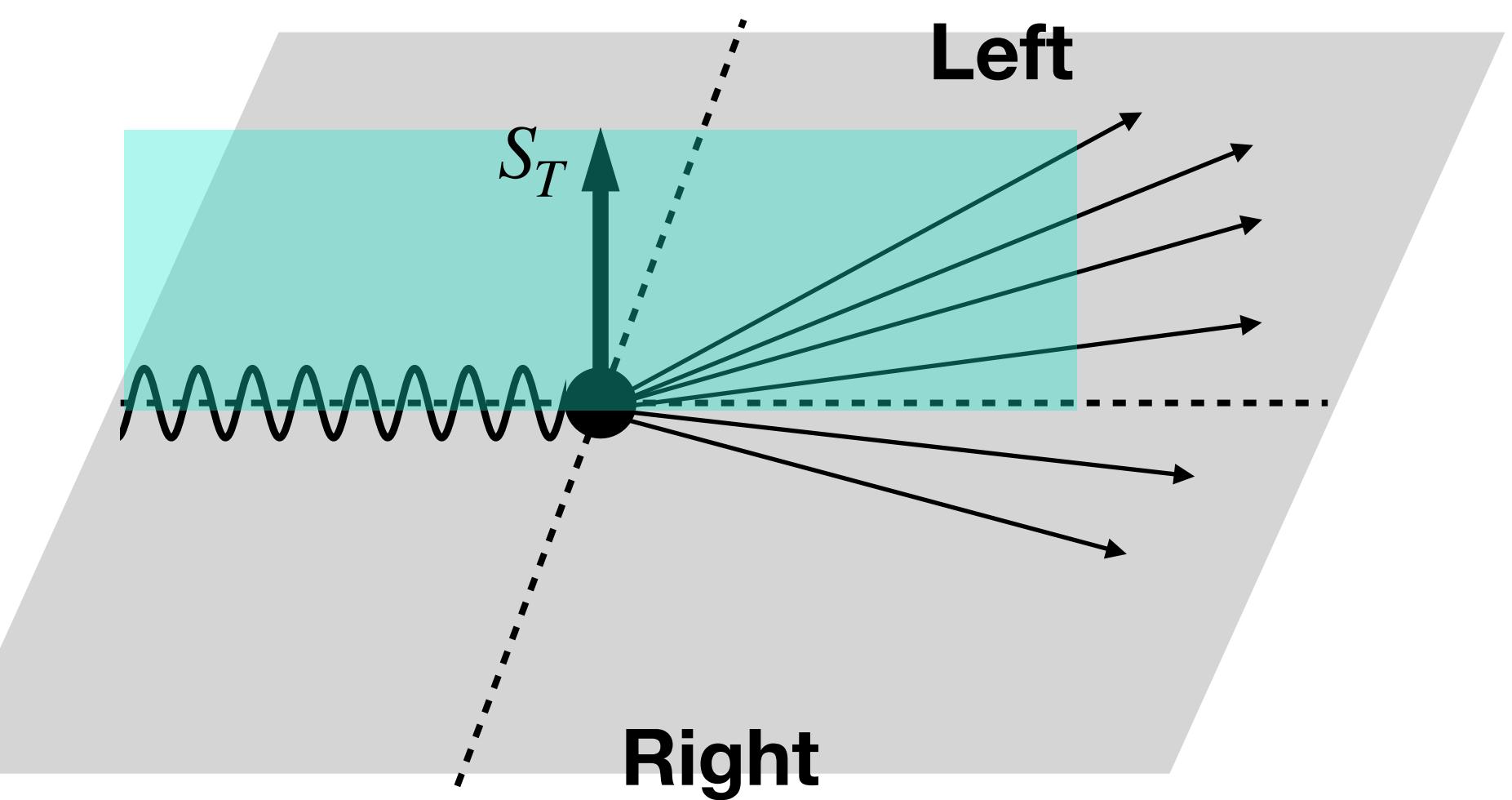
$$\begin{aligned}
& \frac{d\sigma^h}{dx dy d\phi_S dz d\phi_h d\mathbf{P}_{h\perp}^2} = \frac{\alpha^2}{xyQ^2} \frac{y^2}{2(1-\varepsilon)} \left( 1 + \frac{\gamma^2}{2x} \right) \\
& \times \left\{ \begin{aligned}
& \left[ F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\varepsilon(1+\varepsilon)} \cos \phi_h F_{UU}^{\cos \phi_h} + \varepsilon \cos(2\phi_h) F_{UU}^{\cos 2\phi_h} \right] \\
& + \lambda_l \left[ \sqrt{2\varepsilon(1-\varepsilon)} \sin \phi_h F_{LU}^{\sin \phi_h} \right] \\
& + S_L \left[ \sqrt{2\varepsilon(1+\varepsilon)} \sin \phi_h F_{UL}^{\sin \phi_h} + \varepsilon \sin(2\phi_h) F_{UL}^{\sin 2\phi_h} \right] \\
& + S_L \lambda_l \left[ \sqrt{1-\varepsilon^2} F_{LL} + \sqrt{2\varepsilon(1-\varepsilon)} \cos \phi_h F_{LL}^{\cos \phi_h} \right] \\
& + S_T \left[ \begin{aligned}
& \sin(\phi_h - \phi_S) \left( F_{UT,T}^{\sin(\phi_h - \phi_S)} + \varepsilon F_{UT,L}^{\sin(\phi_h - \phi_S)} \right) \\
& + \varepsilon \sin(\phi_h + \phi_S) F_{UT}^{\sin(\phi_h + \phi_S)} + \varepsilon \sin(3\phi_h - \phi_S) F_{UT}^{\sin(3\phi_h - \phi_S)} \\
& + \sqrt{2\varepsilon(1+\varepsilon)} \sin \phi_S F_{UT}^{\sin \phi_S} + \sqrt{2\varepsilon(1+\varepsilon)} \sin(2\phi_h - \phi_S) F_{UT}^{\sin(2\phi_h - \phi_S)} \end{aligned} \right] \\
& + S_T \lambda_l \left[ \begin{aligned}
& \sqrt{1-\varepsilon^2} \cos(\phi_h - \phi_S) F_{LT}^{\cos(\phi_h - \phi_S)} + \sqrt{2\varepsilon(1-\varepsilon)} \cos \phi_S F_{LT}^{\cos \phi_S} \\
& + \sqrt{2\varepsilon(1-\varepsilon)} \cos(2\phi_h - \phi_S) F_{LT}^{\cos(2\phi_h - \phi_S)} \end{aligned} \right] \end{aligned} \right\}
\end{aligned}$$

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

- X: Lepton polarization
- Y: Target polarization
- Z:  $\gamma^*$  polarization

Transversely single spin asymmetry (TSSA):

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



# Introduction

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& + \sqrt{2\epsilon(1-\epsilon)} \cos(2\phi_h - \phi_S) F_{LT}^{\cos(2\phi_h - \phi_S)}
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\end{aligned}$$

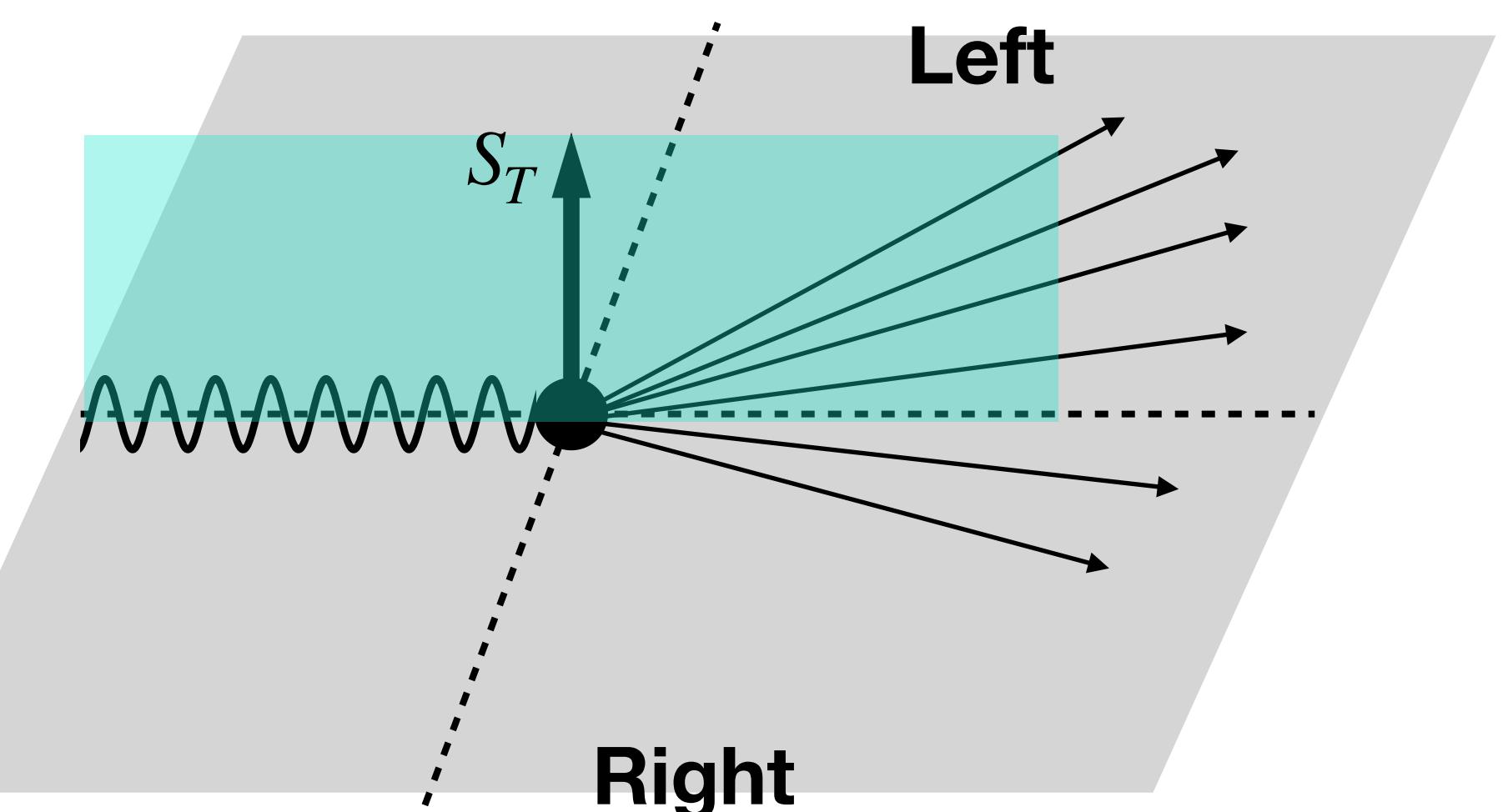
Contribute to TSSA

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

X: Lepton polarization  
 Y: Target polarization  
 Z:  $\gamma^*$  polarization

Transversely single spin asymmetry (TSSA):

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



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 & \quad \left. + \epsilon \sin(\phi_h + \phi_S) F_{UT}^{\sin(\phi_h + \phi_S)} + \epsilon \sin(3\phi_h - \phi_S) F_{UT}^{\sin(3\phi_h - \phi_S)} \right. \\
 & \quad \left. + \sqrt{2\epsilon(1+\epsilon)} \sin \phi_S F_{UT}^{\sin \phi_S} + \sqrt{2\epsilon(1+\epsilon)} \sin(2\phi_h - \phi_S) F_{UT}^{\sin(2\phi_h - \phi_S)} \right] \\
 & + S_T \lambda_l \left[ \sqrt{1-\epsilon^2} \cos(\phi_h - \phi_S) F_{LT}^{\cos(\phi_h - \phi_S)} + \sqrt{2\epsilon(1-\epsilon)} \cos \phi_S F_{LT}^{\cos \phi_S} \right. \\
 & \quad \left. + \sqrt{2\epsilon(1-\epsilon)} \cos(2\phi_h - \phi_S) F_{LT}^{\cos(2\phi_h - \phi_S)} \right] \end{aligned} \right\}
 \end{aligned}$$

Contribute to TSSA

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

X: Lepton polarization  
 Y: Target polarization  
 Z:  $\gamma^*$  polarization

The diagram illustrates the decomposition of the total asymmetry. A red oval labeled "Sivers function" encloses the term  $F_{UT,T}^{\sin(\phi_h - \phi_S)}$ . A green oval labeled "Unpolarized FF" encloses the term  $f_{1T}^\perp D_1$ . A green arrow points from the Unpolarized FF term to the Unpolarized FF oval. A red arrow points from the Sivers function term to the Sivers function oval.

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

**Sivers asymmetry:**

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

# Introduction

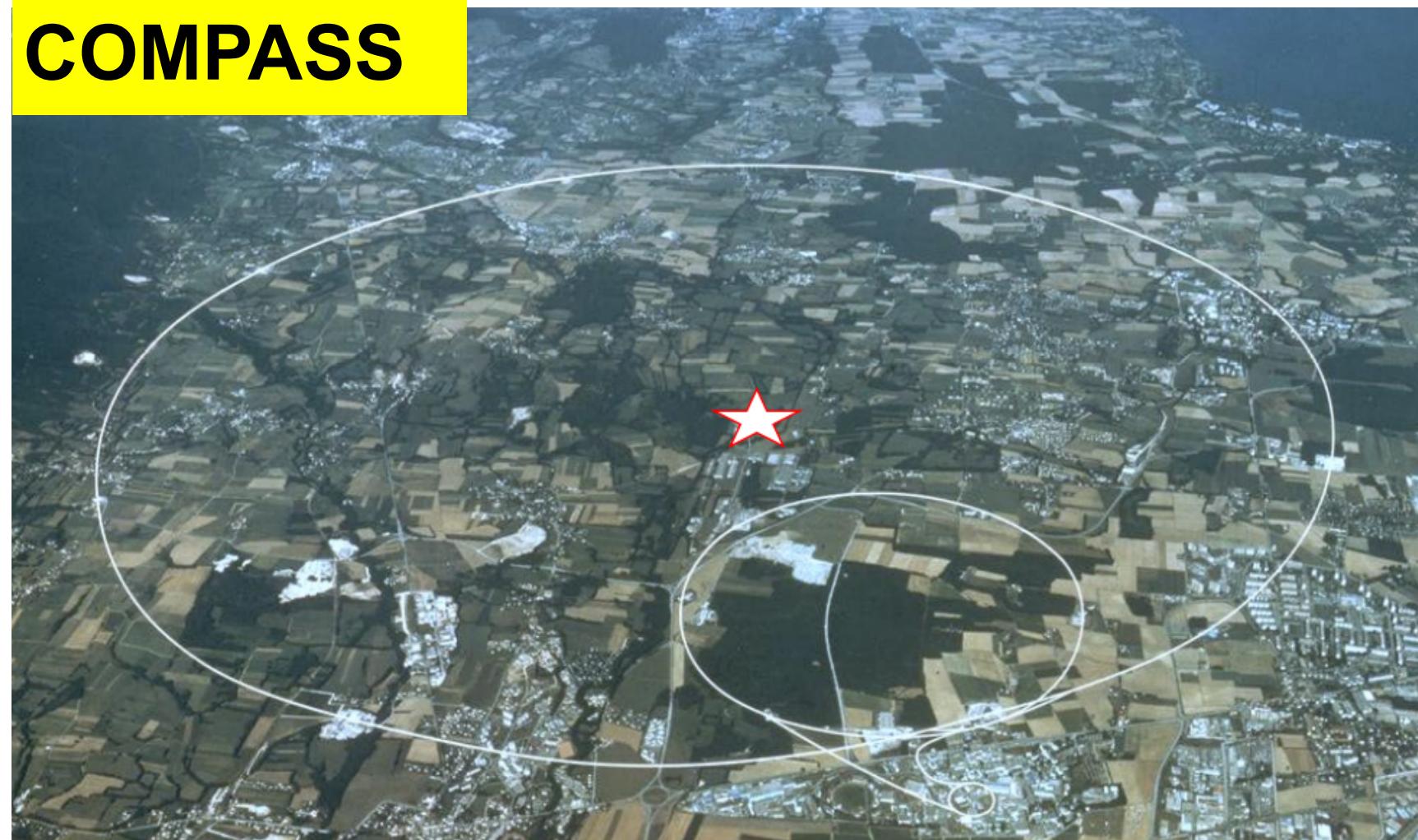
## Collins and Sivers transverse-spin asymmetries in inclusive muoproduction of $\rho^0$ mesons

The COMPASS Collaboration

### Abstract

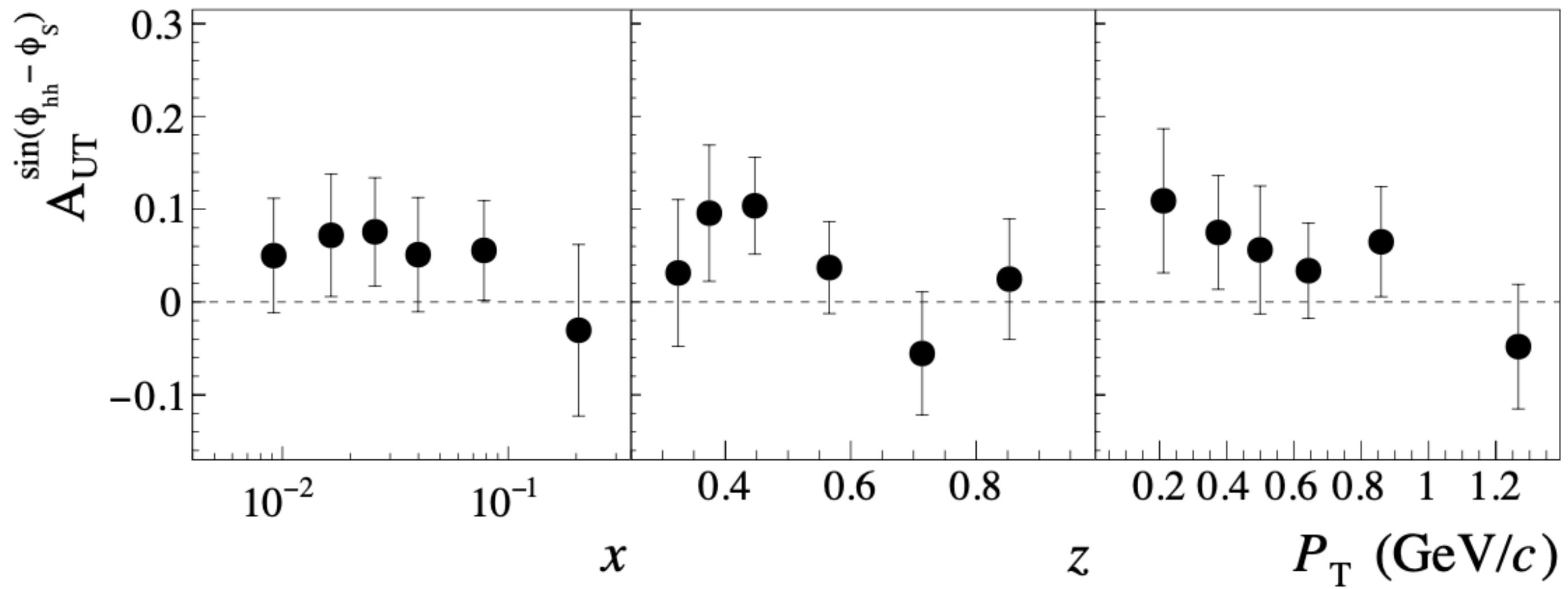
The production of vector mesons in deep inelastic scattering is an interesting yet scarcely explored channel to study the transverse spin structure of the nucleon and the related phenomena. The COMPASS collaboration has performed the first measurement of the Collins and Sivers asymmetries for inclusively produced  $\rho^0$  mesons. The analysis is based on the data set collected in deep inelastic scattering in 2010 using a 160 GeV/c  $\mu^+$  beam impinging on a transversely polarized NH<sub>3</sub> target. The  $\rho^0$  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.

G.D. Alexeev, M.G. Alexeev, C. Alice, A. Amoroso, V. Andrieux et al., Phys.Lett.B 843 (2023) 137950



**The Sivers asymmetry of  $\rho^0$  meson in SIDIS process has been measured firstly.**

### Sivers asymmetry



# Framework

TMD factorization and evolution:

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

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

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

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

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

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

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

# Framework

## TMD Factorization

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

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

$$f_{1,q/p}(x, k_\perp^2, \mu, \zeta) = \frac{1}{2\pi} \int db b J_0(bk_\perp) \widetilde{f}_{1,q/p}(x, b, \mu, \zeta)$$

$$D_{1,h/q}(z, p_\perp^2, \mu, \zeta) = \frac{1}{2\pi} \int db b J_0\left(b \frac{p_\perp}{z}\right) \widetilde{D}_{1h/q}(z, b, \mu, \zeta)$$

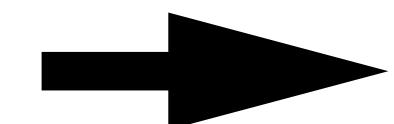
$$\frac{k_\perp}{M} f_{1T}^\perp(x, k_\perp^2, \mu, \zeta) = \int_0^\infty \frac{db b^2 M}{2\pi} J_1(bk_\perp) \widetilde{f}_{1T}^\perp(x, b, \mu, \zeta)$$

$\mu$ : the renormalization scale

$$\mu^2 = Q^2$$

$\zeta$ : 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.

TMDs evolution equation:

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

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

RG equation:

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

$\gamma_F$ : the TMD anomalous dimension

The solution:  $\tilde{F}(x, b; \mu_f, \zeta_f) = R[b; (\mu_f, \zeta_f) \rightarrow (\mu_i, \zeta_i)] \tilde{F}(x, b; \mu_i, \zeta_i)$

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

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

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

# Framework

TMD evolution:

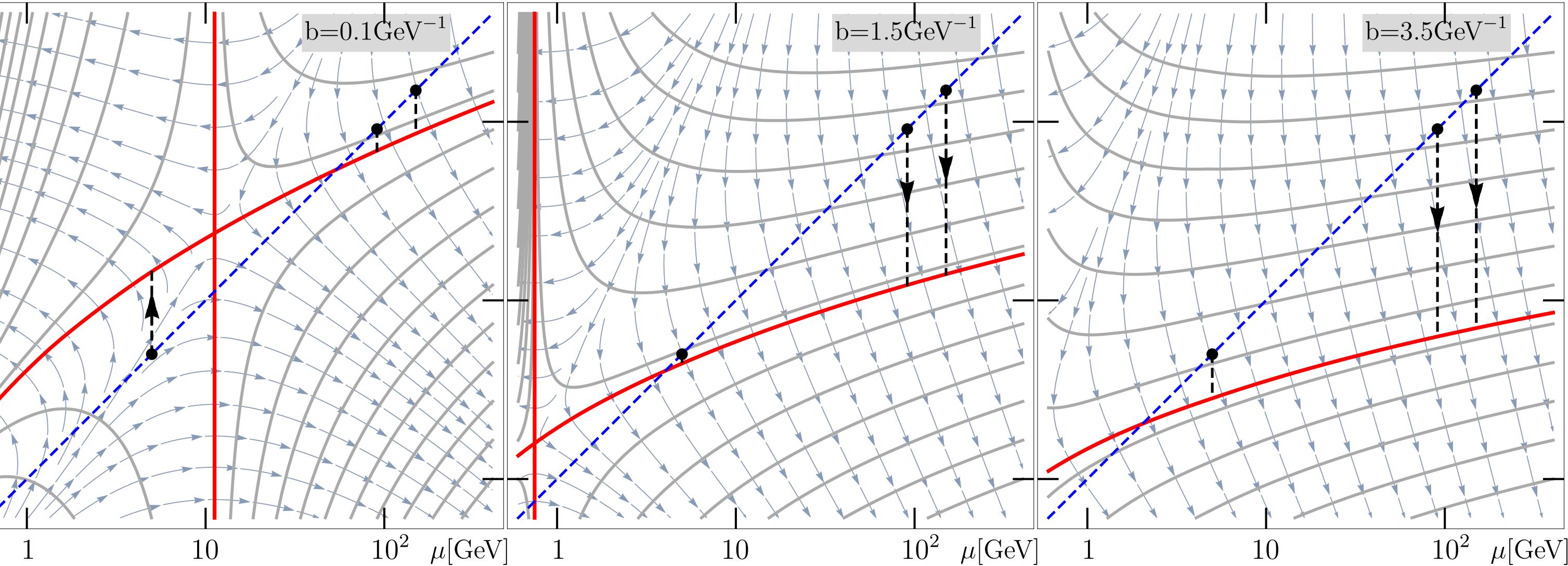
$$\frac{\partial \ln \tilde{F}(x, b, \mu, \zeta)}{\partial \ln \mu^2} = \frac{\gamma_F(\mu, \zeta)}{2}$$

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

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

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

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



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

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

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

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

# Framework

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

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

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

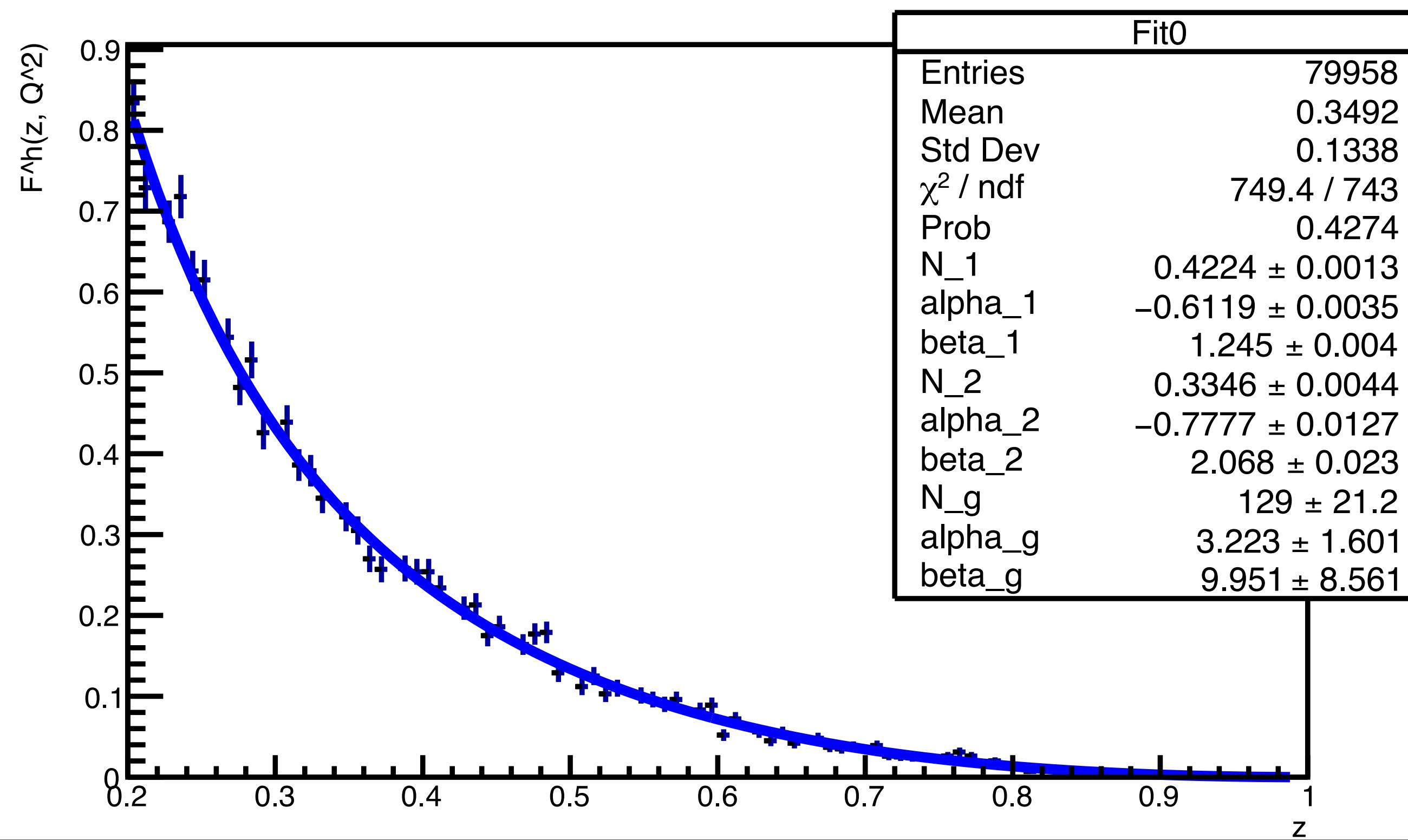
$$\begin{aligned} F_{UU}(x_B, z_h, P_{h\perp}, Q) &= H(\mu, Q) \sum_q e_q^2 \int_0^\infty \frac{db}{2\pi} b J_0 \left( \frac{b P_{h\perp}}{z_h} \right) \left( \frac{Q^2}{\zeta_Q(b)} \right)^{-2\mathcal{D}(b, Q)} \\ &\quad \times \tilde{f}_{1, q/p}(x_B, b) \tilde{D}_{1, h/q}(z_h, b) \end{aligned}$$

# Unpolarized FFs of $\rho^0$ meson

The unpolarized FFs of  $\rho^0$  meson : **Approach** : perform a global fit of Pythia's  $\rho^0$  meson data.

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

**Pythia data :**



**Charge conjugate symmetry**

**Isospin symmetry**

the parameterization is chosen as :

$$D_{\rho^0/u}(z, \mu_0) = D_{\rho^0/d}(z, \mu_0) = D_{\rho^0/\bar{u}}(z, \mu_0)$$

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

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

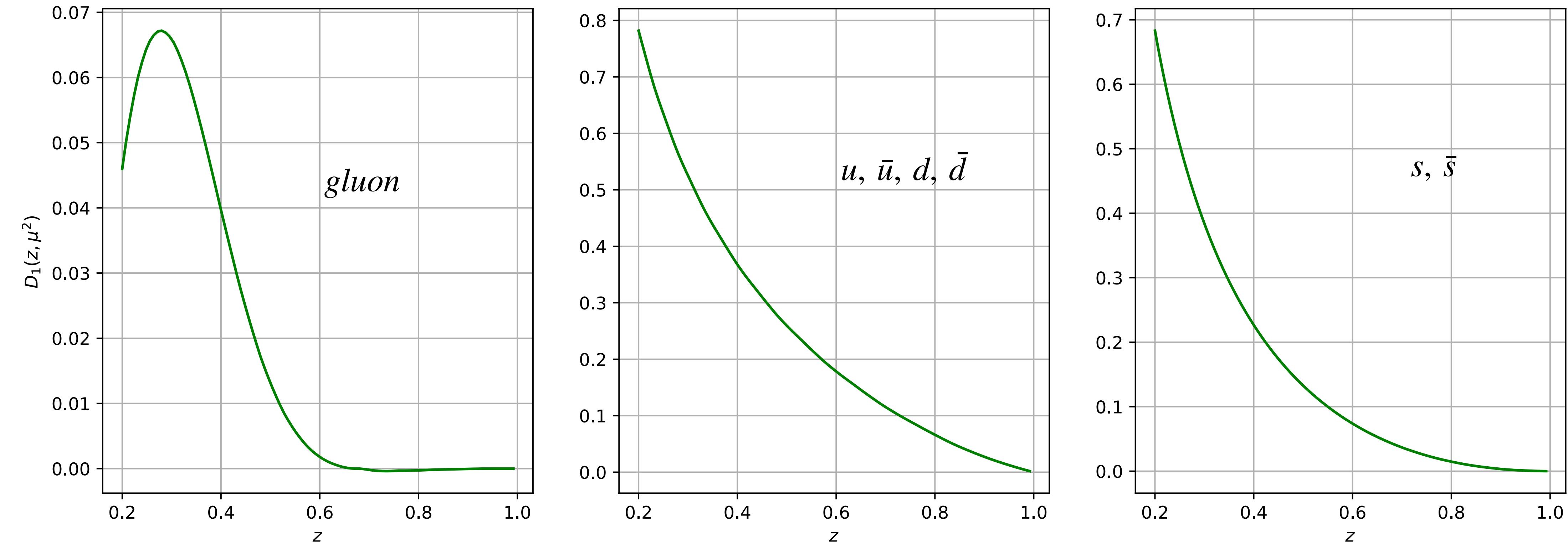
$$D_{\rho^0/g}(z, \mu_0) = N_g \times z^{\alpha_g} \times (1 - z)^{\beta_g}$$

$$\mu_0^2 = 1.2 \text{ GeV}^2$$

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

# Unpolarized FFs of $\rho^0$ meson

Result:



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


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

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

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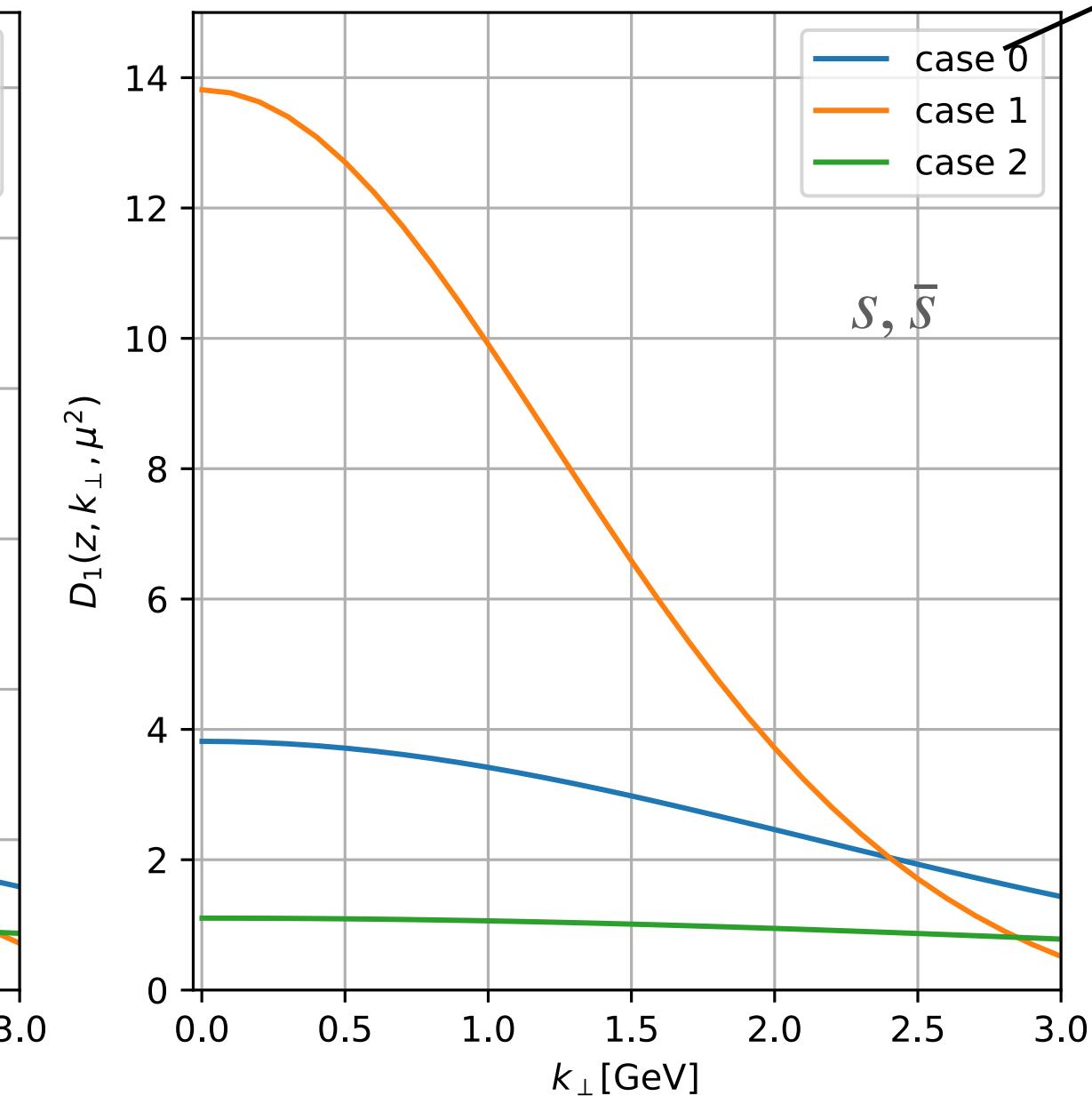
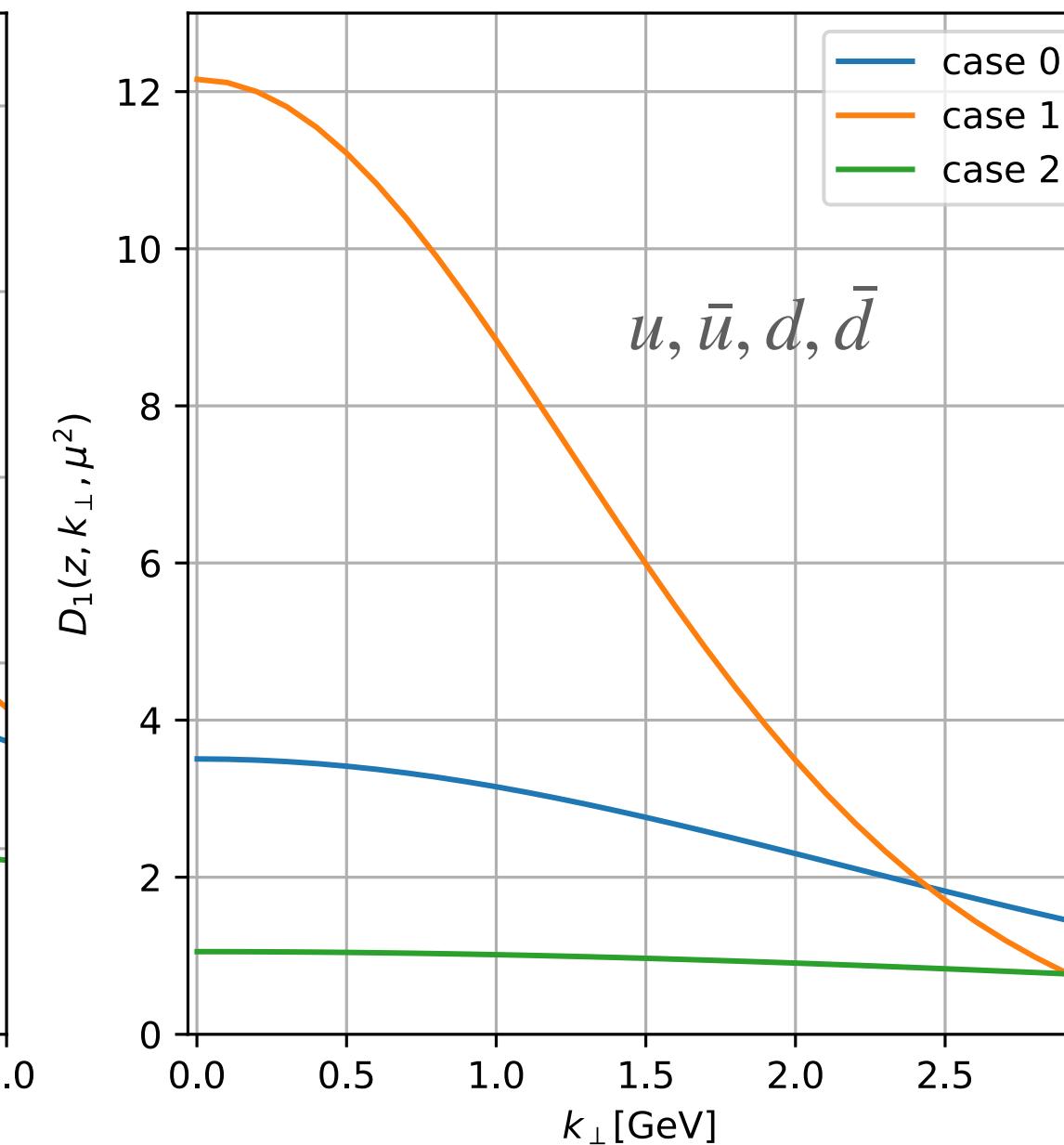
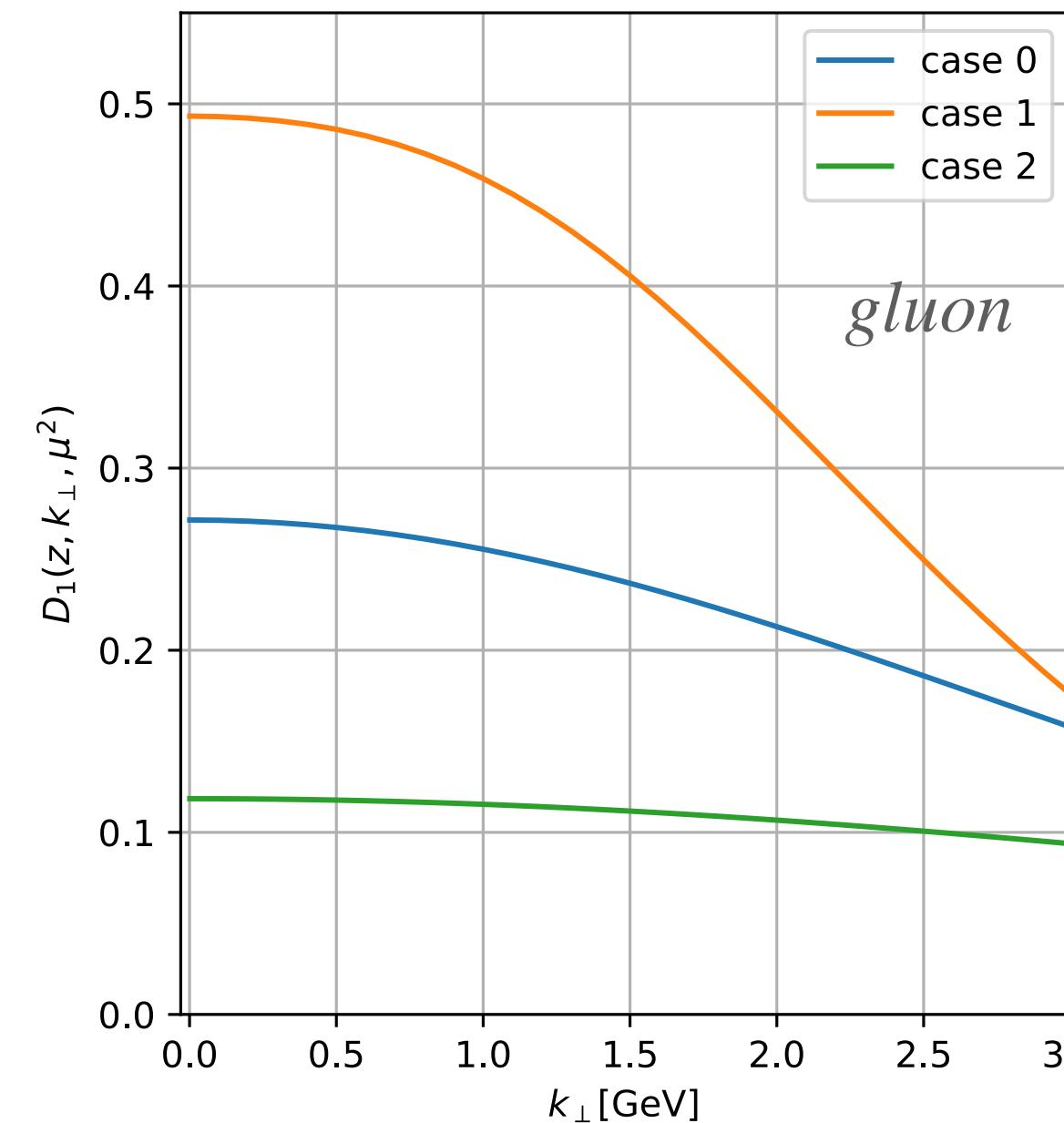
# The TMD FFs

Obtain TMD FFs by collinear FFs:

$$D_{1,h/f}(z, b) = \frac{1}{z^2} \sum_{f'} \int_z^1 \frac{dy}{y} y^2 C_{f \rightarrow f'}(y, b, \mu_{\text{OPE}}^{\text{FF}}) D_{1,h/f'}\left(\frac{z}{y}, \mu_{\text{OPE}}^{\text{FF}}\right) D_{\text{NP}}(z, b)$$

No appropriate parameterization for  $\rho^0$  meson.

**The  $k_\perp$  distributions of three  $D_{NP}$**



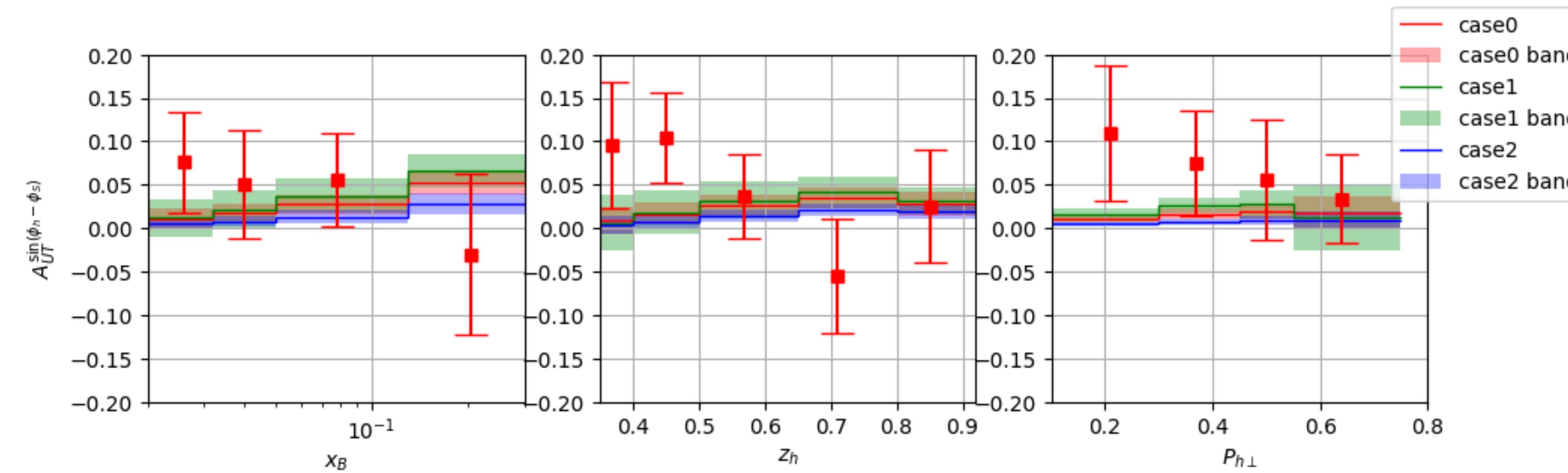
$z = 0.1, \mu^2 = 4 \text{ GeV}^2$

$D_{NP}$  of pion and kaon

We assume three  $D_{NP}(z, b)$  for  $\rho^0$  meson based on that of the pion to perform the numerical calculations

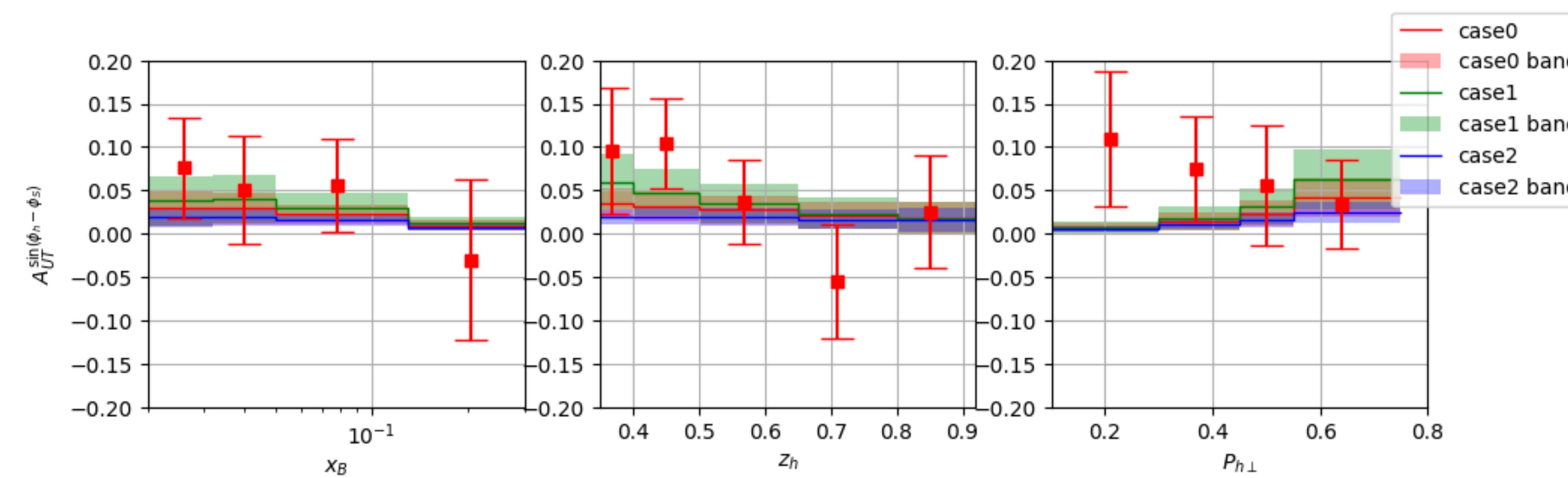
# Numerical Result

The Sivers asymmetry of  $\rho^0$  meson



Sivers function parameterization: **ZLSZ**

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



Sivers function parameterization: **BPV20**

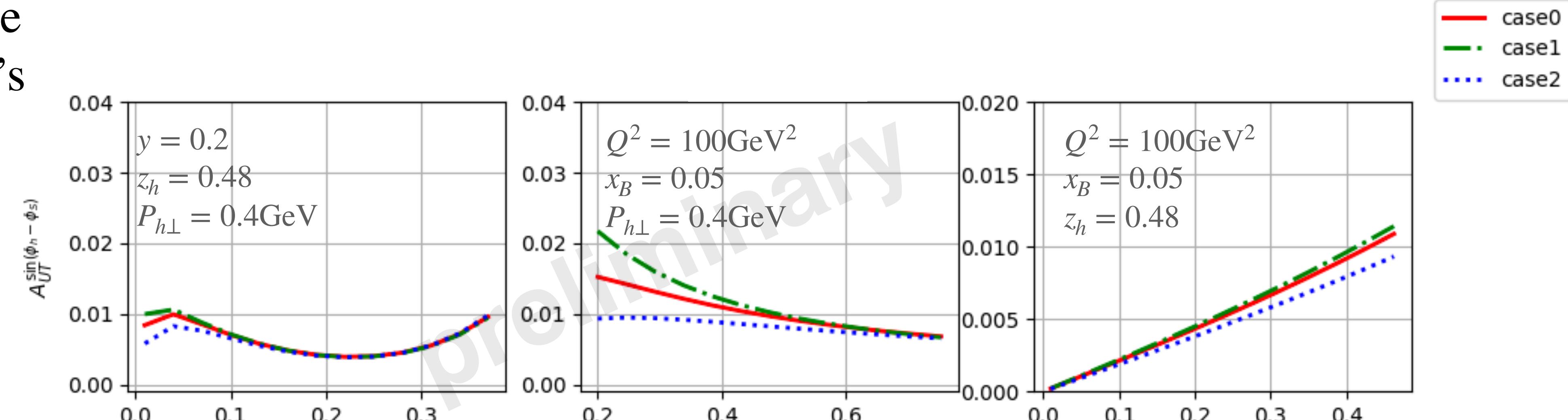
Marcin Bury, Alexei Prokudin, Alexey  
Vladimirov, JHEP 05 (2021) 151

# Numerical Result

Sivers asymmetry at the EIC's and JLab22GeV's kinematics

EIC

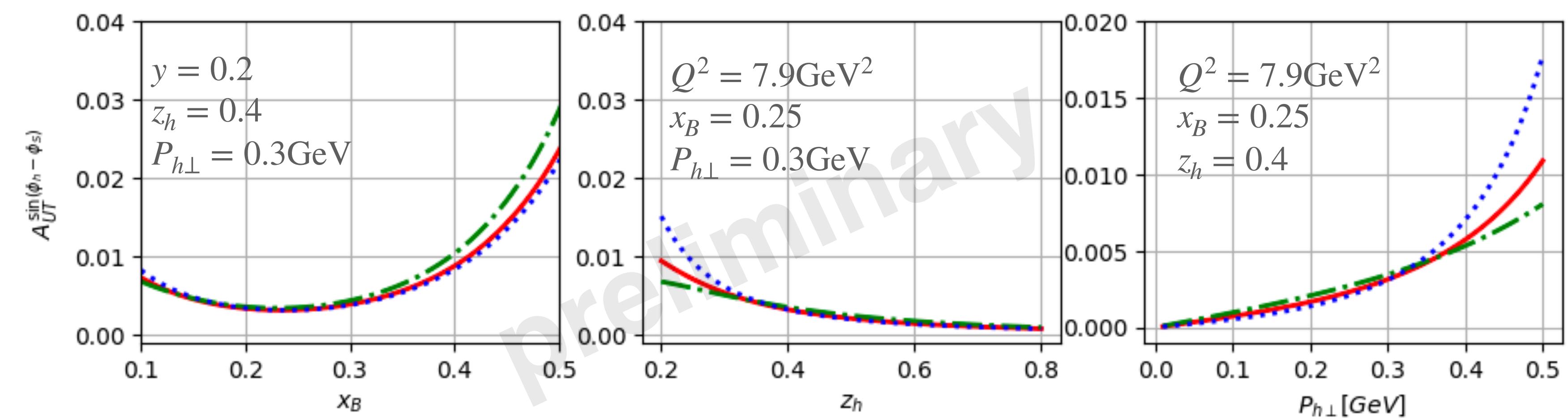
$\sqrt{s} = 100\text{GeV}$



BPV20

JLab22GeV

$\sqrt{s} = 6.7\text{GeV}$



# Numerical Result

Sivers asymmetry at the EIC's and JLab22GeV's kinematics

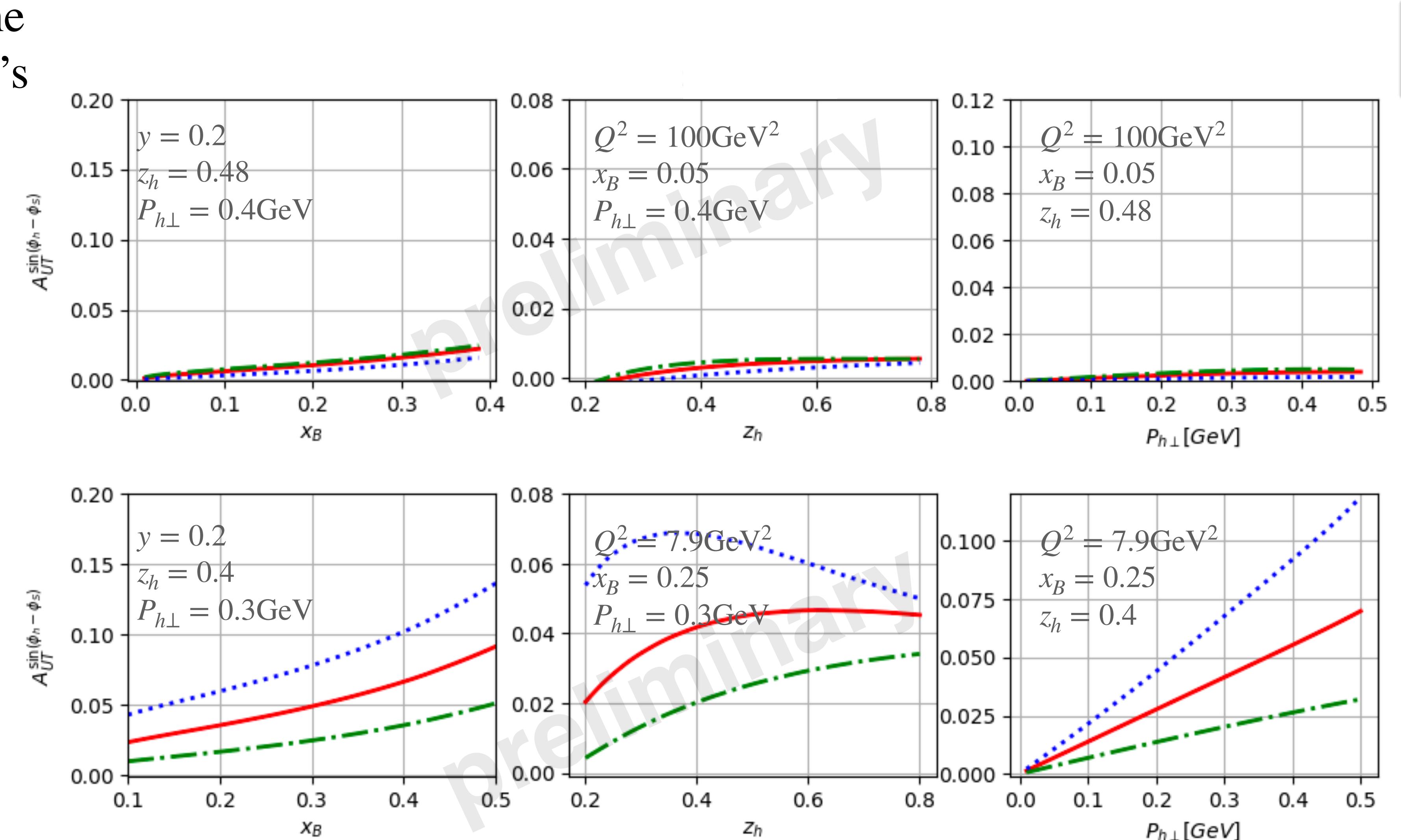
EIC

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

ZLSZ

JLab22GeV

$\sqrt{s} = 6.7\text{GeV}$



# Numerical Result

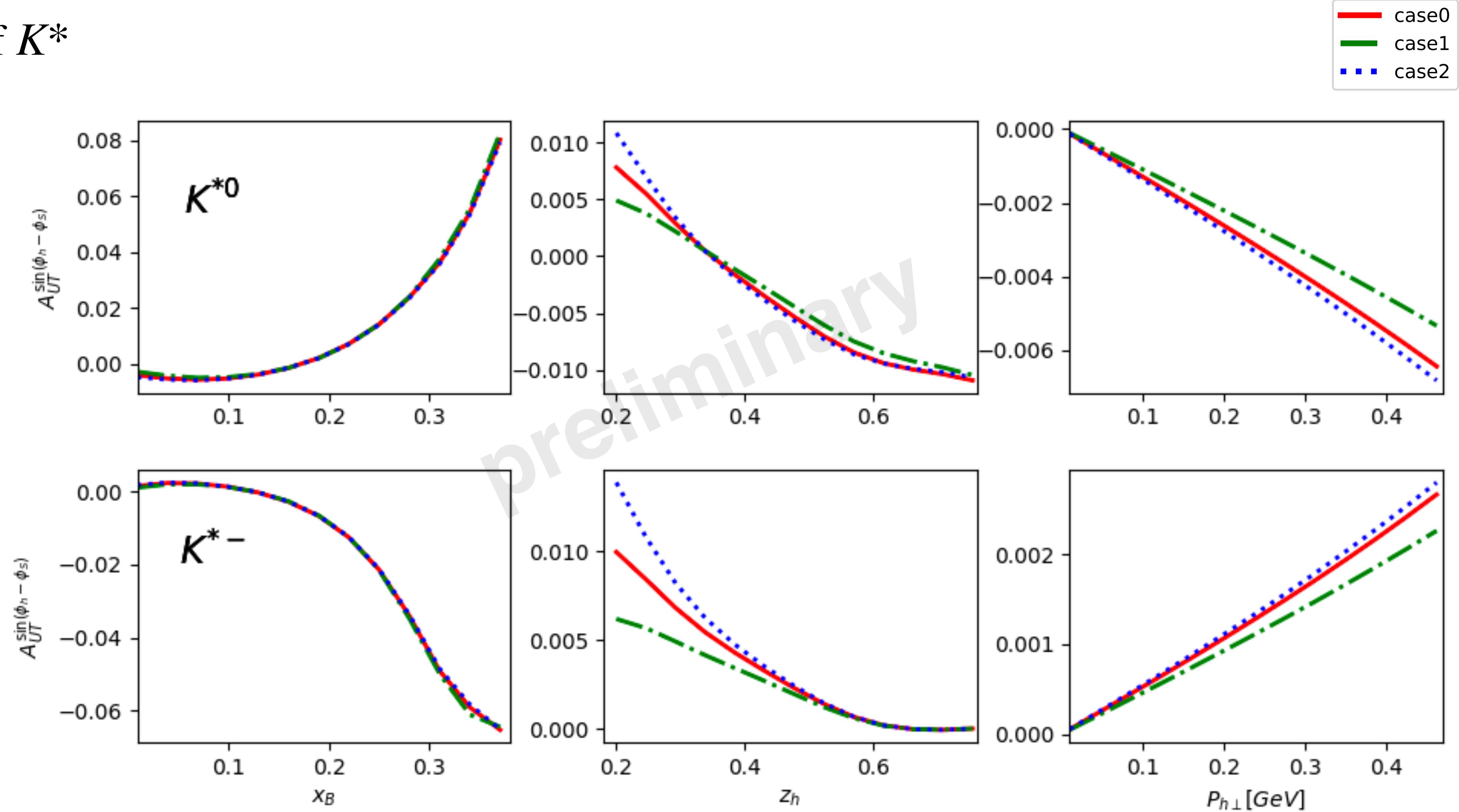
Sivers asymmetry of  $K^*$   
mesons.

EIC  
BPV20  $\sqrt{s} = 100\text{GeV}$

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

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

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



# Numerical Result

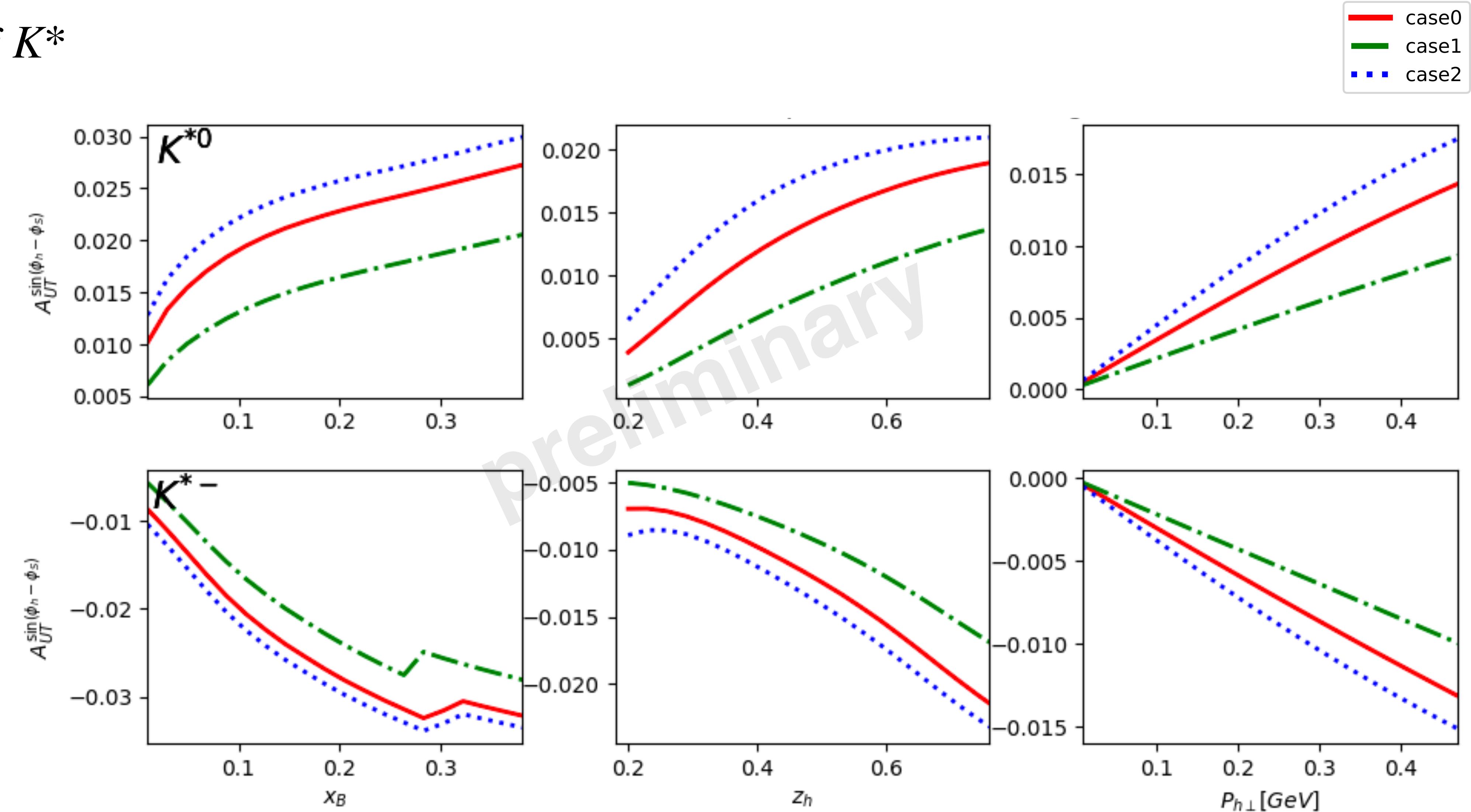
Sivers asymmetry of  $K^*$   
mesons.

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

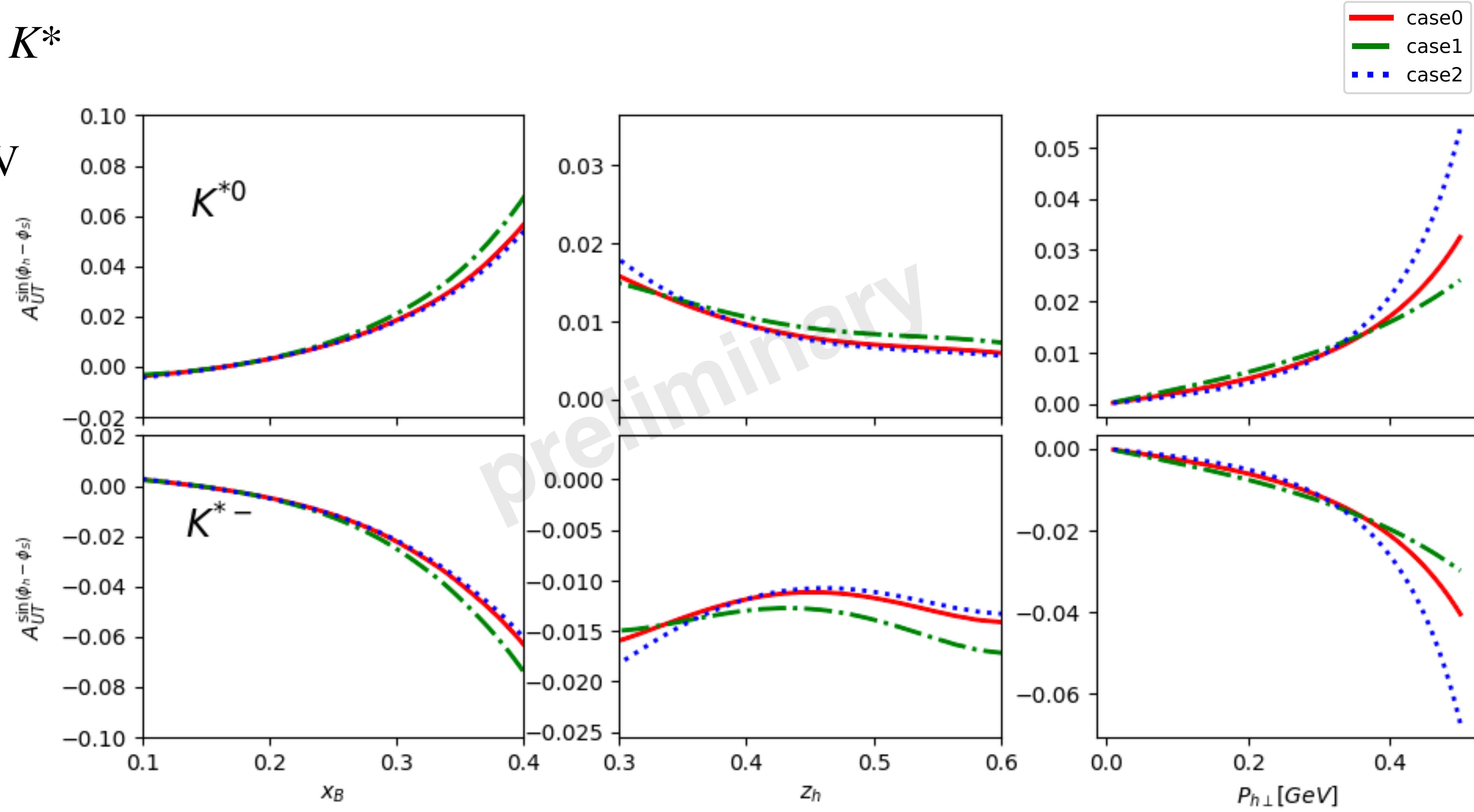
Sivers asymmetry of  $K^*$   
mesons.

JLab22GeV  
 $\sqrt{s} = 6.7\text{GeV}$   
 BPV20

$y = 0.2$   
 $z_h = 0.4$   
 $P_{h\perp} = 0.3\text{GeV}$

$Q^2 = 7.9\text{GeV}^2$   
 $x_B = 0.25$   
 $P_{h\perp} = 0.3\text{GeV}$

$Q^2 = 7.9\text{GeV}^2$   
 $x_B = 0.25$   
 $z_h = 0.4$



# Numerical Result

Sivers asymmetry of  $K^*$   
mesons.

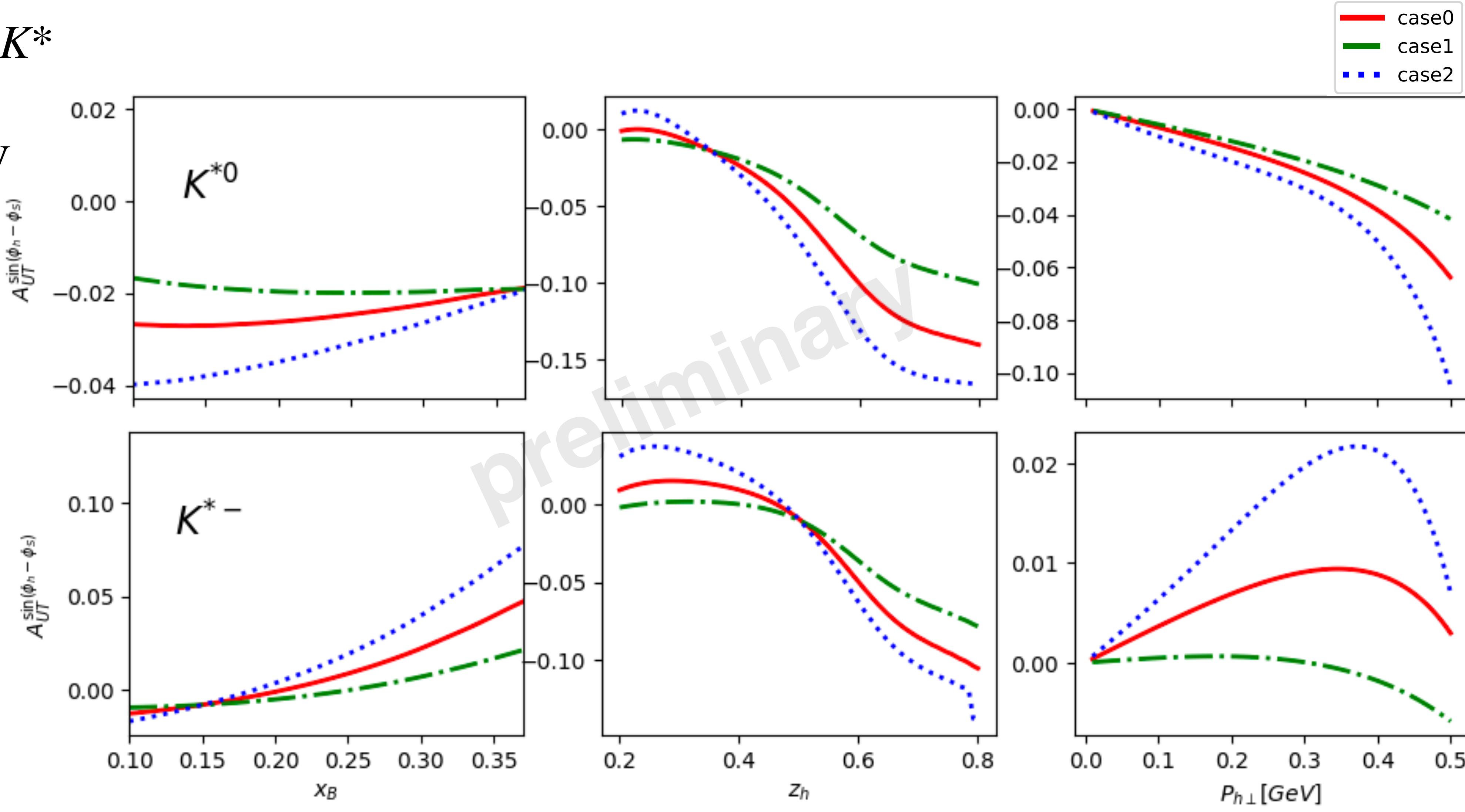
JLab22GeV  
 $\sqrt{s} = 6.7\text{GeV}$

ZLSZ

$y = 0.2$   
 $z_h = 0.4$   
 $P_{h\perp} = 0.3\text{GeV}$

$Q^2 = 7.9\text{GeV}^2$   
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$Q^2 = 7.9\text{GeV}^2$   
 $x_B = 0.25$   
 $z_h = 0.4$



# Summary

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1. The Sivers function extracted from pion's and kaon's data can be well matched with  $\rho^0$ 's data. The universality of Sivers function.
2. There is a large difference between ZLSZ parameterization and BPV20 parameterization. JLab22GeV can provide a test of the Sivers function's universality and constrain the extraction of the Sivers function.

Thanks!