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Sivers Asymmetry in πN Drell-Yan process at COMPASS within TMD factorization

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Based on **Xiaoyu Wang**, Zhun Lu, Ivan Schmidt, JHEP 1708 (2017) 137
Xiaoyu Wang and Zhun Lu , PRD 97, 054005 (2018)

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Parton Distribution Functions (PDFs)

- Leading twist: $f_1(x), g_1(x), h_1(x)$ describe the quark structure of hadrons
- Only have one longitudinal freedom x, *i.e.*, quarks are perfectly collinear

Transverse Momentum Dependent (TMD) PDFs

- Admit a finite quark transverse momentum k_T
- Provide 3D image of hadrons in momentum space: $f\,(x,k_T)$
- Correlation between parton momentum and hadron spin

Leading twist TMD PDFs

Nucleon \ Quark, Gluon	U	L	T
U	number density $f_1^{q,g}(x,k_T^2)$		Boer-Mulders $h_1^{\perp q,g}(x,k_T^2)$
L		Helicity $g_{1L}^{q,g}(x,k_T^2)$	worm-gear L $h_{1L}^{\perp q,g}(x,k_T^2)$
T	Sivers $f_{1T}^{\perp q,g}(x,k_T^2)$	Kotzinian-Mulders worm-gear T $g_{1T}^{\perp q,g}(x,k_T^2)$	Transversity $h_1^{q,g}(x,k_T^2)$ Pretzelosity $h_{1T}^{\perp q,g}(x,k_T^2)$

Unpolarized ⟵ U

Longitudinally polarized ⟵ L

Transversely polarized ⟵ T

TMD-PDFs give the number density of partons, with their intrinsic motion and spin, inside a fast moving proton, with its spin.

INTRODUCTION

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- Test of the sign change of the T-odd TMD PDFs is a fundamental quest in QCD dynamics. Measurement by COMPASS provides some hint on this sign change.

- It is important to have precise measurement and extraction of the proton Sivers function/Boer-Mulders function and pion Boer-Mulders function.

- It is also important to acquire the differential cross-section of the unpolarized process with high accuracy, as it always appears in the denominator of various asymmetries.

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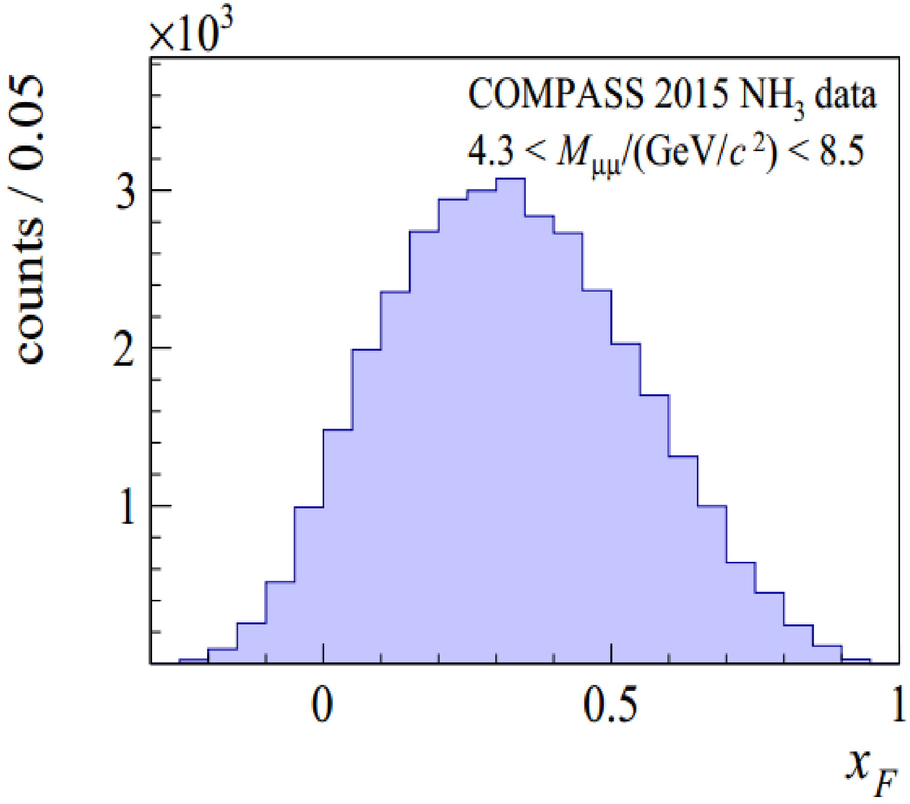
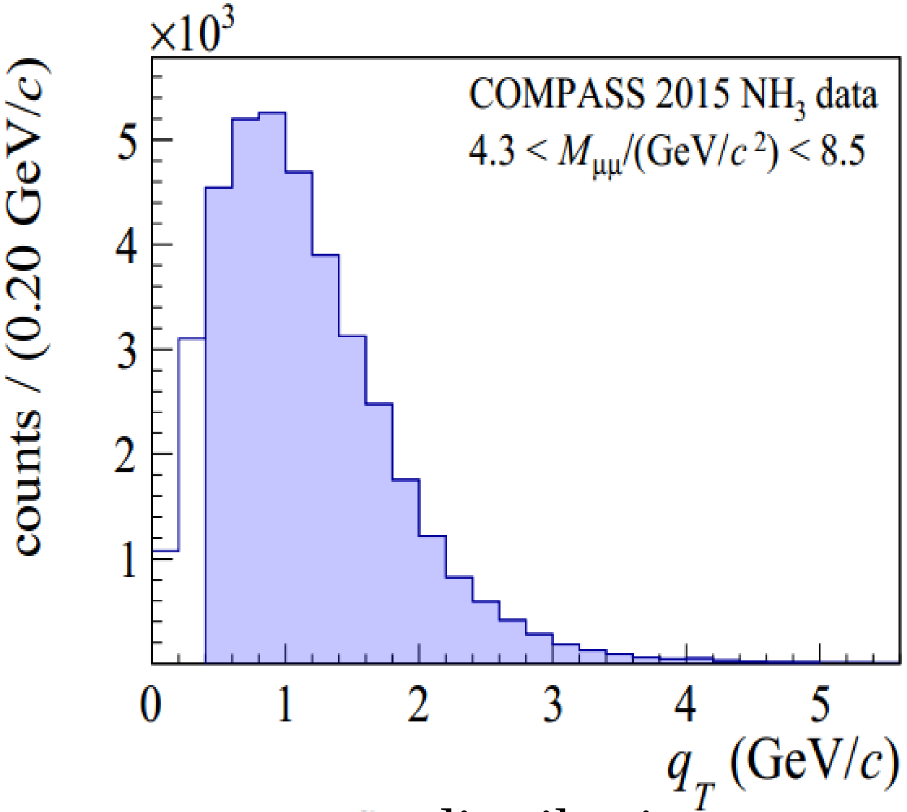
◆ Recent COMPASS measurements (Unpolarized distribution)



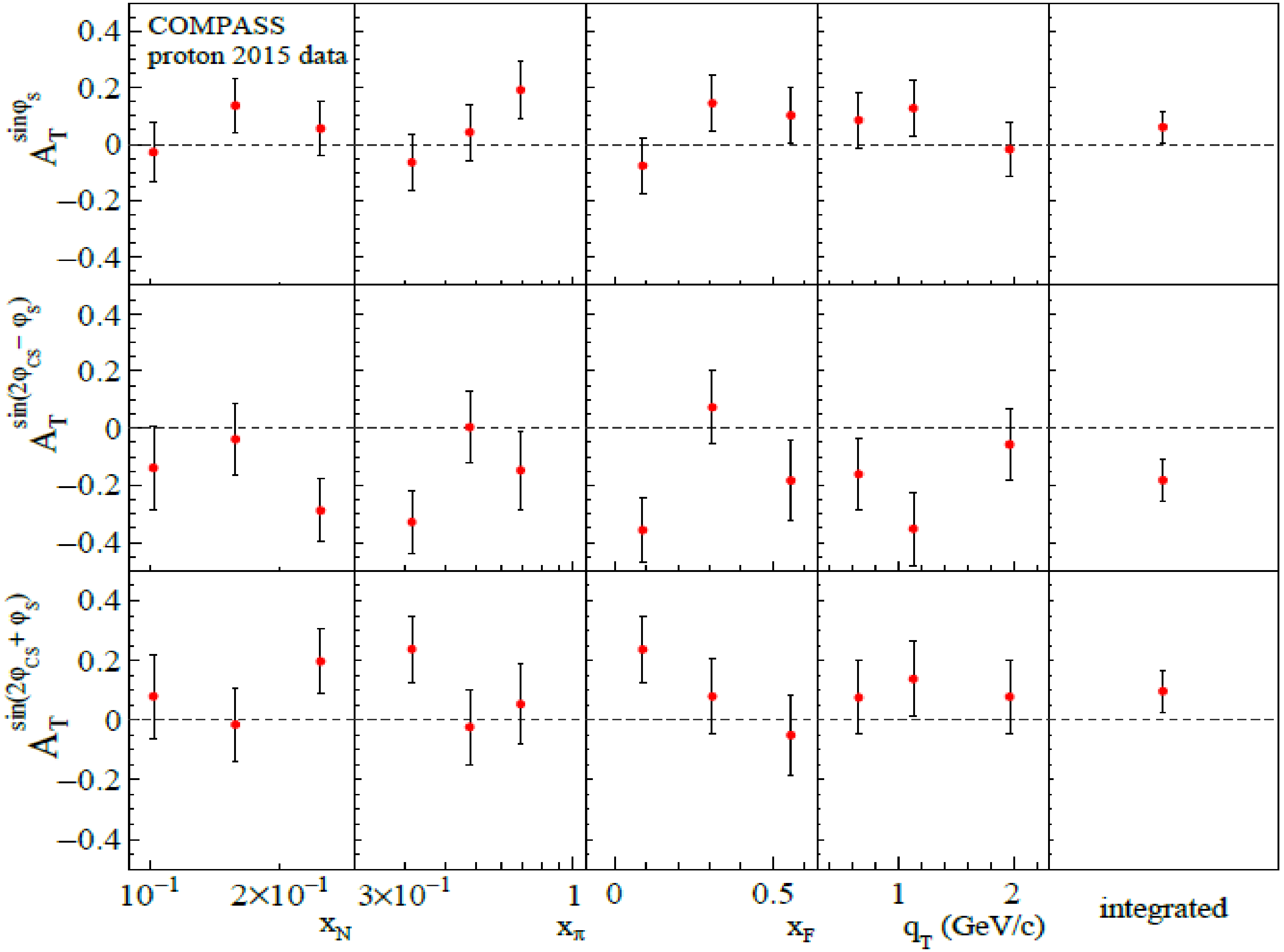
x_F distribution of dilepton events



q_T distribution

PRL119, 112002 (2017)

◆ Recent COMPASS measurements (Single Spin Asymmetries)



PRL119, 112002 (2017)

INTRODUCTION

- **Drell-Yan process** $A\,(P_1) + B\,(P_2) \to l^+\,(\ell) + l^-\,(\ell') + X\,,$
  - The asymmetries

				Beam	Target
$A_{UU}^{\cos(2\phi)}$	$\propto h_{1,\pi}^{\perp q}$	$\otimes$	$h_{1,p}^{\perp q}$	Boer-Mulders	Boer-Mulders
$A_{UT}^{\sin(\phi_S)}$	$\propto f_{1,\pi}^{q}$	$\otimes$	$f_{1T,p}^{\perp q}$	$f_{1,\pi}^{q}$	Sivers
$A_{UT}^{\sin(2\phi-\phi_S)}$	$\propto h_{1,\pi}^{\perp q}$	$\otimes$	$h_{1,p}^{q}$	Boer-Mulders	Transversity
$A_{UT}^{\sin(2\phi+\phi_S)}$	$\propto h_{1,\pi}^{\perp q}$	$\otimes$	$h_{1T,p}^{\perp q}$	Boer-Mulders	Pretzelosity

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- The differential cross section for the unpolarized π^--proton Drell-Yan process has the form

J. C. Collins, D. E. Soper and G. F. Sterman, Nucl. Phys. B 250 (1985) 199

$$\frac{d^4\sigma}{dQ^2 dy d^2\boldsymbol{q}_\perp} = \sigma_0 \int \frac{d^2 b}{(2\pi)^2} e^{i\vec{q}_\perp \cdot \vec{b}} \widetilde{W}_{UU}(Q; b) + Y_{UU}(Q, q_\perp),$$

- $\sigma_0 = \frac{4\pi\alpha_{em}^2}{3N_C s Q^2}$ is the cross section at tree level with $N_c = 3$
- The structure function in the first term with $\widetilde{W}_{UU}(Q; b)$ is dominant at the low $q_\perp \ll Q$ value
- Y_{UU} term provides necessary correction at moderate $q_\perp \sim Q$ value, which was neglected in this work

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- The structure function $\widetilde{W}_{UU}$ can be written as

$$\widetilde{W}_{UU}(Q;b) = H_{UU}(Q;\mu) \sum_{q,\bar{q}} e_q^2 \tilde{f}^{\mathrm{sub}}_{1\,\bar{q}/\pi}(x_\pi, b; \mu, \zeta_F) \tilde{f}^{\mathrm{sub}}_{1\,q/p}(x_p, b; \mu, \zeta_F),$$

- $\tilde{f}^{\mathrm{sub}}_{1\,q/H}$ is the subtracted distribution function in the b-space and universal.
- $H_{UU}(Q;\mu)$is the factor associated with hard scattering and scheme-dependent.
- The way to subtract the soft factor in the distribution function depends on the scheme to regulate the light-cone singularity in the TMD definition.

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- The TMD evolution equation for the ζ_F dependence is encoded in a Collins-Soper (CS) equation through

$$\frac{\partial \ln \tilde{f}^{\rm sub}(x,b;\mu,\zeta_F)}{\partial \sqrt{\zeta_F}} = \tilde{K}(b;\mu)$$

Collins, Soper 81'
Idilbi, Ji, Ma, Yuan 04'

- The TMD evolution equation for the μ dependence is encoded in a RG equation through

$$\frac{d\,\tilde{K}}{d\,\ln\mu} = -\gamma_K(\alpha_s(\mu)),$$

$$\frac{d\,\ln \tilde{f}^{\rm sub}(x,b;\mu,\zeta_F)}{d\,\ln\mu} = \gamma_F(\alpha_s(\mu);\frac{\zeta_F^2}{\mu^2}),$$

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- The overall solution structure is the same as that for the Sudakov form factor.

- The energy evolution of TMDs from initial energy μ_b to another energy Q is encoded in the Sudakov-like form factor S by the exponential form exp(−S)

$$f(x,b,Q) = \mathcal{F} \times e^{-S} \times f(x,b,\mu_b)$$

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- When Fourier transform back to the momentum space, one needs the whole b region (large b): need some non-perturbative extrapolation

Many different methods/proposals to model this non-perturbative part

$$F(x,k_\perp;Q)=\frac{1}{(2\pi)^2}\int d^2be^{ik_\perp\cdot b}F(x,b;Q)=\frac{1}{2\pi}\int_0^\infty db\,bJ_0(k_\perp b)F(x,b;Q)$$

- To combine the information at small b (perturbative region) with that at large b(non-perturbative region), a matching procedure must be introduced.

$$b_*=b/\sqrt{1+b^2/b_{\max}^2}$$

$b_*\approx b$ at low values of b

$b_*\approx b_{\max}$ at large b values.

- The Sudakov-like form factor in can be separated into a perturbatively calculable part and a nonperturbative part

$$S = S_{\mathrm{pert}} + S_{\mathrm{NP}}.$$

- The perturbative part of S being

$$S_{\mathrm{pert}}(Q,b) = \int_{\mu_b^2}^{Q^2} \frac{d\bar{\mu}^2}{\bar{\mu}^2}\left[A(\alpha_s(\bar{\mu}))\ln\frac{Q^2}{\bar{\mu}^2} + B(\alpha_s(\bar{\mu}))\right].$$

- Non-perturbative form factor of S from pp DY (SIYY parameterization)

$$S_{\mathrm{NP}} = g_1 b^2 + g_2 \ln\frac{b}{b_*}\ln\frac{Q}{Q_0} + g_3 b^2\left((x_0/x_1)^\lambda + (x_0/x_2)^\lambda\right)$$

Sun, Isaacson, Yuan, Yuan 14' arXiv: 1406.3073

$$g_1 = 0.212, \quad g_2 = 0.84, \quad g_3 = 0$$

$$S_{\mathrm{NP}}^{f_1^{q/p}}(Q,b) = \frac{g_2}{2}\ln\frac{b}{b_*}\ln\frac{Q}{Q_0} + \frac{g_1}{2}b^2,$$

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- In the small b region,

$$F(x,b;\mu,\zeta_F)=\sum_i C_{q\leftarrow i}\otimes f_i(x,\mu),$$

$$F(x,b;Q)\approx C\otimes F(x,c/b^*)\times\exp\left\{-\int_{c/b^*}^{Q}\frac{d\mu}{\mu}\left(A\ln\frac{Q^2}{\mu^2}+B\right)\right\}\times\exp\left(-S_{\text{non-pert}}(b,Q)\right)$$

longitudinal/collinear part

perturbative
Sudakov part

Non-perturbative Sudakov:
fitted from data

Collins, Soper, Sterman 85, ResBos, Qiu, Zhang 99, Echevarria, Idilbi, Kang, Vitev, 14,
Aidala, Field, Gamberg, Rogers, 14, Sun, Yuan 14, D'Alesio, Echevarria, Melis, Scimemi, 14, Rogers, Collins, 15, ⋯ mostly for the proton case

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- With all the ingredients above, we can obtain the TMD distribution for proton

$$\tilde{f}_1^{u/p}(x,b;Q) = e^{-\frac{1}{2}S_{\rm pert}(Q,b_*) - S_{\rm NP}^{f_1^{q/p}}(Q,b)} \mathcal{F}(\alpha_s(Q)) \sum_i C_{q\leftarrow i}^{f_1} \otimes f_1^{i/p}(x,\mu_b)$$

$$C_{q\leftarrow q'}(x,b;\mu,\zeta_F) = \delta_{qq'}\left[\delta(1-x) + \frac{\alpha_s}{\pi}\left(\frac{C_F}{2}(1-x)\right)\right],$$

$$C_{q\leftarrow g}(x,b;\mu,\zeta_F) = \frac{\alpha_s}{\pi} T_R x(1-x),$$

- If we perform a Fourier Transformation on $\tilde{f}_{1q/p}^{\rm sub}(x,b;Q)$

$$f_{1q/p}(x,k_\perp;Q) = \int_0^\infty \frac{dbb}{2\pi} J_0(k_\perp b) \tilde{f}_{1q/p}^{\rm sub}(x,b;Q),$$

UNPOLARIZED PROCESS

- Assuming the non-perturbative Sudakov form factor $S_{\rm NP}^{f_1^{q/\pi}}(Q,b)$ for quark distribution function of π meson as

X. Wang, Z. Lu, I. Schmidt, JHEP 1708 (2017) 137

$$S_{\rm NP}^{f_1^{q/\pi}} = g_1^\pi b^2 + g_2^\pi \ln\frac{b}{b_*}\ln\frac{Q}{Q_0}.$$

- With the assumption above, we can obtain the TMD distribution for pion

$$f_1^{i/\pi}(x,b;Q) = e^{-\frac{1}{2}S_{\rm pert}(Q,b_*)-S_{\rm NP}^{f_1^{q/\pi}}(Q,b)}\mathcal{F}(\alpha_s(Q))\sum_i C_{q\leftarrow i}^{f_1}\otimes f_1^{i/\pi}(x,\mu_b)$$

$$f_{1q/\pi}(x,k_\perp;Q) = \int_0^\infty \frac{dbb}{2\pi} J_0(k_\perp b)\tilde{f}_{1q/\pi}^{\rm sub}(x,b;Q).$$

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- The structure function is as follows

$$\widetilde{W}_{UU}(Q;b) = H_{UU}(Q;\mu)\sum_{q,\bar{q}} e_q^2 \tilde{f}_{q/\pi}^{\rm sub}(x_1,b;\mu,\zeta_F)\tilde{f}_{q/p}^{\rm sub}(x_2,b;\mu,\zeta_F),$$

- If we absorb the hard factors H_{UU} and $\mathcal{F}(\alpha_s(Q))$ into the definition of C-coefficients, the C-coefficients become process-dependent

S. Catani, D. de Florian and M. Grazzini, Nucl. Phys. B 596 (2001) 299

$$C_{q\leftarrow q'}(x,b;\mu_b) = \delta_{qq'}\left[\delta(1-x) + \frac{\alpha_s}{\pi}\left(\frac{C_F}{2}(1-x) + \frac{C_F}{4}(\pi^2-8)\delta(1-x)\right)\right],$$

$$C_{q\leftarrow g}(x,b;\mu_b) = \frac{\alpha_s}{\pi}T_R x(1-x).$$

UNPOLARIZED PROCESS

- The structure function W_{UU} in b-space can be written as

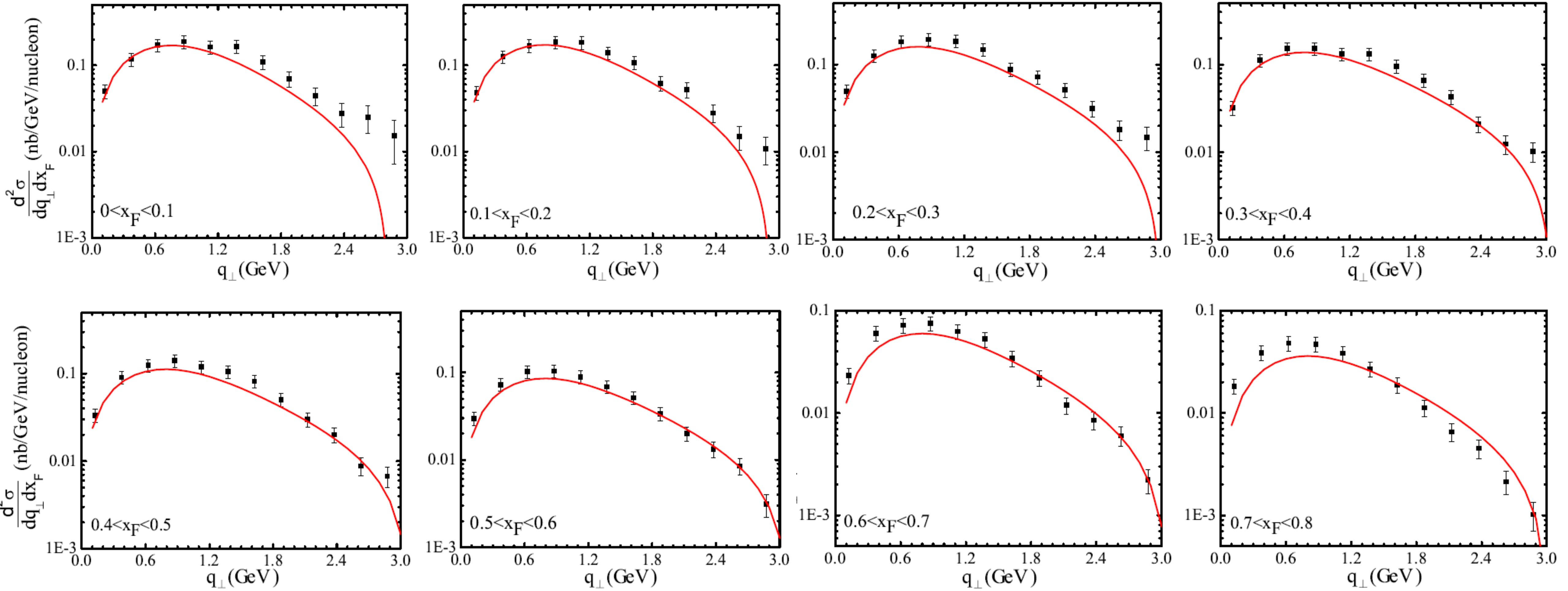
$$\widetilde{W}_{UU}(Q;b) = e^{-S(Q^2,b)} \times \sum_{q,\bar{q}} e_q^2 C_{q\leftarrow i} \otimes f_{i/\pi^-}(x_1,\mu_b) C_{\bar{q}\leftarrow j} \otimes f_{j/p}(x_2,\mu_b)$$

- The differential cross section is

$$\frac{d^4\sigma}{dQ^2 dy d^2\boldsymbol{q}_\perp} = \sigma_0 \int_0^\infty \frac{dbb}{2\pi} J_0(q_\perp b) \times \widetilde{W}_{UU}(Q;b),$$

UNPOLARIZED PROCESS

- Fit the theoretical estimate with the experimental data from E615, we can obtain the parameters in $S_{\mathrm{NP}}^{f_1^{q/\pi}}(Q,b)$ X. Wang, Z. Lu, I. Schmidt, JHEP 1708 (2017) 137



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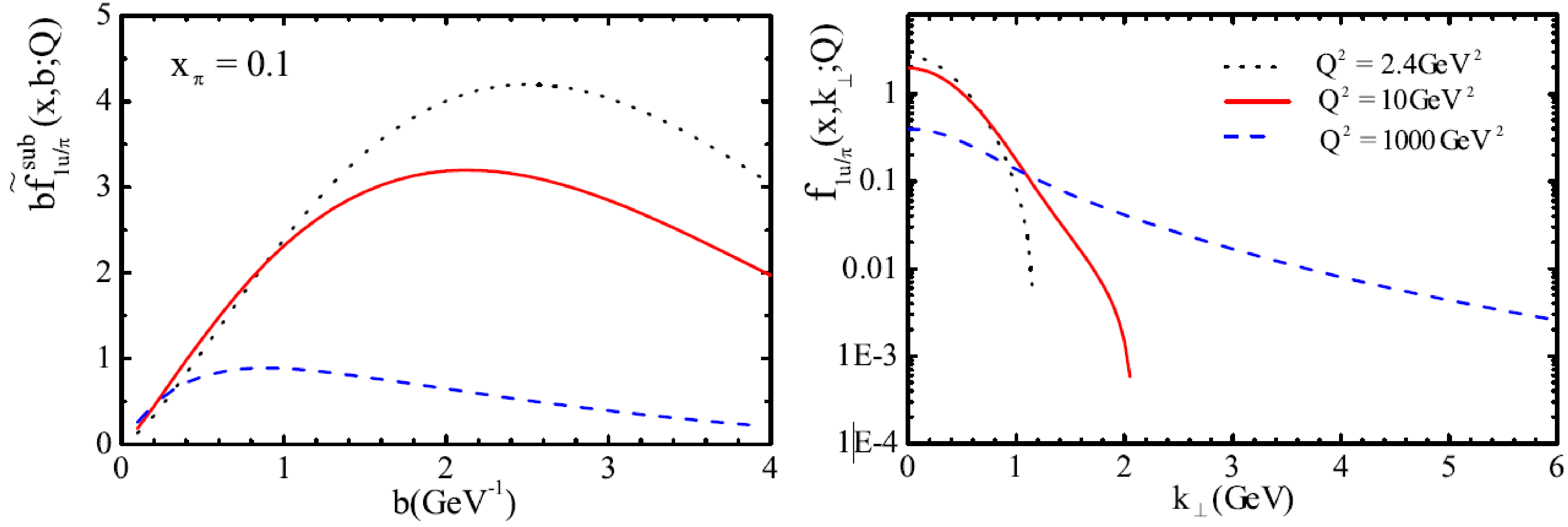
- The fitting parameters are as

$$g_1^{\pi} = 0.082 \pm 0.022, \quad g_2^{\pi} = 0.394 \pm 0.103,$$

- The fit coincides with the experimental data well when $0 < x_F < 0.8$.
- The fit breaks down when x_F is above 0.8 since at that region the TMD factorization is invalid and the higher twist effects dominant.
- For the pion-induced Drell-Yan process in fixed-target scattering, the NLL threshold resummation effects are also important in the kinematic higher x_F.

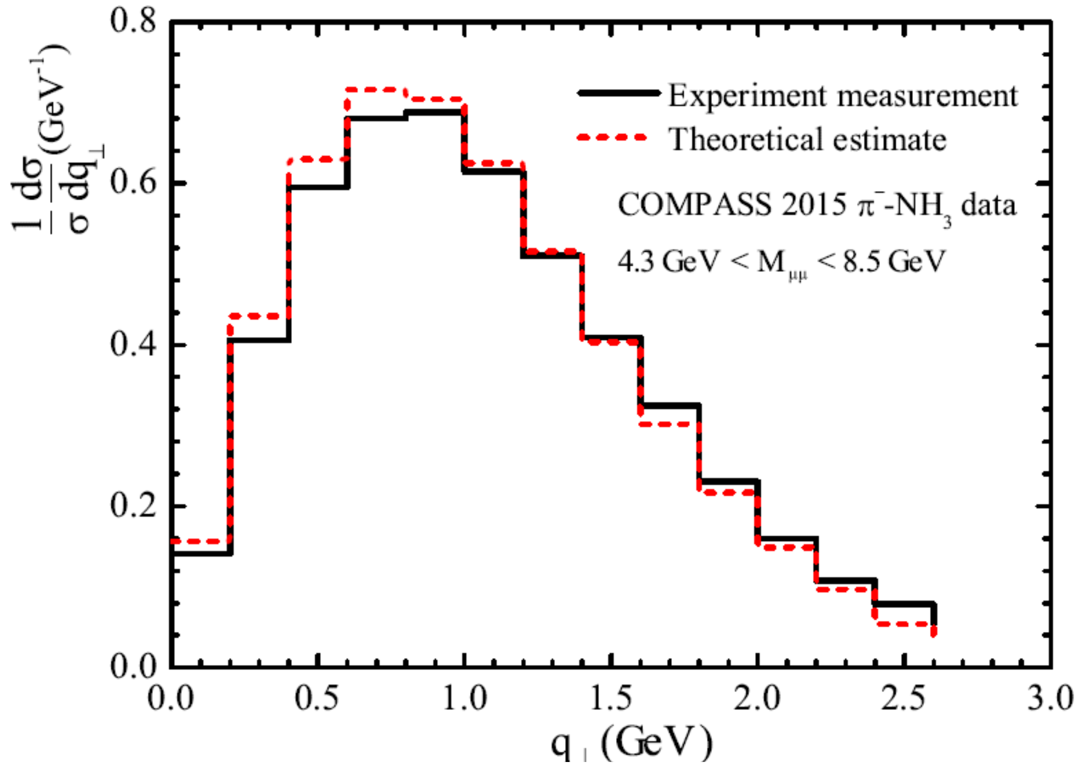
UNPOLARIZED PROCESS



Subtracted unpolarized TMD distribution of the pion meson for valence quarks in b-space (left panel) and $k_\perp$-space (right panel), at energies: $Q^2 = 2.4$ GeV^2 (dotted lines), $Q^2 = 10$ GeV^2 (solid lines) and $Q^2 = 1000$ GeV^2 (dashed lines).

X. Wang, Z. Lu, I. Schmidt, JHEP 1708 (2017) 137

UNPOLARIZED PROCESS



The transverse spectrum of lepton pair production in the unpolarized pion-nucleon Drell-Yan process, with an NH_3 target at COMPASS. The dashed line is our theoretical calculation using the extracted Sudakov form factor for the pion TMD PDF. The solid line shows the experimental measurement at COMPASS.

X. Wang, Z. Lu, I. Schmidt, JHEP 1708 (2017) 137

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- The theoretical is compatible with the COMPASS measurement at small $q_\perp$ region with $q_\perp \ll Q$, indicating that our approach can be used as a first step to study the Drell-Yan process at COMPASS.

- Our study may provide a better understanding on the pion TMD distribution as well as its role in Drell-Yan process.

- The framework applied in this work can also be extended to the study of the azimuthal asymmetries in the $\pi^- N$ Drell-Yan process.

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SIVERS ASYMMETRY

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- The transverse single spin asymmetry can be defined as

M. G. Echevarria, A. Idilbi, Z. B. Kang, and I. Vitev, Phys. Rev. D 89, 074013(2014)

$$A_{UT} = \frac{d^4\Delta\sigma}{dQ^2 dy d^2\boldsymbol{q}_\perp} \Big/ \frac{d^4\sigma}{dQ^2 dy d^2\boldsymbol{q}_\perp},$$

Spin-dependent

Spin-independent(Unpolarized)

$$\frac{d^4\sigma}{dQ^2 dy d^2\boldsymbol{q}_\perp} = \sigma_0 \int \frac{d^2b}{(2\pi)^2} e^{i\vec{q}_\perp\cdot\vec{b}} \widetilde{W}_{UU}(Q;b) + Y_{UU}(Q,q_\perp).$$

$$\frac{d^4\Delta\sigma}{dQ^2 dy d^2\boldsymbol{q}_\perp} = \sigma_0 \epsilon_\perp^{\alpha\beta} S_\perp^\alpha \int \frac{d^2b}{(2\pi)^2} e^{i\vec{q}_\perp\cdot\vec{b}} \widetilde{W}_{UT}^\beta(Q;b) + Y_{UT}^\beta(Q,q_\perp).$$

SIVERS ASYMMETRY

- Spin-dependent structure function

$$\widetilde{W}^{\alpha}_{UT}(Q;b) = H_{UT}(Q;\mu) \sum_{q,\bar{q}} e_q^2 \tilde{f}_{1\,\bar{q}/\pi}(x_\pi, b; \mu, \zeta_F) \tilde{f}^{\perp\alpha(\mathrm{DY})}_{1T\,q/p}(x_p, b; \mu, \zeta_F).$$

$$\tilde{f}^{\perp\alpha(\mathrm{DY})}_{1T\,q/p}(x, b; \mu, \zeta_F) = \int d^2\boldsymbol{k}_\perp e^{-i\vec{\boldsymbol{k}}_\perp\cdot\vec{\boldsymbol{b}}} \frac{k_\perp^\alpha}{M_p} f^{\perp(\mathrm{DY})}_{1T,q/p}(x, \boldsymbol{k}_\perp; \mu),$$

Follows the same evolution equations and the solution structure can be written in the same form

SIVERS ASYMMETRY

- Perturbative Sudakov form factor has the same form as unpolarized PDF
- Nonperturbative Sudakov form factor has the parameterization as

M. G. Echevarria, A. Idilbi, Z. B. Kang, and I. Vitev, Phys. Rev. D 89, 074013(2014)

$$S_{\rm NP}^{\rm Siv} = \left(g_1^{\rm Siv} + g_2^{\rm Siv} \ln\frac{Q}{Q_0}\right) b^2,$$

$$g_1^{\rm Siv} = \langle k_{s\perp}^2\rangle_{Q_0}/4 = 0.071\mathrm{GeV}^2 \qquad g_2^{\rm Siv} = \frac{1}{2}g_2 = 0.08\mathrm{GeV}^2$$

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- In the small b region, the Sivers function can be also expressed as the convolution of perturbatively calculable hard coefficients and the corresponding collinear correlation functions as

$$\tilde{f}_{1T\,q/p}^{\perp\alpha(\mathrm{DY})}(x,b;\mu) = \left(\frac{-ib^\alpha}{2}\right)\sum_i \Delta C^T_{q\leftarrow i} \otimes f^{(3)}_{i/p}(x',x'';\mu).$$

Qiu-Sterman matrix element $T_{q,F}(x,x)$ is the most relevant one

$$T_{q,F}(x,x) = \int d^2k_\perp \frac{|k_\perp^2|}{M_p} f_{1T\,q/p}^{\perp\mathrm{DY}}(x,k_\perp) = 2M_p\, f_{1T\,q/p}^{\perp(1)\mathrm{DY}}(x),$$

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- Sivers function in the b space

$$\tilde{f}^{\perp}_{1T,q/p}(x,b;Q) = \frac{b^2}{2\pi}\sum_i \Delta C^T_{q\leftarrow i}\otimes T_{i,F}(x,x;\mu_b)e^{-S^{\rm siv}_{\rm NP}-\frac{1}{2}S_{\rm P}},$$

- Sivers function in the transverse momentum space

$$\frac{k_\perp}{M_p} f^{\perp}_{1T,q/p}(x,k_\perp;Q) = \int_0^\infty db\frac{b^2}{2\pi}J_1(k_\perp b)\sum_i \Delta C^T_{q\leftarrow i}\otimes f^{\perp(1)}_{1T,i/p}(x,\mu_b)e^{-S^{\rm siv}_{\rm NP}-\frac{1}{2}S_{\rm P}}.$$

- The spin-dependent differential cross section

$$\frac{d^4\Delta\sigma}{dQ^2dyd^2\boldsymbol{q}_\perp} = \sigma_0\epsilon^{\alpha\beta}S_\perp^\alpha\int\frac{d^2b}{(2\pi)^2}e^{i\vec{q}_\perp\cdot\vec{b}}\widetilde{W}_{UT}^\beta(Q;b)$$

$$= \frac{\sigma_0}{4\pi}\int_0^\infty dbb^2J_1(q_\perp b)\sum_{q,i,j}e_q^2\Delta C_{q\leftarrow i}^T T_{i,F}(x_p,x_p;\mu_b)$$

$$\times C_{\bar{q}\leftarrow j}\otimes f_{1,j/\pi}(x_\pi,\mu_b)e^{-\left(S_{\rm NP}^{\rm Siv}+S_{\rm NP}^{f_{1q/\pi}}+S_{\rm P}\right)}.$$

$$\Delta C_{q\leftarrow q'}^T(x,b;\mu_b) = \delta_{qq'}\left[\delta(1-x)+\frac{\alpha_s}{\pi}\left(-\frac{1}{4N_c}(1-x)+\frac{C_F}{4}(\pi^2-8)\delta(1-x)\right)\right].$$

- Qiu-Sterman function parameterization

M. G. Echevarria, A. Idilbi, Z. B. Kang, and I. Vitev, Phys. Rev. D 89, 074013(2014)

$$T_{q,F}(x,x;\mu) = N_q \frac{(\alpha_q+\beta_q)^{(\alpha_q^{\alpha_q}+\beta_q^{\beta_q})}}{\alpha_q^{\alpha_q}\beta_q^{\beta_q}} x^{\alpha_q}(1-x)^{\beta_q} f_{q/p}(x,\mu),$$

Energy dependence

Set 1:propotional to unpolarized PDF

Set 2:adopt approximate evolution kernel

$$P_{qq}^{\rm QS} \approx P_{qq}^{f_1} - \frac{N_c}{2}\frac{1+z^2}{1-z} - N_c\delta(1-z),$$

$$P_{qq}^{f_1} = \frac{4}{3}\left(\frac{1+z^2}{(1-z)_+} + \frac{3}{2}\delta(1-z)\right).$$

QS function

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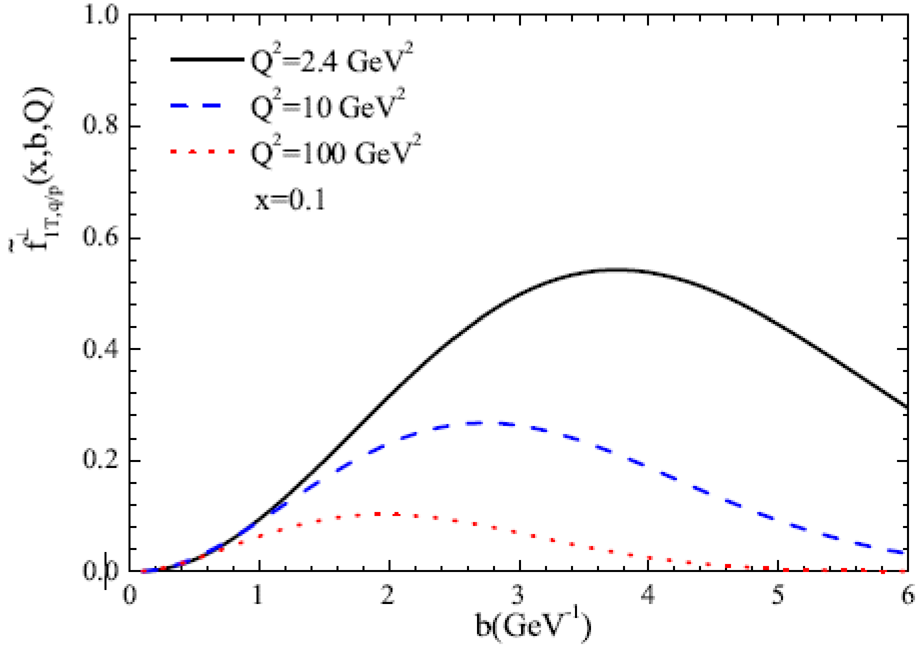
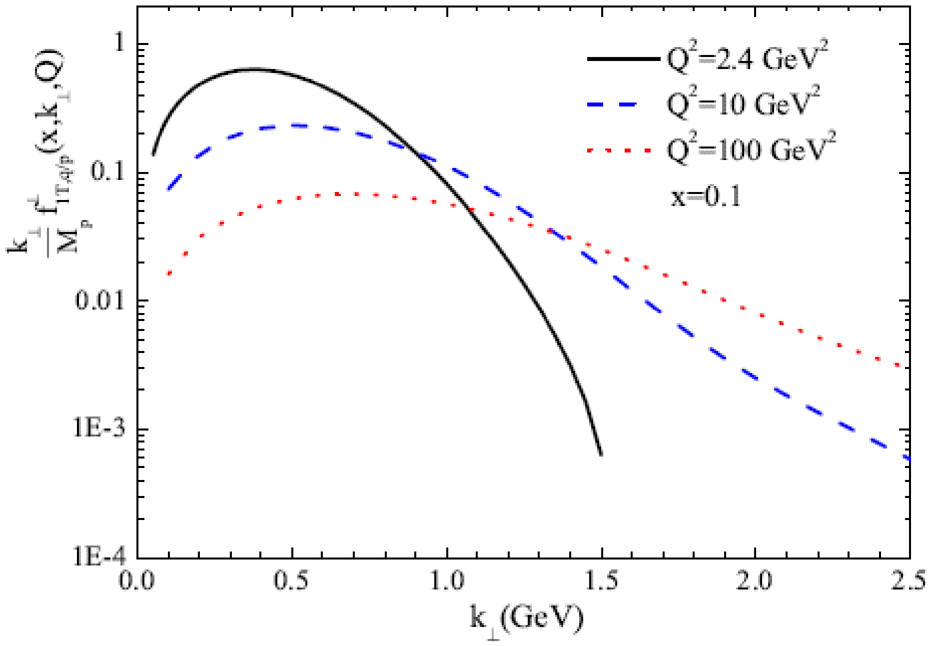
- Set 1





X. Wang and Z. Lu, Phys. Rev. D 97, 054005 (2018)

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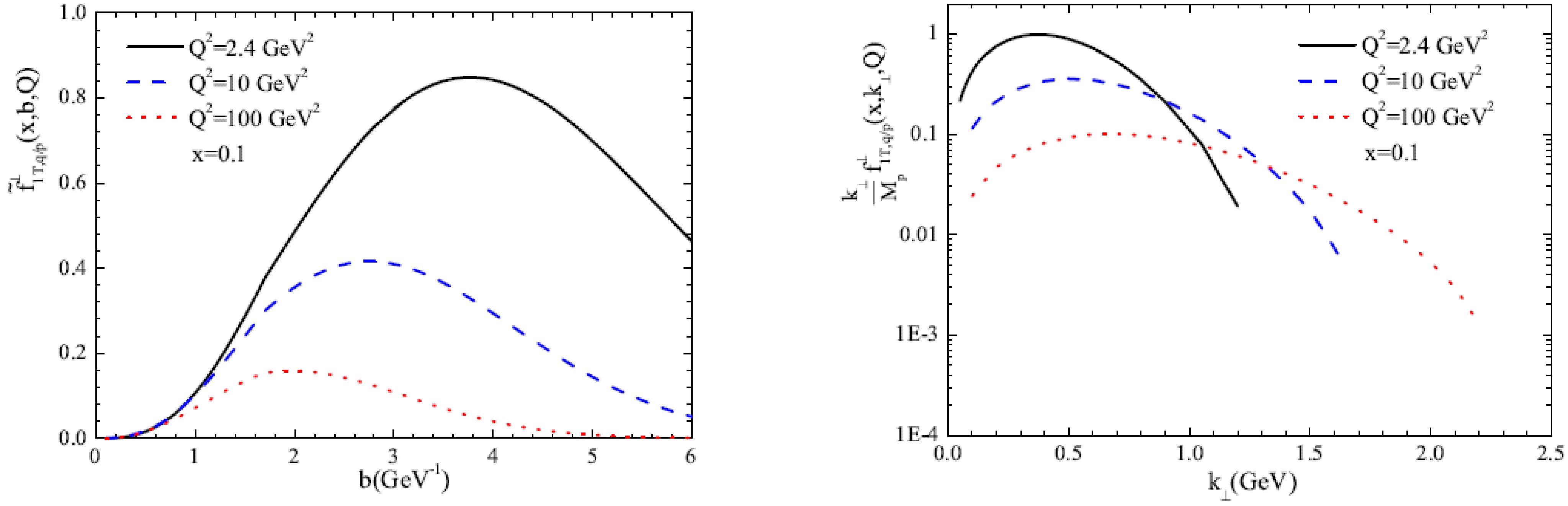
- Set 2

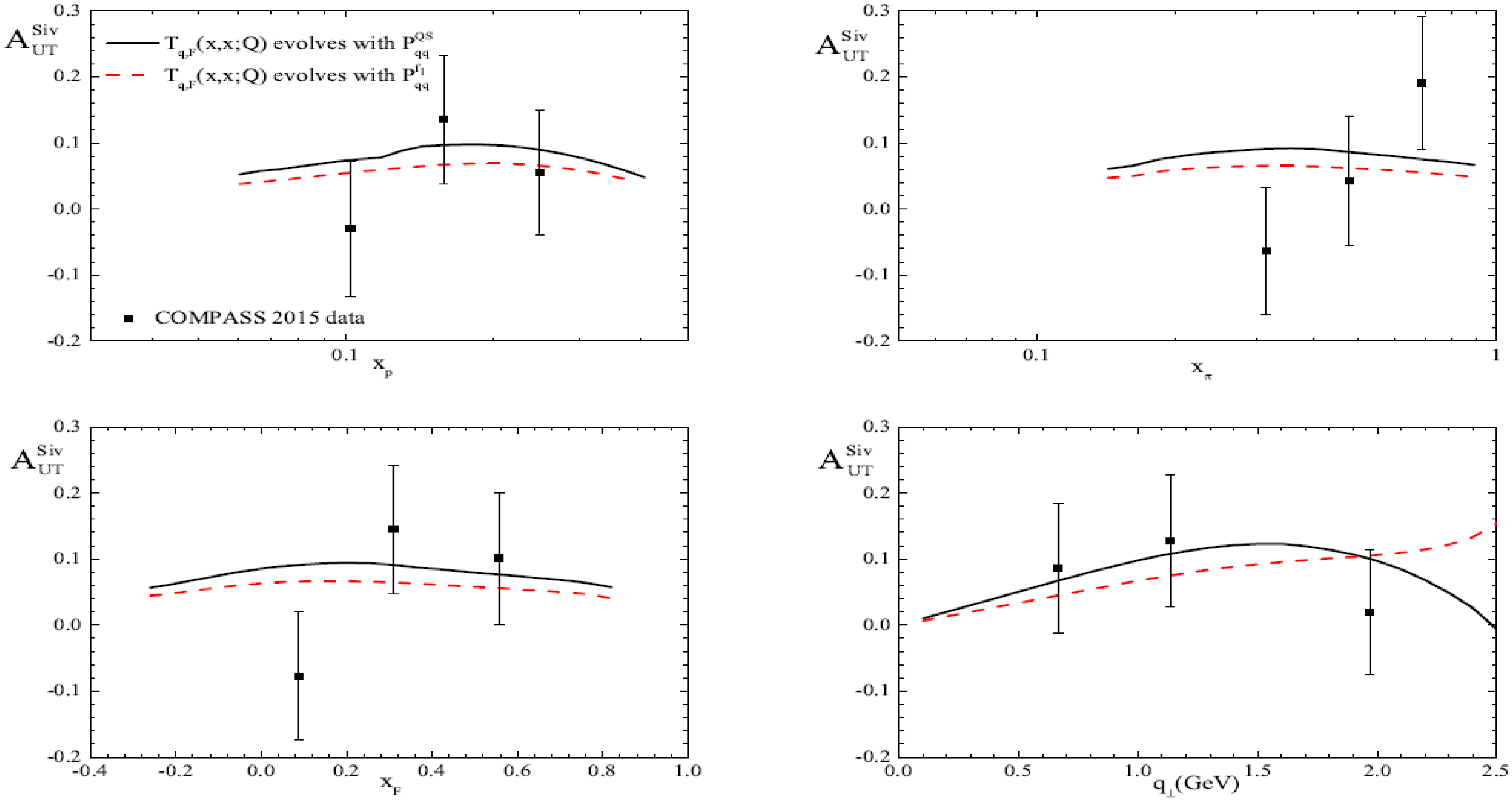


X. Wang and Z. Lu, Phys. Rev. D 97, 054005 (2018)

SIVERS ASYMMETRY

- Sivers asymmetry with the COMPASS measurement

X. Wang and Z. Lu, Phys. Rev. D 97, 054005 (2018)



SIVERS ASYMMETRY

- The Sivers asymmetry calculated from the TMD evolution formalism is consistent with the COMPASS measurement.

- The scale dependence of the Qiu-Sterman function will play a role in the interpretation of the experimental data, and it should also be considered in the phenomenological studies.

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SUMMARY

- The Non-perturbative Sudakov form factor for the unpolairzed TMD of the pion is extracted for the first time from the E615 DY data within the TMD factorization incorporating TMD evolution.

- The transvere momentum spectrum of the dilepton agrees with the COMPASS measurement at small q_T region, indicating that our approach can be used a first step for precision study of pion-nucleon DY.

- The Sivers asymmetry calculated from the TMD evolution formalism is qualitatitvely consistent with the data at COMPASS.

SUMMARY

- The results might be improved by including higher order calcuatoin of the hard coefficients , and with more flexible parameterization on the nonperturbative part.

- The framework applied here can be also extended to the study of the other azimuthal asymmetries in the pion-nucleon DY.

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BACKUPS

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- **Drell-Yan process** $A(P_1) + B(P_2) \to l^+(\ell) + l^-(\ell') + X\,,$

  - General form of the cross section
    (Beam: unpolarized Target: unpolarized/transversely polarized)

$$\frac{d\sigma}{d^4q\,d\Omega} \overset{\mathrm{LO}}{=} \frac{\alpha^2}{Fq^2}\hat{\sigma_U}\Bigg\{\left(1+\cos^2(\theta)+\sin^2(\theta)A_{UU}^{\cos(2\phi)}\cos(2\phi)\right)$$
$$+S_T\Bigg[(1+\cos^2(\theta))A_{UT}^{\sin(\phi_S)}\sin(\phi_S)$$
$$+\sin^2(\theta)\left(A_{UT}^{\sin(2\phi+\phi_S)}\sin(2\phi+\phi_S)+A_{UT}^{\sin(2\phi-\phi_S)}\sin(2\phi-\phi_S)\right)\Bigg]\Bigg\}$$

Leading-twist

BACKUPS

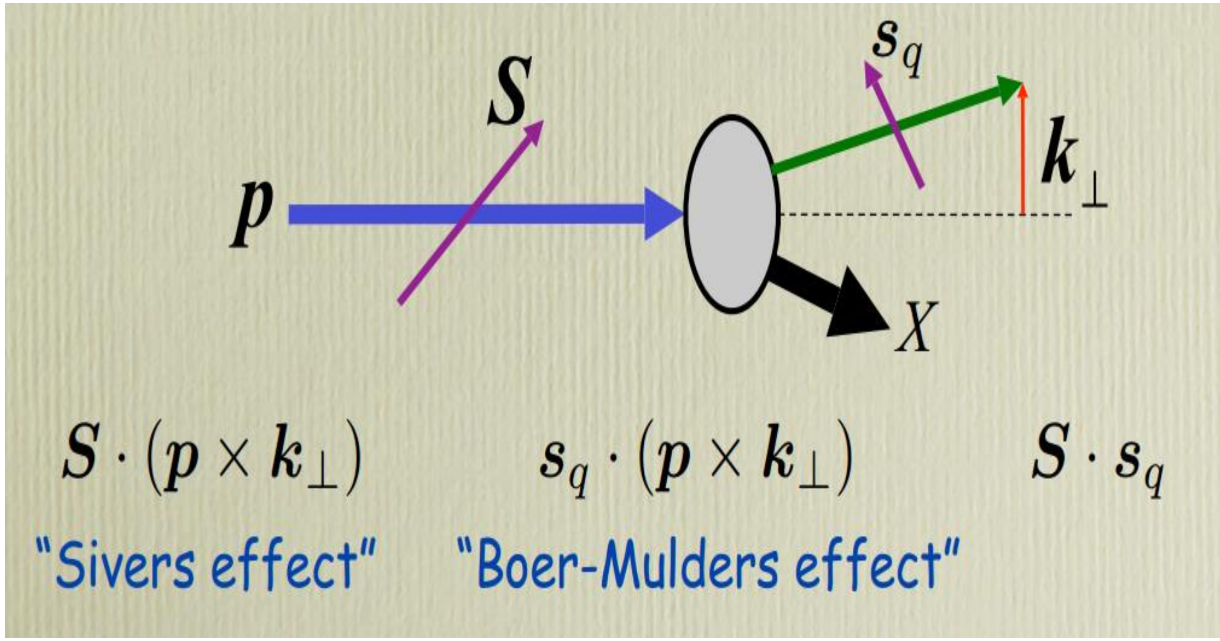
The kinematical variables defined as

$$
\begin{aligned}
s &= (P_a + P_b)^2, && \text{the total centre-of-mass energy squared,} \\
x_{a(b)} &= q^2/(2P_{a(b)} \cdot q), && \text{the momentum fraction carried by a parton from } H_{a(b)}, \\
x_F &= x_a - x_b, && \text{the Feynman variable,} \\
M_{\mu\mu}^2 &= Q^2 = q^2 = s\ x_a\ x_b, && \text{the invariant mass squared of the dimuon.}
\end{aligned}
$$

$$
\tau = Q^2/s = x_\pi x_p, \qquad y = \frac{1}{2}\ln\frac{q^+}{q^-} = \frac{1}{2}\ln\frac{x_\pi}{x_p}, \qquad x_{\pi/p} = \frac{\pm x_F + \sqrt{x_F^2 + 4\tau}}{2}, \quad x_{\pi/p} = \sqrt{\tau}e^{\pm y}.
$$

T-odd TMD PDFs

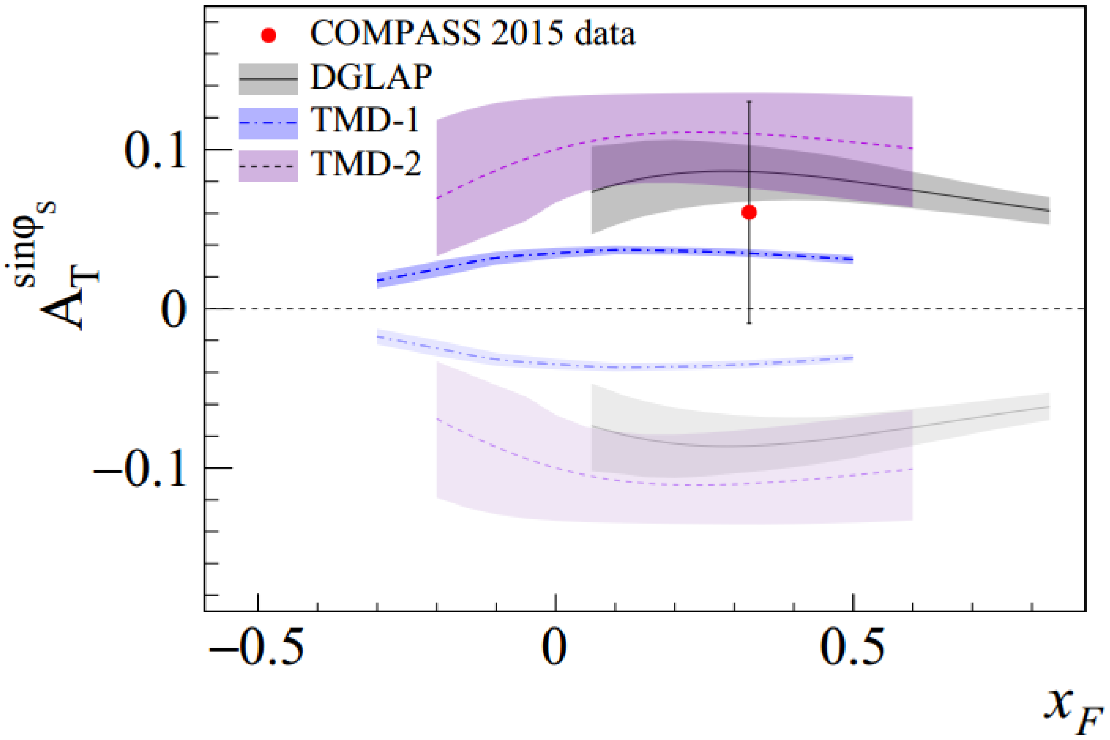
- Sivers function: correlation between the transverse spin of the nucleon and parton transverse momentum
- Boer-Mulders function: correlation between the transverse spin of the quark and quark transverse momentum



BACKUPS

Test of sign change at COMPASS

PRL119, 112002 (2017)



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TMD-1 : Echevarria, Idilbi, Kang, Vitev, PRD89,074013

TMD-2 : Sun, Yuan, PRD88,114012