

Single Transverse Spin Asymmetries: Sivers vs Collins **in the collinear approach** (who wins?)

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Quarkonia as tools 2020@Aussois

Outline

- Introduction to Single Spin Asymmetry
- TMD and collinear twist-3 as tools to study the SSA
- Summary of the leading-order calculations
- Observations from numerical calculations for Sivers and Collins
- Discussion on “who wins ?”
- Some issues in higher order

Large single spin asymmetry

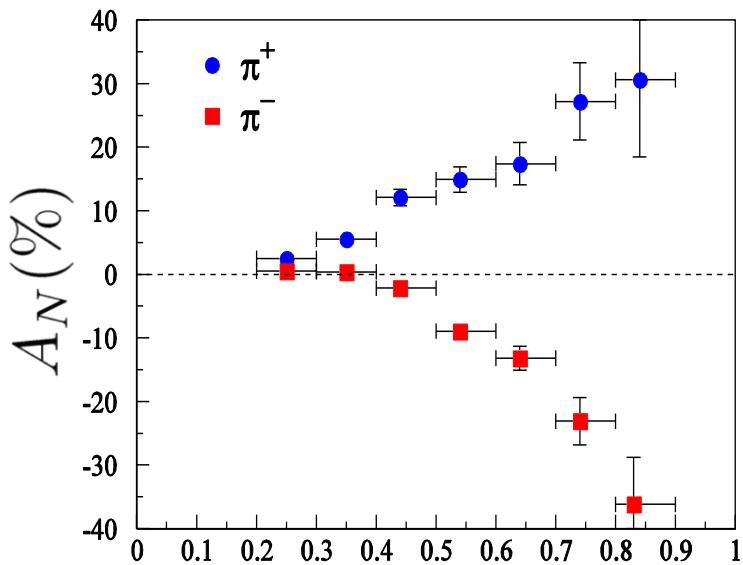
Single Spin Asymmetry (SSA)

$$A_N = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}}$$

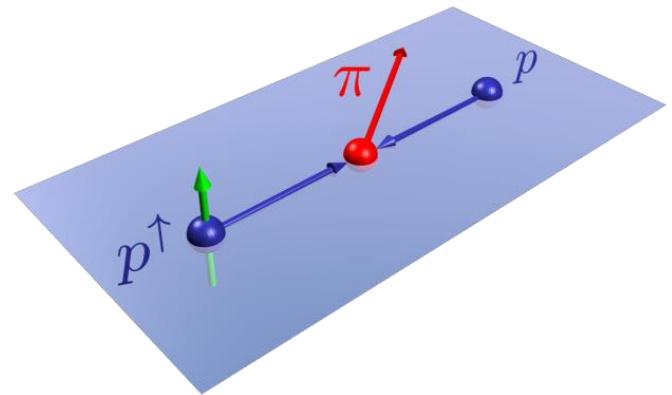
FNAL-E704 ($p^{\uparrow} p \rightarrow \pi X$)

$\sqrt{s} = 20$ GeV

P.L. B264 ('91) 462
P.L. B261 ('91) 201



$$x_F \left(= \frac{2p_l}{\sqrt{s}}\right)$$



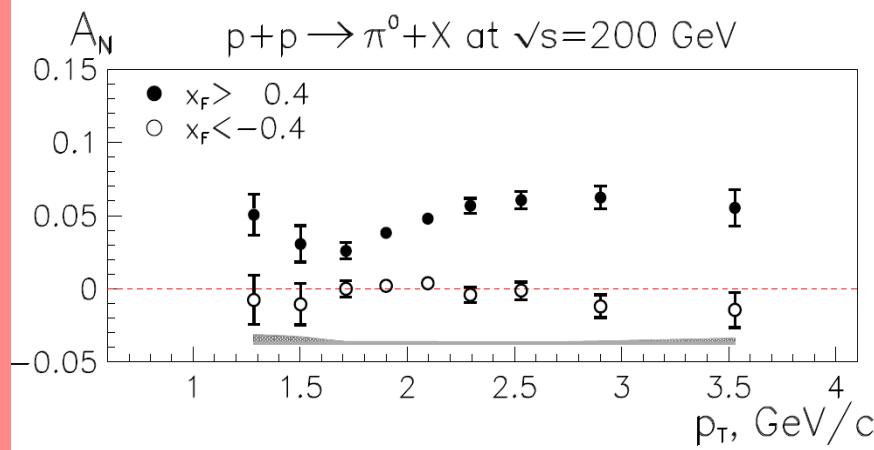
left-right asymmetry of pion distribution

Large asymmetries were first observed in late 70s

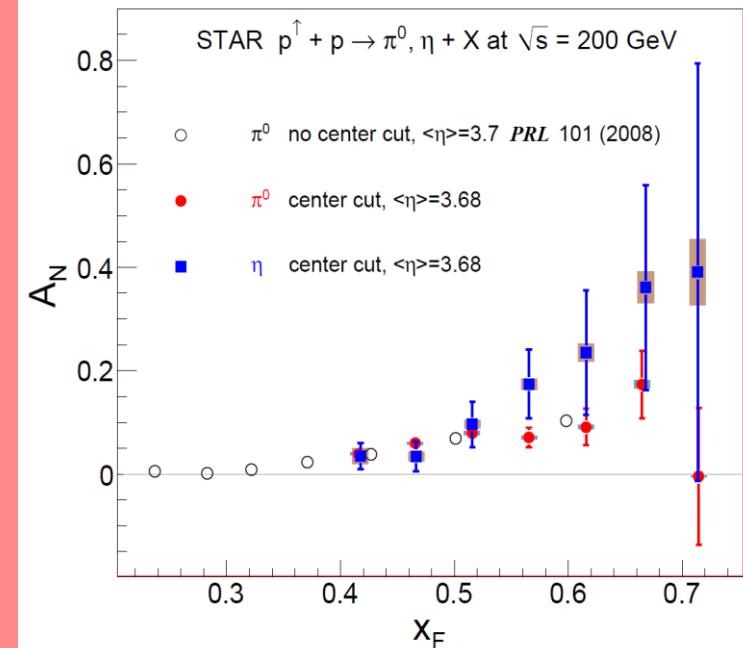
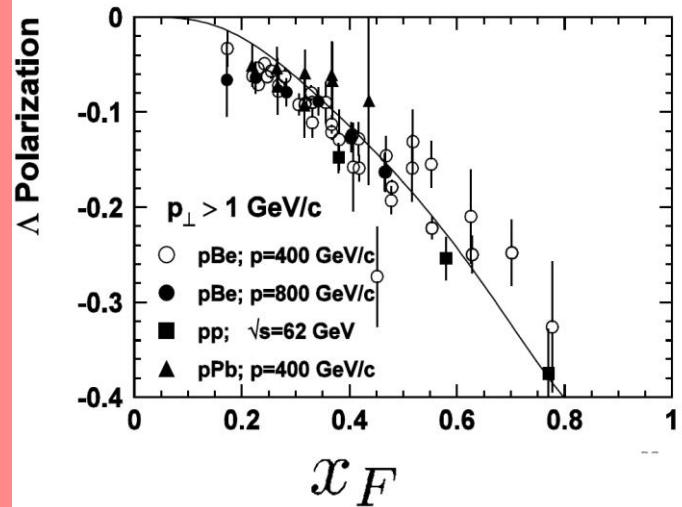
Large single spin asymmetries

40-years mystery in high-energy QCD physics

$p^\uparrow p \rightarrow \pi X$



$pp \rightarrow \Lambda^\uparrow X$ (in 80's and 90's)



SSA estimated by pQCD

Kane *et al.* ('78)

$$A_N \sim \alpha_s \frac{m_q}{P_T} \sim \text{negligible!}$$

New pQCD frameworks

Transverse Momentum Dependent(TMD) factorization

- Applicable in small $P_T(Q \gg P_T \geq \Lambda_{QCD})$ region cf. Sivers function $f_{1T}^\perp(x, \textcolor{red}{k}_\perp)$
- Nonperturbative functions depend on the transverse momentum of partons

advantage: TMD functions have definite physical interpretation

disadvantage: limited applicable processes $\times pp \rightarrow \pi X$

collinear factorization

- Applicable in large $P_T(P_T \gg \Lambda_{QCD})$ region
- twist-3 multiparton correlation inside hadrons causes the large SSA

advantage: Applicable to many processes such as $pp \rightarrow \pi X$

disadvantage: Physical interpretation of the twist-3 functions is unclear

Leading order calculations in twist-3 framework

Collinear twist-3 is a possible framework to reproduce the large SSA

$$p^\uparrow p \rightarrow \pi X$$

Sivers vs Collins

- Twist-3 distribution effect of p^\uparrow (Sivers type)

Qiu, Sterman(1998) Kouvaris, Qiu, Vogelsang, Yuan(2006) Koike, Tomita(2009)
Beppu, Kanazawa, Koike, Yoshida(2014)

- Twist-3 distribution effect of p (Boer-Mulders type)

Kanazawa, Koike(2000)

small

- Twist-3 fragmentation effect of π (Collins type)

Metz, Pitonyak(2013)

$$pp \rightarrow \Lambda^\uparrow X$$

- Twist-3 distribution effect of p (Boer-Mulders type)

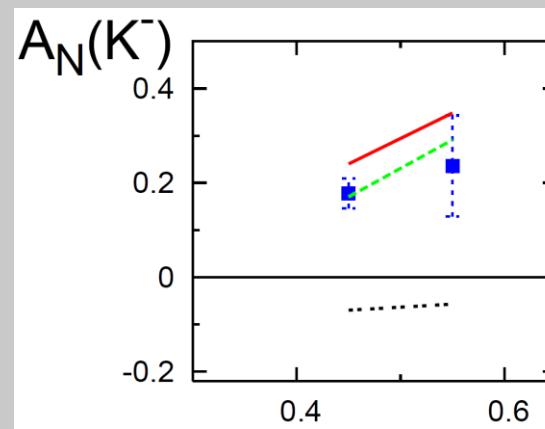
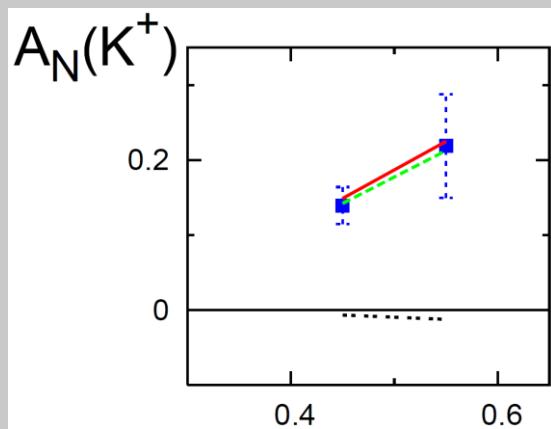
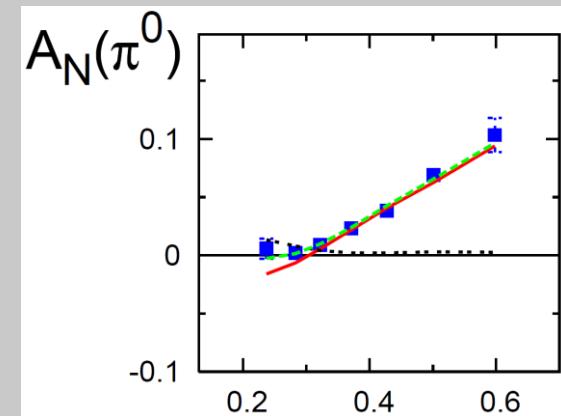
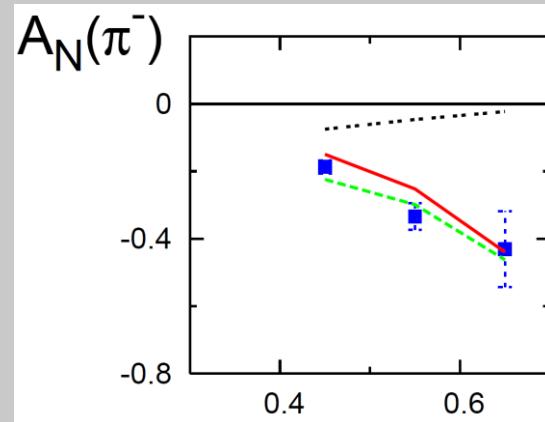
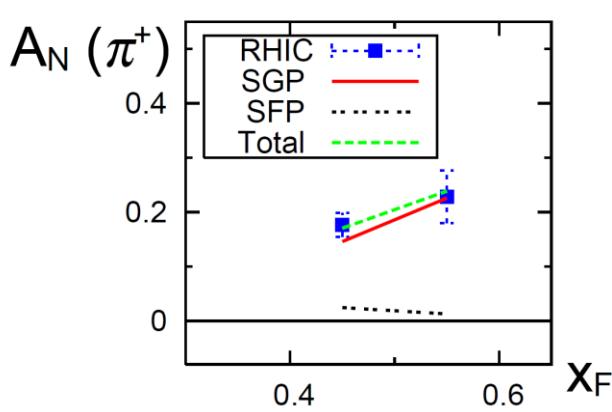
Kanazawa, Koike(2001) Zhou, Yuan, Liang(2008) Koike, Yabe, Yoshida(2015)

- Twist-3 fragmentation effect of Λ^\uparrow

Koike, Metz, Pitonyak, Yabe, Yoshida(2017)

Numerical simulation for Sivers

K. Kanazawa and Y. Koike, Phys. Rev. D83 (2011)

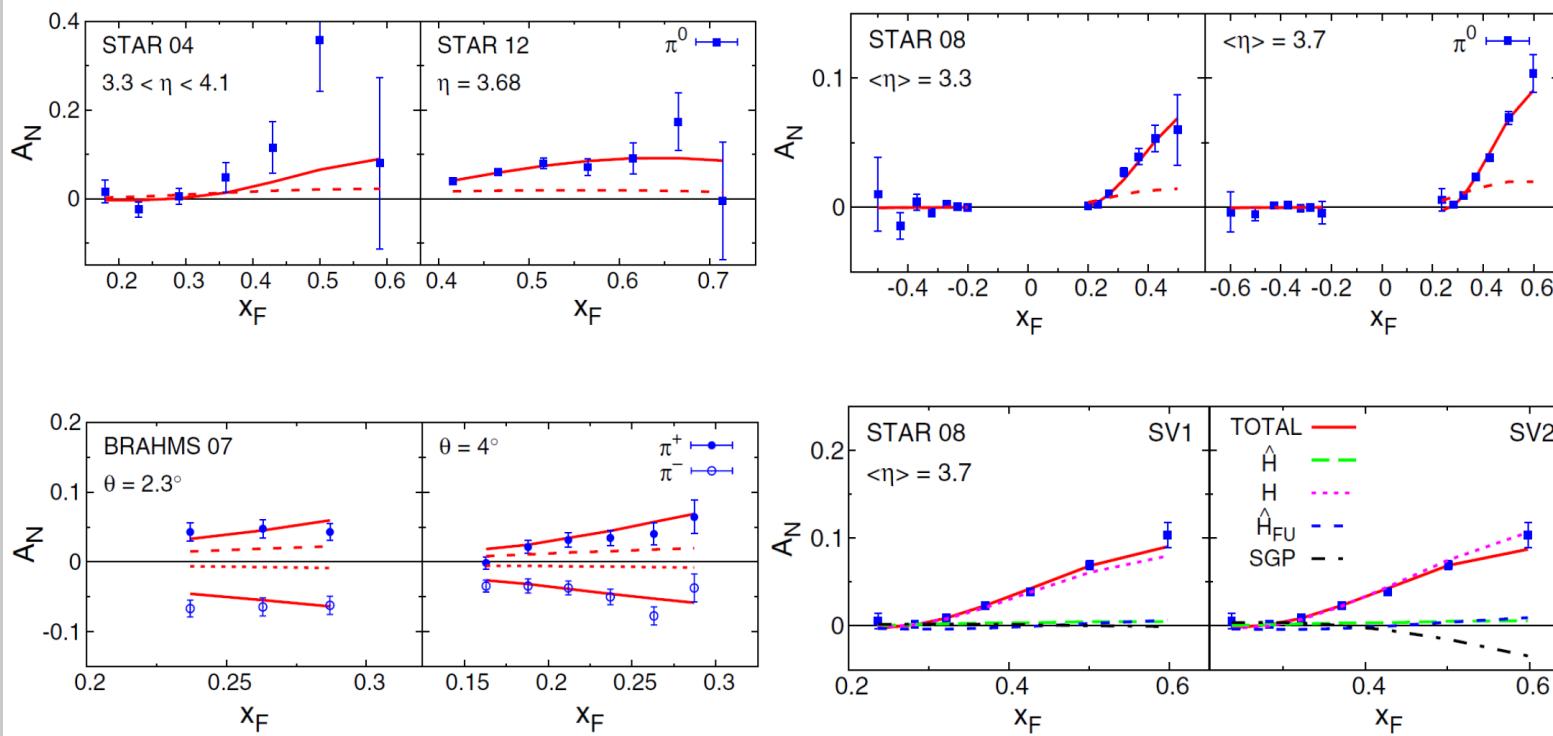


The derivative term $\frac{d}{dx} F_{FT}(x, x)$ gives large contribution in large x_F

The SSA could be dominated by the twist-3 distribution contribution

Numerical simulation for Collins

K. Kanazawa, Y. Koike, A. Metz and D. Pitonyak, Phys. Rev. D 89(2014)



The SSA could be dominated by the twist-3 fragmentation contribution

but the origin is different

(2014) \rightarrow dynamical $\hat{H}_{FU}(z_1, z_2)$

Gamberg, Kang, Pitonyak, Prokudin (2017) (2017) \rightarrow kinematical $H_1^{\perp(1)}(z)$

k_T -moment of Collins

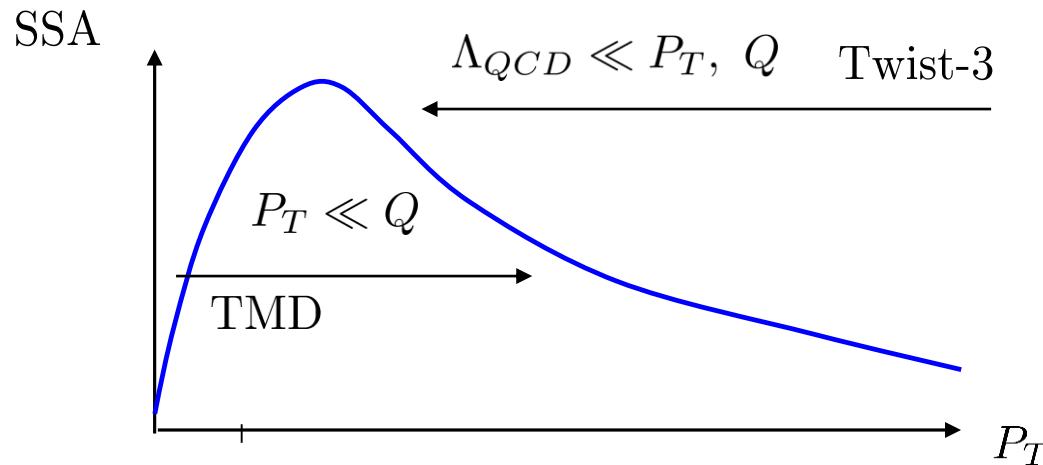
Latest numerical simulation also suggests that the fragmentation effect is dominant source

Unfavorable result for Sivers

TMD and the collinear twist-3 are equivalent in intermediate P_T region

X. Ji, J.-W. Qiu, W. Vogelsang and F. Yuan, PRD73(2006)

PLB638(2006)



QS-function

$$\pi F_{FT}(x, x) = f_{1T}^{\perp(1)}(x)$$

k_T -moment of Sivers

Determine Sivers function from ep
and use the relation

Directly determine from pp

Is Collins dominant ?

The sign of SSA is different between the two ways !

Kang, Qiu, Vogelsang, Yuan, Phys. Rev. D83 (2011) 094001

Kang, Prokudin, Phys. Rev. D85 (2012) 074008

Nuclear dependence

The atomic mass number dependence was studied

Hatta, Xiao, Yoshida, Yuan, Phys. Rev. D94 (2016)

Sivers

$$\frac{d}{dx} F_{FT}(x, x) \quad O(A^0)$$

No nuclear dependence

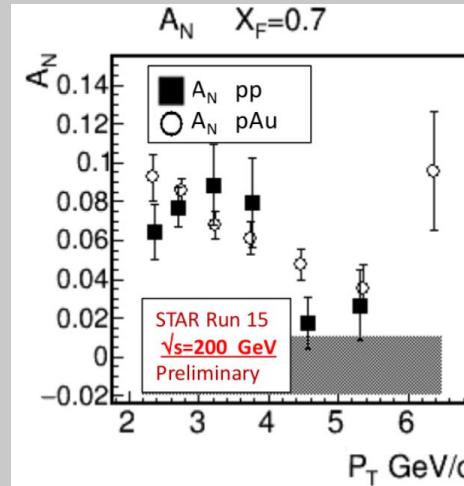
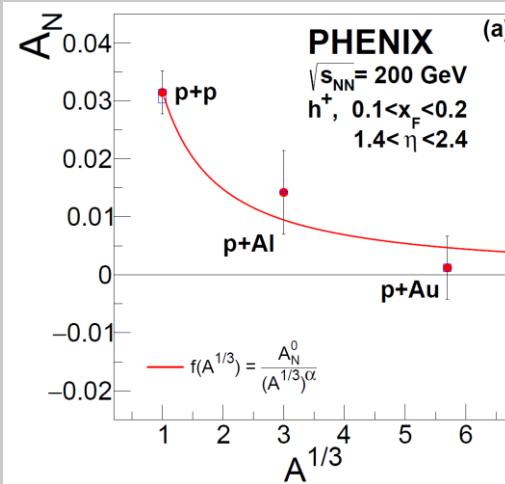
Phys. Rev. D95 (2017)

Collins

There are 3 functions and 2 of them could be large

kinematical $H_1^{\perp(1)}(z) \quad O(A^{-\frac{1}{3}})$
 k_T -moment of Collins

dynamical $\hat{H}_{FU}(z_1, z_2) \quad O(A^0) + O(A^{-\frac{1}{3}})$



Heavy-ion collision could give useful data to distinguish the contributions

Scale evolution of twist-3 functions

evolution equation for Sivers

$$\begin{aligned}
& \frac{\partial}{\partial \ln \mu^2} F_{FT}(x_B, x_B, \mu^2) \\
= & \frac{\alpha_s(\mu)}{2\pi} \left\{ \int_{x_B}^1 \frac{dx}{x} \left[P_{qq}(\hat{x}) F_{FT}(x, x, \mu^2) + \frac{N}{2} \left(\frac{(1+\hat{x})F_{FT}(x_B, x, \mu^2) - (1+\hat{x}^2)F_{FT}(x, x, \mu^2)}{(1-\hat{x})_+} \right. \right. \right. \\
& \left. \left. \left. + \tilde{F}_{FT}(x_B, x, \mu^2) \right) \right] - N F_{FT}(x_B, x_B, \mu^2) \right. \\
& \left. + \frac{1}{2N} \int_{x_B}^1 \frac{dx}{x} \left((1-2\hat{x})F_{FT}(x_B, x_B-x, \mu^2) + \tilde{F}_{FT}(x_B, x_B-x, \mu^2) \right) \right\}
\end{aligned}$$

V. M. Braun, A. N. Manashov and B. Pirnay, PRD80 (2009)

Calculation code is ready B. M. Pirnay, arXiv:1307.1272

evolution equation for Collins(fragmentation)

J. P. Ma and G. P. Zhang, Phys. Lett. B772 (2017)

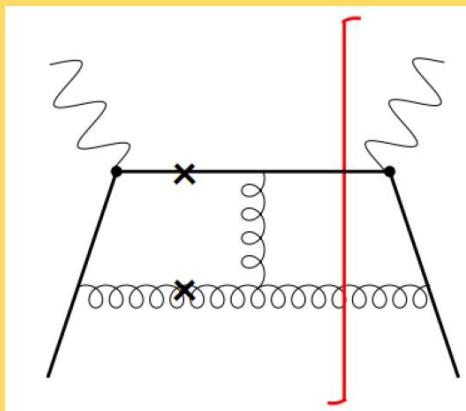
$$\begin{aligned}
\mu \frac{\partial \hat{e}_\partial(z, \mu)}{\partial \mu} = & \frac{\alpha_s C_F}{\pi} \left[\frac{3}{2} \hat{e}_\partial(z) + 2 \int_z^1 \frac{d\xi}{\xi} \frac{1}{(1-\xi)_+} \hat{e}_\partial(x) \right] + \frac{\alpha_s}{\pi} \int \frac{d\xi_1 d\xi_2}{\xi_1 \xi_2} \left\{ \text{Im} \hat{E}_F(x_1, x_2) \right. \\
& + \left[\frac{N_c \xi_2}{2(\xi_2 - \xi_1)^2} \left(-\xi_1 - \frac{\xi_2(1-\xi_2)}{1-\xi_1} \right) - C_F \left(\xi_2 + \frac{\xi_2}{\xi_1 - \xi_2} \right) \right] - \frac{C_F}{N_c} \text{Im} \hat{E}_G(x_1, x_2) \frac{(1-\xi_2)^2}{1-\xi_2 + \xi_1} \left. \right\} \\
\mu \frac{\partial \hat{E}_F(z_1, z_2)}{\partial \mu} = & \frac{\alpha_s}{\pi} \left\{ \left(C_F \left(\frac{3}{2} + \ln \frac{z_2}{z_1} \right) + N_c \ln \frac{z_3}{z_2} \right) \hat{E}_F(z_1, z_2) + N_c \int_{z_2/z_1}^1 \frac{d\xi_2}{(1-\xi_2)_+} \hat{E}_F(z_1, x_2) \right. \\
& \left. + (7 \text{ lines}) \right\}
\end{aligned}$$

No calculation code

Much data is needed

Non-trivial contribution in higher order

S. Benic, Y. Hatta, H. n. Li and D. J. Yang, Phys. Rev. D100 (2019)



$$d\sigma^{(2)} = \boxed{g_T^{(0)}} \otimes H_{\gamma_5 \gamma^y, \gamma^+}^{(2)} \otimes D_1^{(0)}$$

intrinsic twist-3 distribution

suppressed by the coupling constant α_s

→ Convergence of the perturbative series should be checked

Systematic way to calculate the higher-order correction to the twist-3 cross section has not been well developed

First one-loop calculation for differential- P_T SSA was done for $e^+e^- \rightarrow \Lambda^\uparrow X$ in the last year

Gamberg, Kang, Pitonyak, Schlegel and Yoshida, JHEP1901 (2019)

Development of the calculation technique will be a major topic in next 10 years

Summary

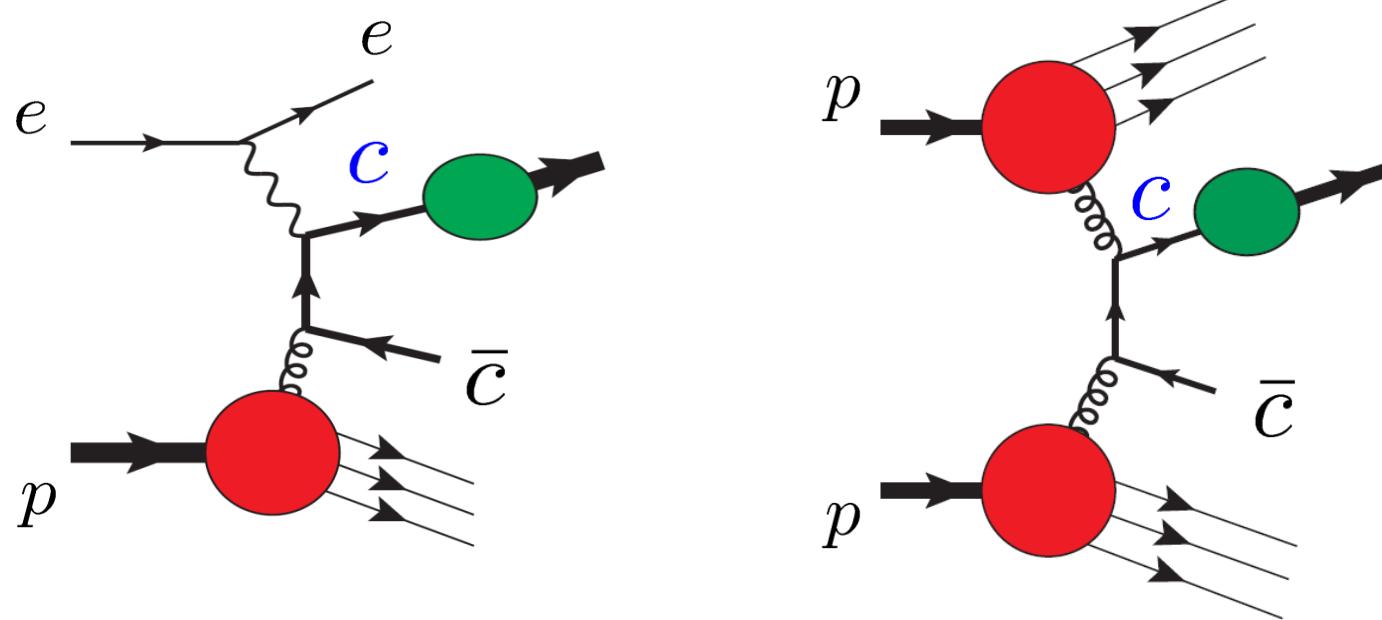
- The SSAs in the collinear approach have been well discussed at the leading-order level during the last couple of decades
- The fragmentation effect seems to dominate over the distribution
But the simulations rely on TMD inputs due to the lack of data in high- P_T
The Universality should be checked in other processes like ep^\uparrow collision
in EIC experiment
- There could be non-trivial contributions in higher-order
We need to develop the calculation technique in order to control
the higher-order corrections to the twist-3 cross section

Backup

2, SSAs in heavy meson production(role of gluon Sivers)

heavy quark production

Heavy quarks are mainly produced through gluon fusion.

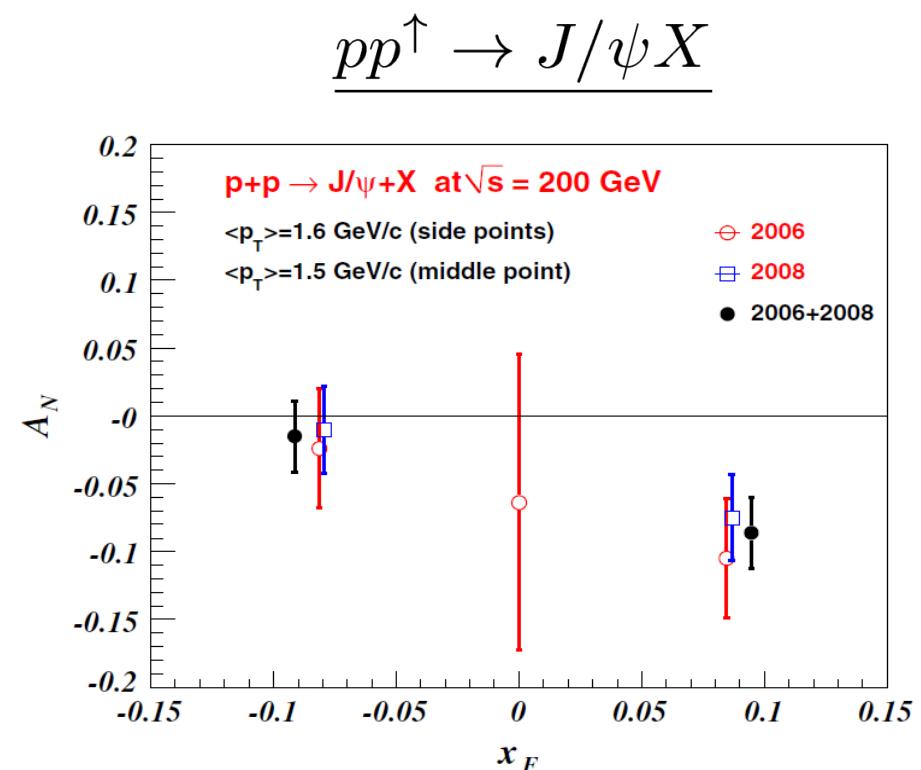
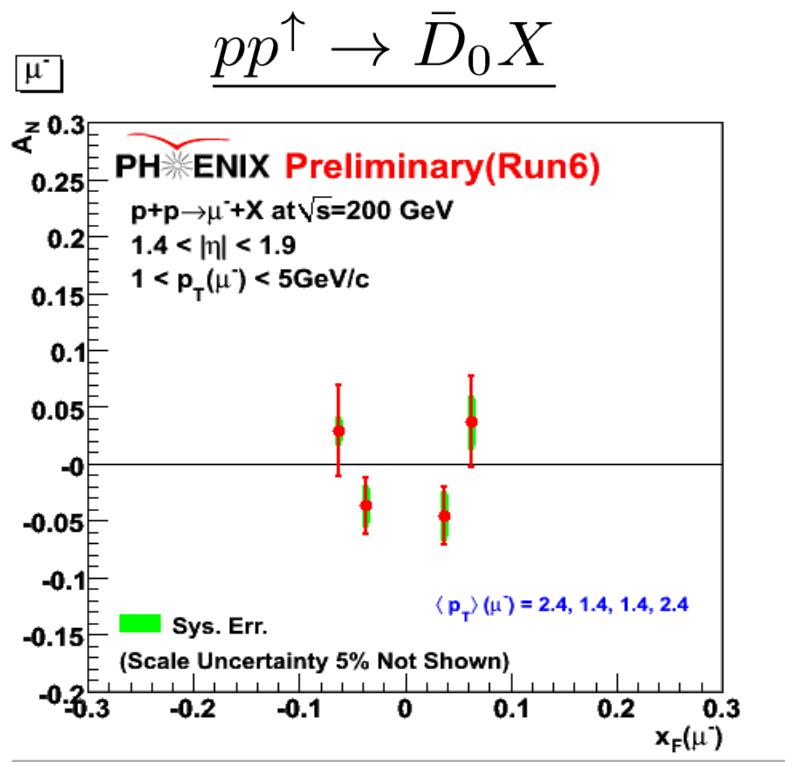


Heavy flavored meson productions reveal the gluon effects inside the initial proton.

$$D^0(c\bar{u}), \bar{D}^0(\bar{c}u), J/\psi(c\bar{c}), \dots$$

Experimental data

The PHENIX has reported the SSA data for the heavy meson productions.



PRD82('10) 112008

twist-3 gluon distribution

2 independent functions

Beppu, Koike, Tanaka and Yoshida, PRD82 (2010)

$$O(x_1, x_2), N(x_1, x_2)$$

One of them has a relation with the gluon Sivers function

Koike, Yabe and Yoshida, arXiv:1912.11199

$$f_{1T}^{\perp g(1)}(x) = -4\pi \left(N(x, x) - N(x, 0) \right)$$

SSAs for heavy meson productions in pp can give indirect information about the gluon Sivers function

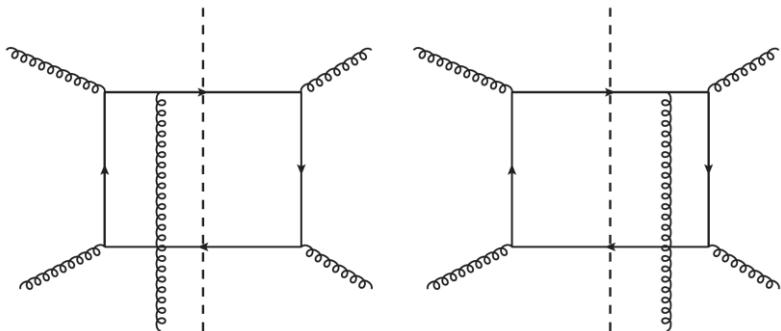
- LO cross sections for D -meson production
 - Kang and Qiu, Phys. Rev. D78 (2008)
 - Kang, Qiu, Vogelsang and Yuan, Phys. Rev. D78 (2008)
 - Beppu, Koike, Tanaka and Yoshida, PRD82 (2010)
 - Y. Koike and S. Yoshida, Phys. Rev. D84 (2011)
- LO cross sections for J/ψ production
 - Nothing!**

Problem in J/ψ

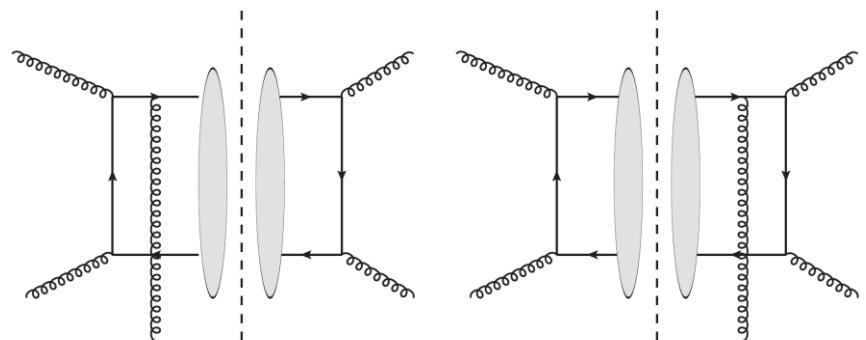
Twist-3 formula requires a relation

$$\frac{\partial}{\partial k_2^\alpha} H(k_1, k_2, q, \frac{P_h}{z}) \Big|_{k_i=x_ip} = - \frac{\partial}{\partial k_1^\alpha} H(k_1, k_2, q, \frac{P_h}{z}) \Big|_{k_i=x_ip}$$

D-meson



J/ψ (NRQCD)



Two diagrams are the same topologically

Left are right amplitudes are separated

We developed a new method to derive the twist-3 cross section

H. Xing and S. Yoshida, Phys. Rev. D100 (2019)

The above condition is not necessary

Twist-3 calculation for the J/ψ SSA is in progress