Single transverse-spin asymmetry in the forward and backward directions at RHIC

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4. Summary

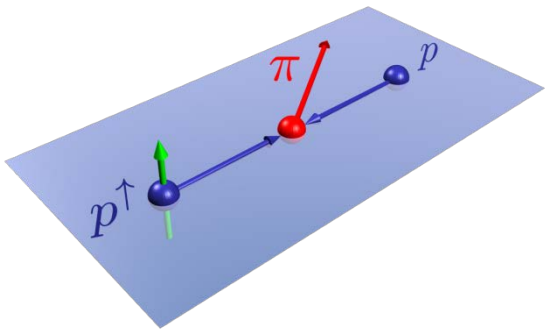
1. Introduction

⋆ Single spin asymmetry (SSA)

- $p^{\uparrow}p \to \pi X$ $\qquad A_N = \dfrac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}}$

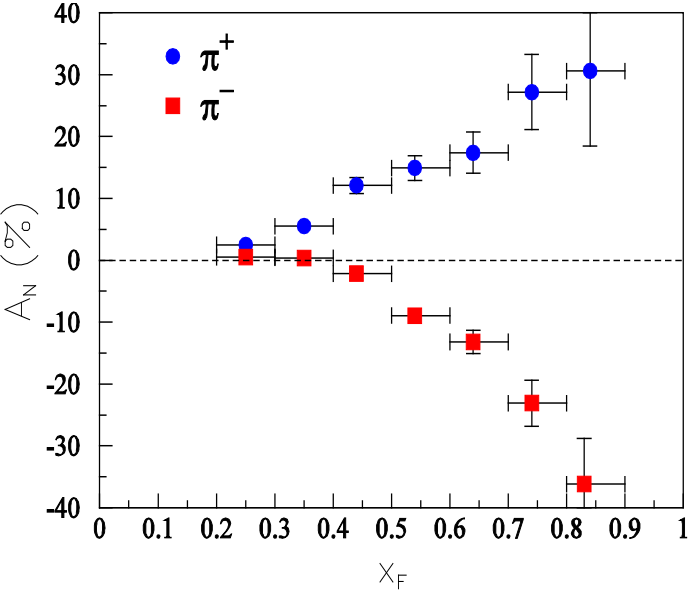
- FNAL-E704('91)($\sqrt{s} = 20$ GeV), RHIC($\sqrt{s} = 200$, 62 GeV):
  $A_N \sim 0.3$ at large $x_F = 2p_{\|}/\sqrt{s}$.

$x_F > 0$



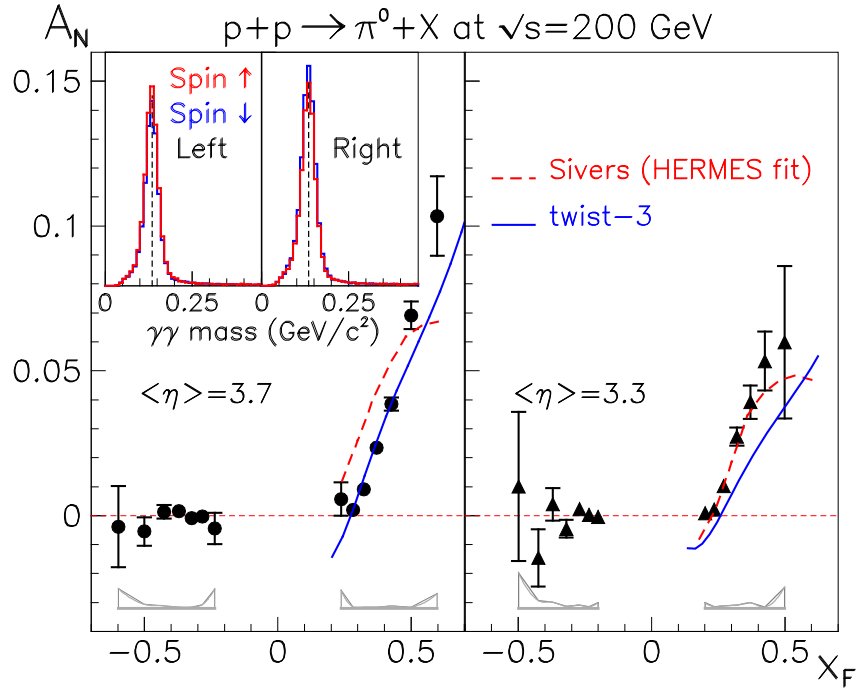
FNAL-E704

$\sqrt{s} = 20$ GeV



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

RHIC-STAR, PRL92('04)
hep-ex/0801.2990, PRL 101(2008)
$\sqrt{s} = 200$ GeV



⋆ QCD-mechanisms for SSA in the two regions of P_T

- Naively "T-odd" distribution/fragmentation functions (Sivers, Collins *etc*)

  · Describes SSA in the region of $\Lambda_{\rm QCD} \leq q_\perp \ll Q$ in the framework of TMD factorization.

  · TMD distributions are process dependent!

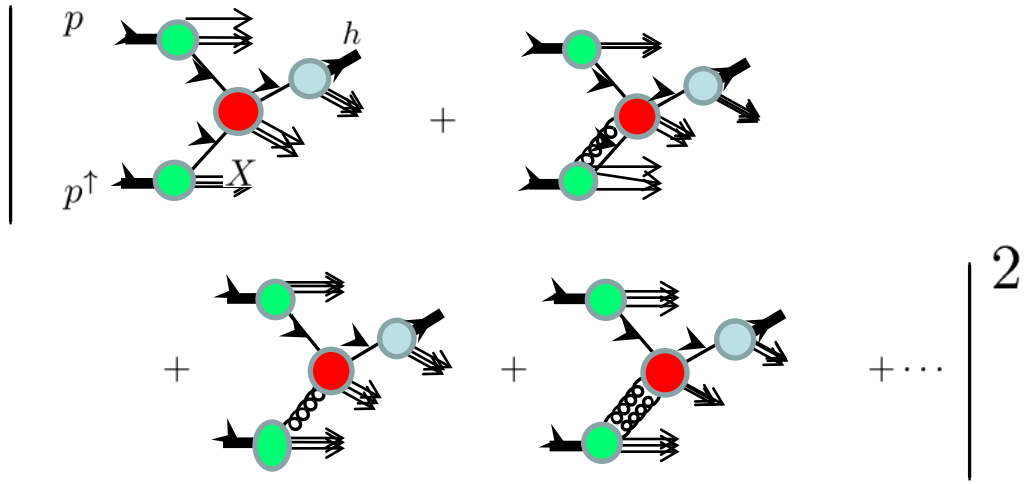
- Multi-parton correlation functions (quark-gluon, purely gluonic *etc*)
  (Efremov-Teryaev, Qiu-Sterman, Eguchi-YK-Tanaka,..)

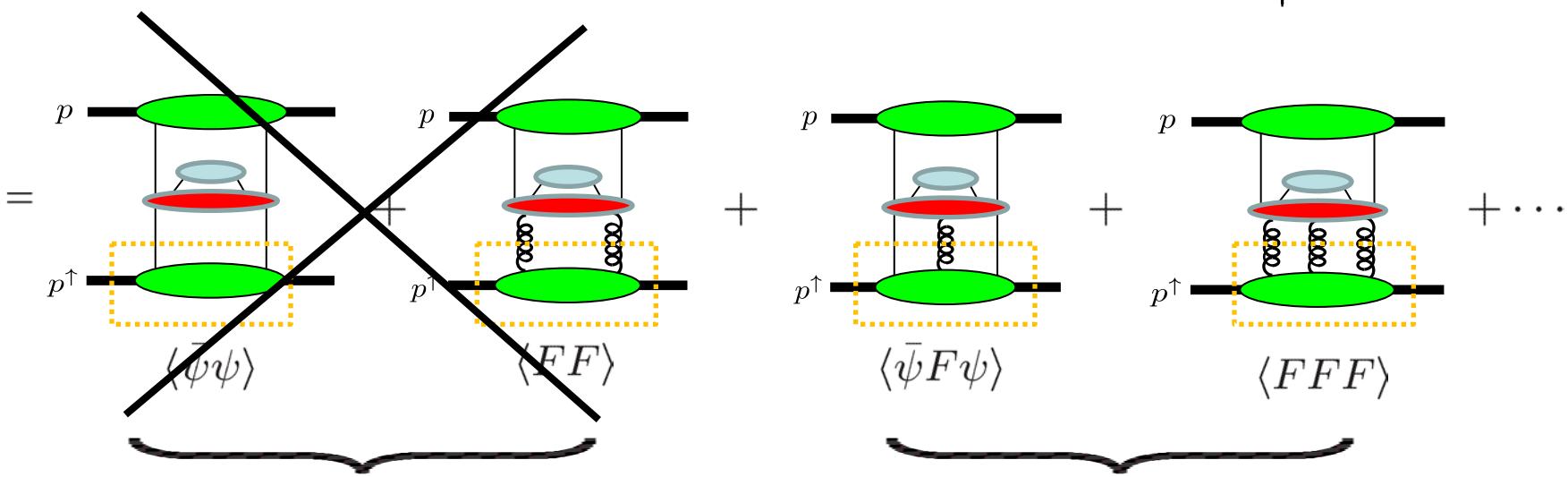
  · Describes SSA in the region of $q_\perp \sim Q \gg \Lambda_{\rm QCD}$ as a twist-3 observable in the framework of collinear factorization.

  · Multi-parton correlation functions are process-independent!

⋆ Inclusive cross section for $pp \to hX$

$$\sigma(p^{\uparrow}p \to hX) =$$





twist-2 ("parton model")

NO SSA

twist-3 ("multi-parton correlation")

SSA

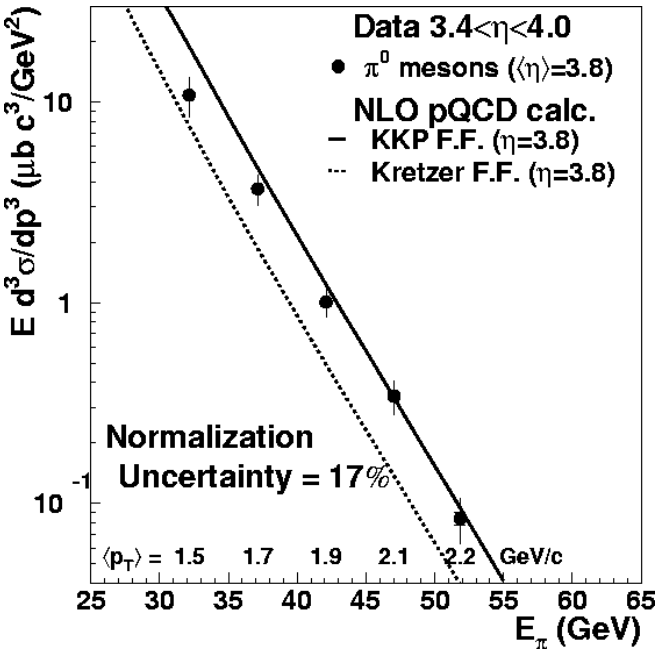
2. Twist-3 analysis/predition for SSA at RHIC based on the quark-gluon correlation functions

· Present the prediction/outcome for $p^{\uparrow}p \to (\eta, \gamma, \text{jet})X$, using our previous twist-3 analysis of the RHIC data on $p^{\uparrow}p \to (\pi, K)X$.

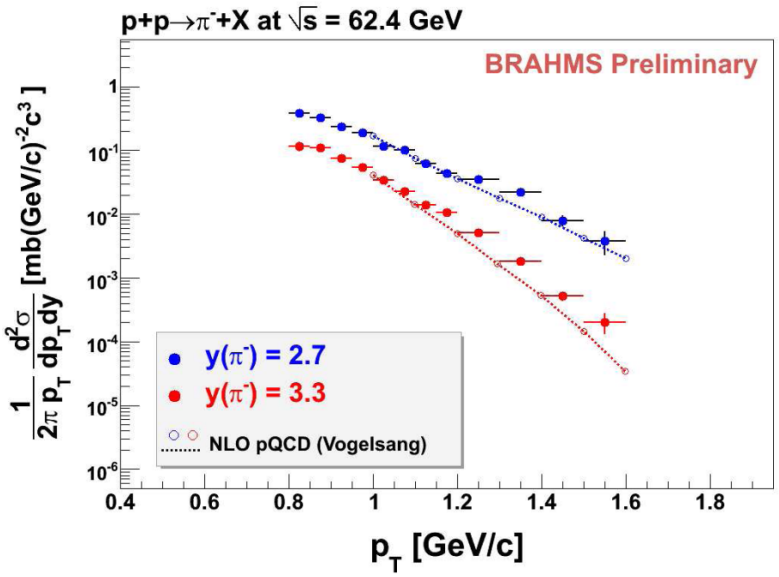
K. Kanazawa and YK, PRD82,034009 (2010), PRD83,114024 (2011), and in preparation.

· Unpolarized cross section can be well-described by NLO QCD in the collinear factorization at $P_T \geq 1$ GeV for RHIC data.

★ RHIC-STAR ('04)



★ RHIC-BRAHMS ('07)

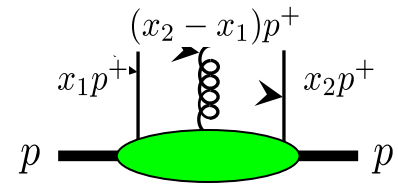


Theory calculation: Jäger, Schäfer, Stratmann, Vogelsang, PRD67,054005('03)

· RHIC + EIC (eRHIC) provides us with a good opportunity to understand SSA in terms of the twist-3 mechanism.

⋆ Quark-gluon correlation functions in the ⊥ polarized nucleon.

$$\int \frac{d\lambda}{2\pi} \int \frac{d\mu}{2\pi} e^{i\lambda x_1} e^{i\mu(x_2-x_1)} \langle PS|\bar{\psi}_j(0) g F^{\alpha\beta}(\mu n) n_\beta \psi_i(\lambda n)|PS\rangle$$
$$= \frac{M_N}{4} (\not{p})_{ij}\, \epsilon^{\alpha p n S_\perp} G_F(x_1,x_2) + i\frac{M_N}{4} (\gamma_5 \not{p})_{ij}\, S_\perp^\alpha \widetilde{G}_F(x_1,x_2) + \cdots$$



M_N: Nucleon mass.

$p^2 = n^2 = 0,\ p\cdot n = 1$

- Symmetry property from P- and T- invariance.

$$G_F(x_1,x_2) = G_F(x_2,x_1), \qquad \widetilde{G}_F(x_1,x_2) = -\widetilde{G}_F(x_2,x_1)$$

⋆ The twist-3 contribution to SSA can be expressed in terms of $\left\{G_F(x_1,x_2), \widetilde{G}_F(x_1,x_2)\right\}$.

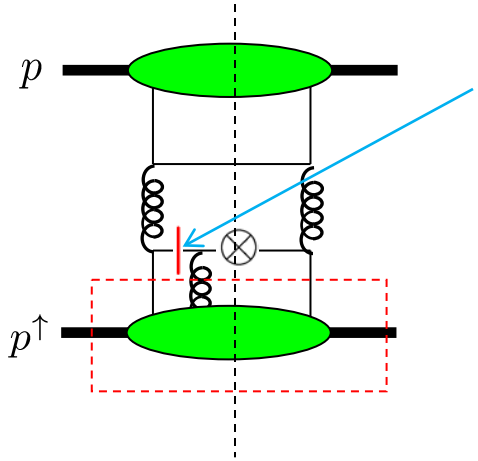
(Factorization and Gauge invariance proved in LO QCD.)

(Eguchi, YK, Tanaka, NPB763('07)198.)

· Cross section from the twist-3 distributions occurs as pole contributions in the hard part.

"Complex phase" is given by this imaginary part!

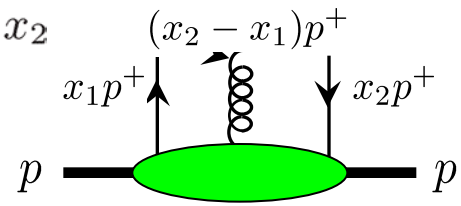
$p^\uparrow p \to \pi X$

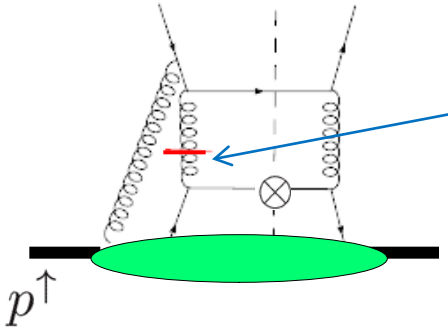


The pole of this propagator sets $x_1 = x_2$

$\to$soft-gluon-pole (SGP)

$\to G_F(x,x)$ (Note: $\widetilde{G}_F(x,x) \equiv 0$)





This pole sets $x_1 = 0$.

$\to$ Soft-fermion-pole (SFP).

$\to G_F(x,0)$ and $\widetilde{G}_F(x,0)$

⋆ Description of RHIC data

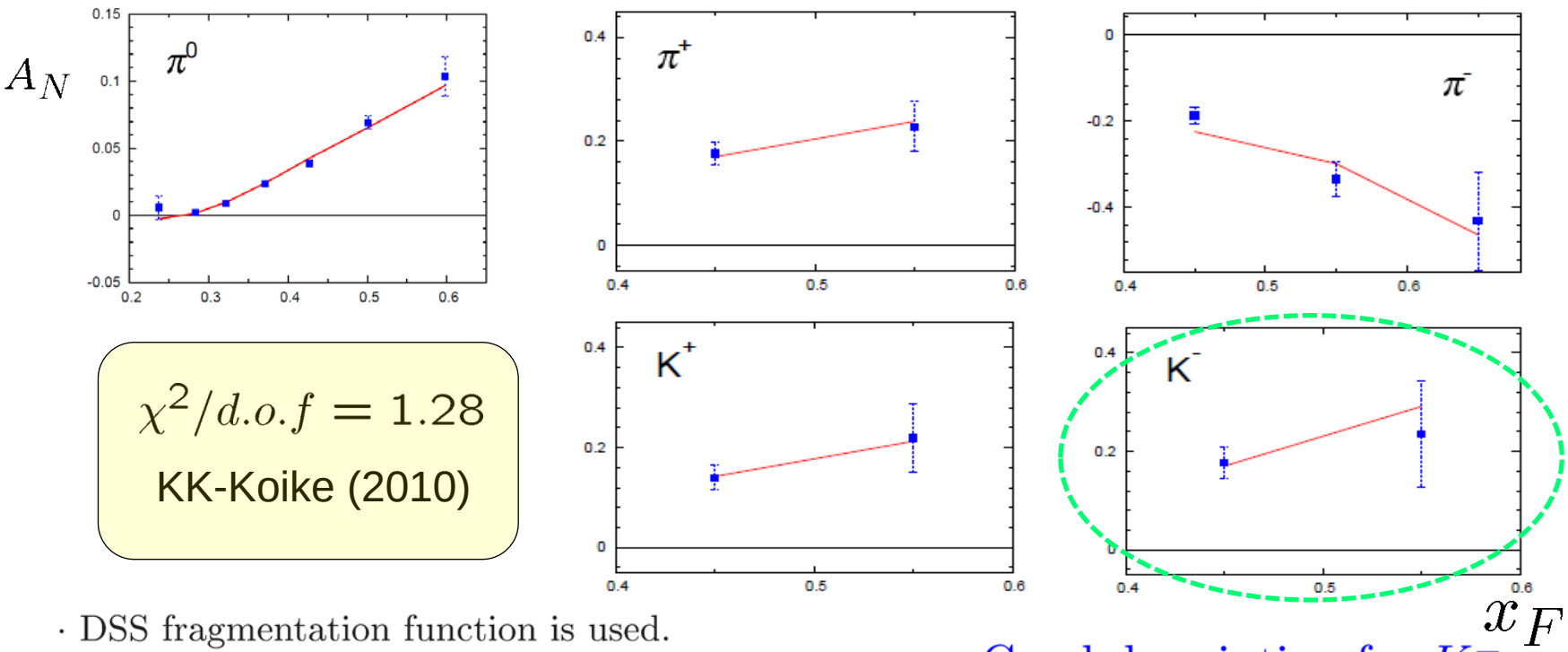
K. Kanazawa and YK, PRD82,034009 (2010), PRD83,114024 (2011)

- Inclusion of all contributions from the quark-gluon correlation functions.

$$\Delta\sigma \sim \{\hat{\sigma}_{\mathsf{SGP}} \otimes \left(G_F(x,x) - x\frac{dG_F(x,x)}{dx}\right) + \hat{\sigma}_{\mathsf{SFP}} \otimes \left(G_F(0,x) + \tilde{G}_F(0,x)\right)\} \otimes f(x') \otimes D(z)$$

Kouvaris-Qiu-Vogelsang-Yuan (2006) Koike-Tomita (2009)

- Reasonable description of SSA for pions and kaons with this formula:



$\chi^2/d.o.f = 1.28$

KK-Koike (2010)

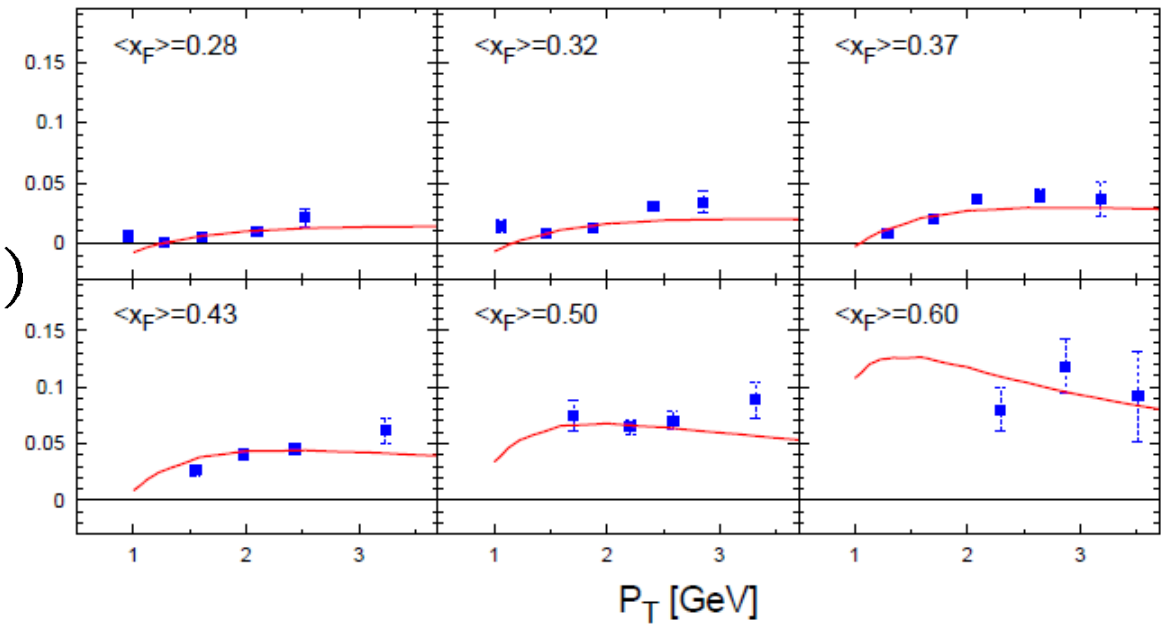
· DSS fragmentation function is used.
(de Florian *el al*, PRD75(2007)114010)

Good description for K^-

SFP is also important!

⋆ Comparison of P_T-dependence with the STAR result.

$A_N(\pi^0)$



★ STAR (2008)

PT dependence is well reproduced :

$$A_N^{\text{tw3}} = \frac{\Delta\sigma^{\text{tw3}}}{\sigma^{\text{unp}}} \sim \mathcal{O}\left(\frac{M_N}{Q}\right) \otimes \frac{N_q(P_T^2) - N_g(P_T^2)}{D_q(P_T^2) + D_g(P_T^2)}$$

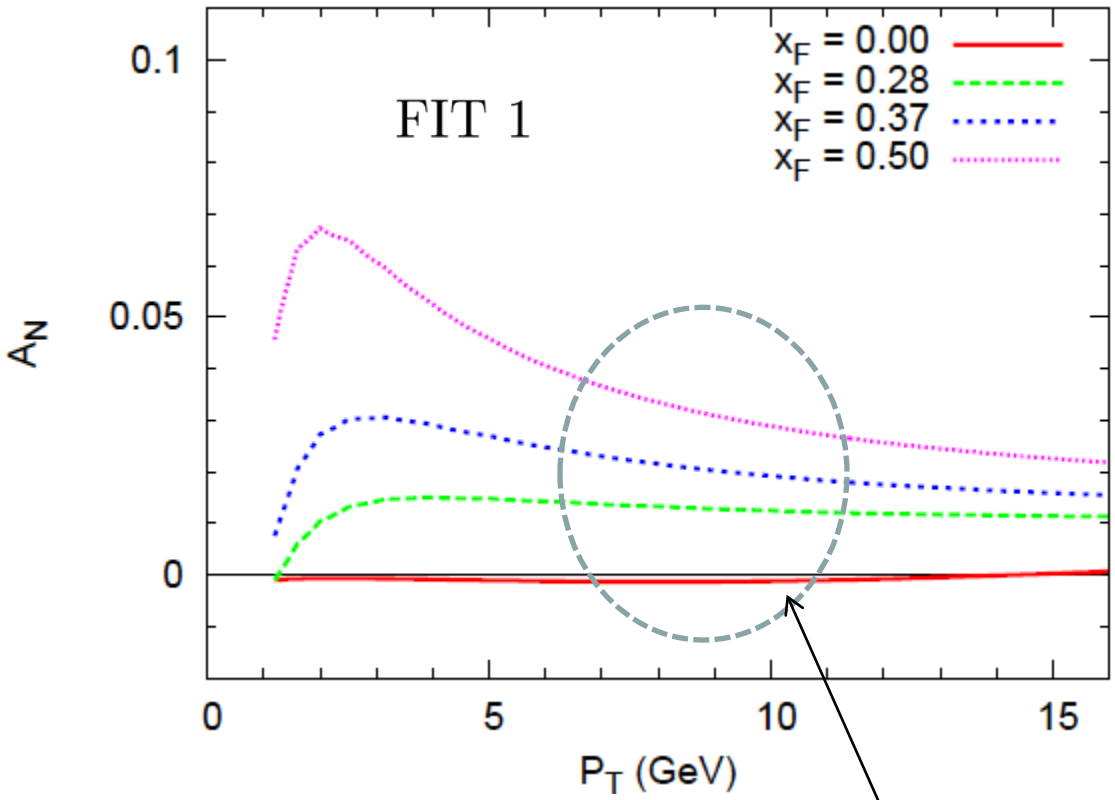
rapid decrease of $N_g(P_T^2)$ and $D_g(P_T^2)$ is crucial. (DSS FF)

$D_q,\ N_q(>0)$ from quark-frag. channel
$D_g,\ N_g(>0)$ from gluon-frag. channel

at low P_T, $\begin{cases} \Delta\sigma^{\text{tw3}} \text{ decrease } \textit{slowly} \\ \sigma^{\text{unp}} \text{ decrease } \textit{rapidly} \end{cases}$ as a function of $P_T(=Q)$.

$\Rightarrow$ A_N slightly increase at low P_T.

⋆ P_T-dependence of $A_N^{\pi^0}$ at large P_T region for various x_F.



$$A_N \sim O\left(\frac{M_N P_T}{-T}\right) + O\left(\frac{M_N P_T}{-U}\right)$$

$$T = -\frac{S}{2}\left(\sqrt{x_T^2 + x_F^2} - x_F\right)$$

$$U = -\frac{S}{2}\left(\sqrt{x_T^2 + x_F^2} + x_F\right)$$

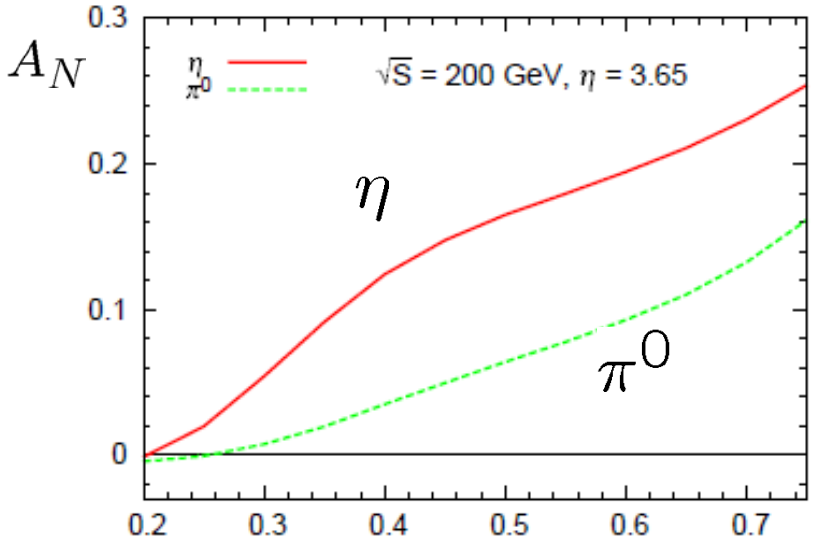
At $x_F \gg x_T$:

$$-T \to P_T^2/x_F$$

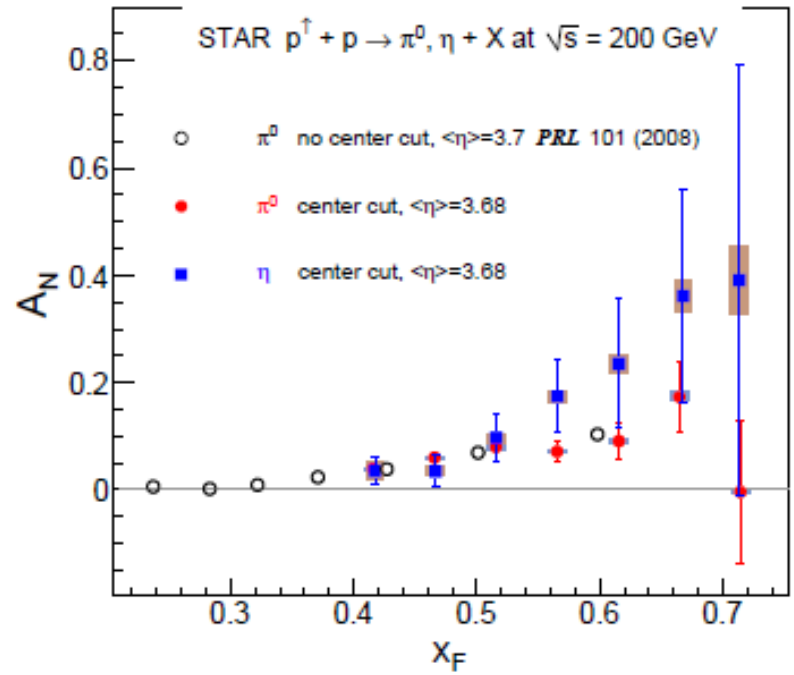
$$-U \to x_F S$$

Does not fall off as fast as $1/P_T$
by the coexistence of two terms.

⋆ Prediction of A_N for the η-meson production.



STAR, arXiv:1205.6826[nucl-ex]



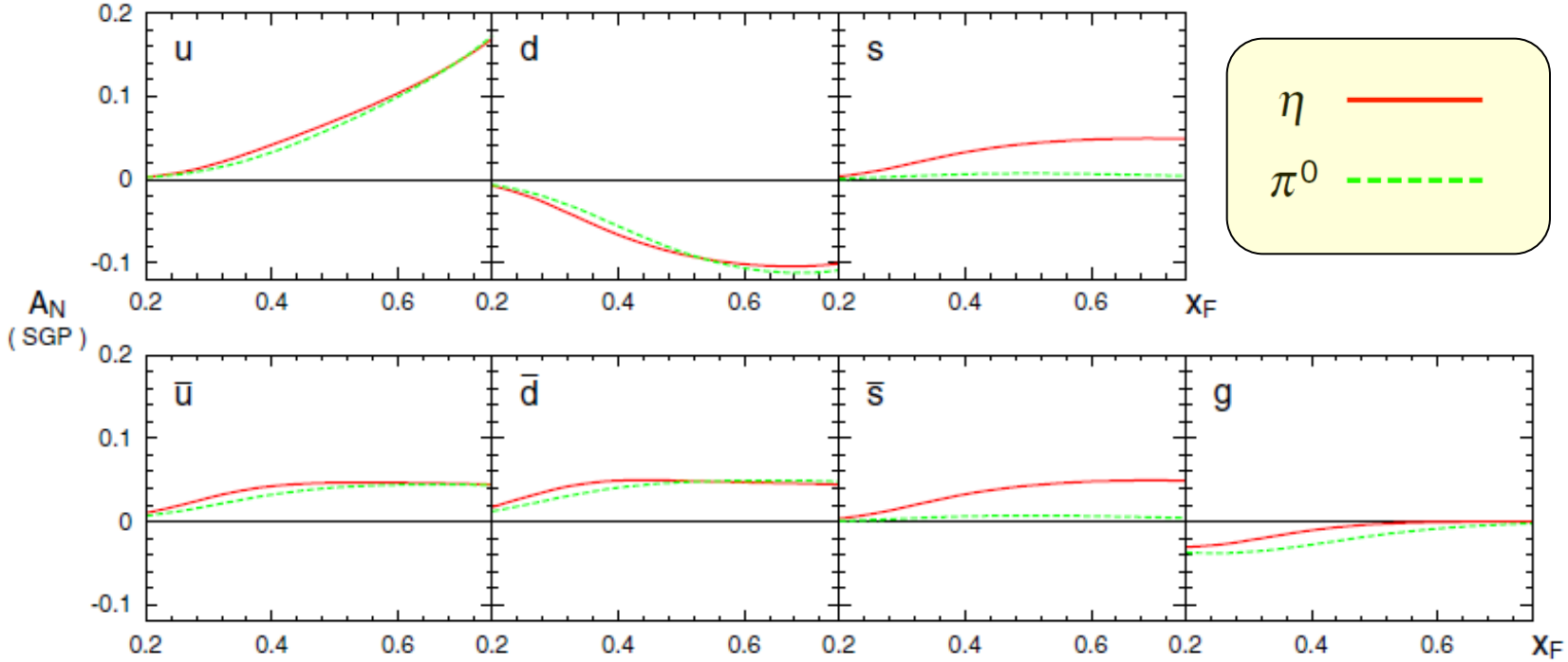
- Calculated A_N^η is consistent with the STAR data.

  - $A_N^\eta > A_N^{\pi^0}$ is due to the $\langle \bar{s} F^{+\perp} s \rangle$ in $p^\uparrow$ and the larger strangeness component in the η fragmentation function (Aidala *et al.*,PRD83,034002(2011).

- Caveat: Our analysis does not include the contribution from the 3-gluon correlation functions and the twist-3 fragmentation function.

⋆ Origin of the difference between π and η

★ Decomposition of the asymmetries into *each fragmentation channel*

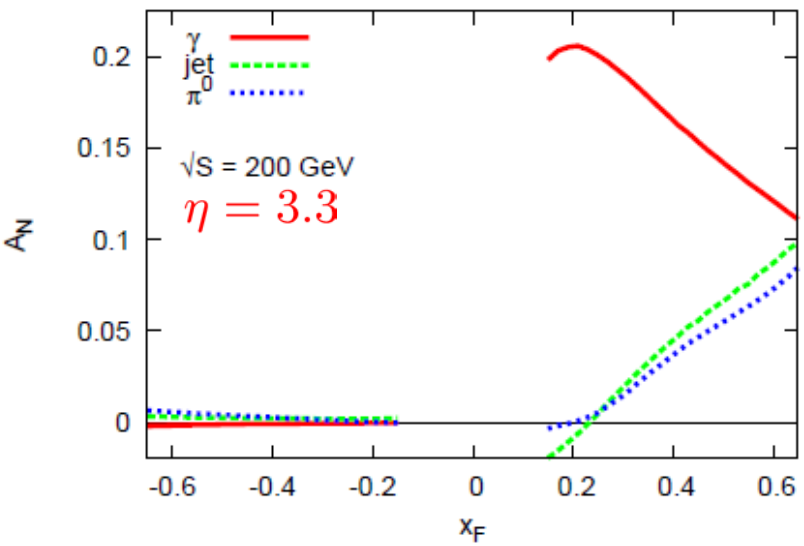


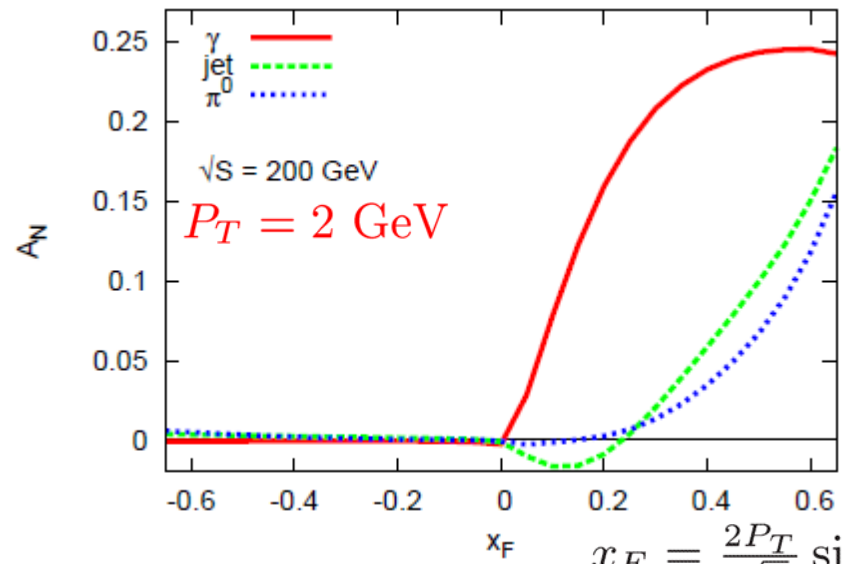
- The difference comes from the strange components.

⋆ A_N for $p^\uparrow p \to \gamma X$ and $p^\uparrow p \to \text{jet}X$.

No contribution from the twist-3 fragmentation function!

(Kang, Qiu, Vogelsang, Yuan, Phys. Rev. D **83** (2011) 094001)





$x_F = \frac{2P_T}{\sqrt{S}} \sinh \eta$

· SGP contributions dominate for all these processes.

· Color factors for the polarized $\Delta\hat{\sigma}$ are much smaller for $\Delta\hat{\sigma}^{\pi,\text{jet}}$ compared with $\Delta\hat{\sigma}^{\gamma}$ relative to the unpolarized $\hat{\sigma}$.

· In $\Delta\hat{\sigma}^{\pi,\text{jet}}$, FSI dominates at large x_F due to the kinematic factor $\hat{s}/\hat{t}$.

$\leftrightarrow$ Only ISI exists in $\Delta\hat{\sigma}^{\gamma}$.

· A_N^{γ} is caused through $\Delta\hat{\sigma}^{qg\to q\gamma}$, while $A_N^{\pi,\text{jet}}$ is caused through $\Delta\hat{\sigma}^{qg\to qg}$ and $\Delta\hat{\sigma}^{qg\to gq}$.

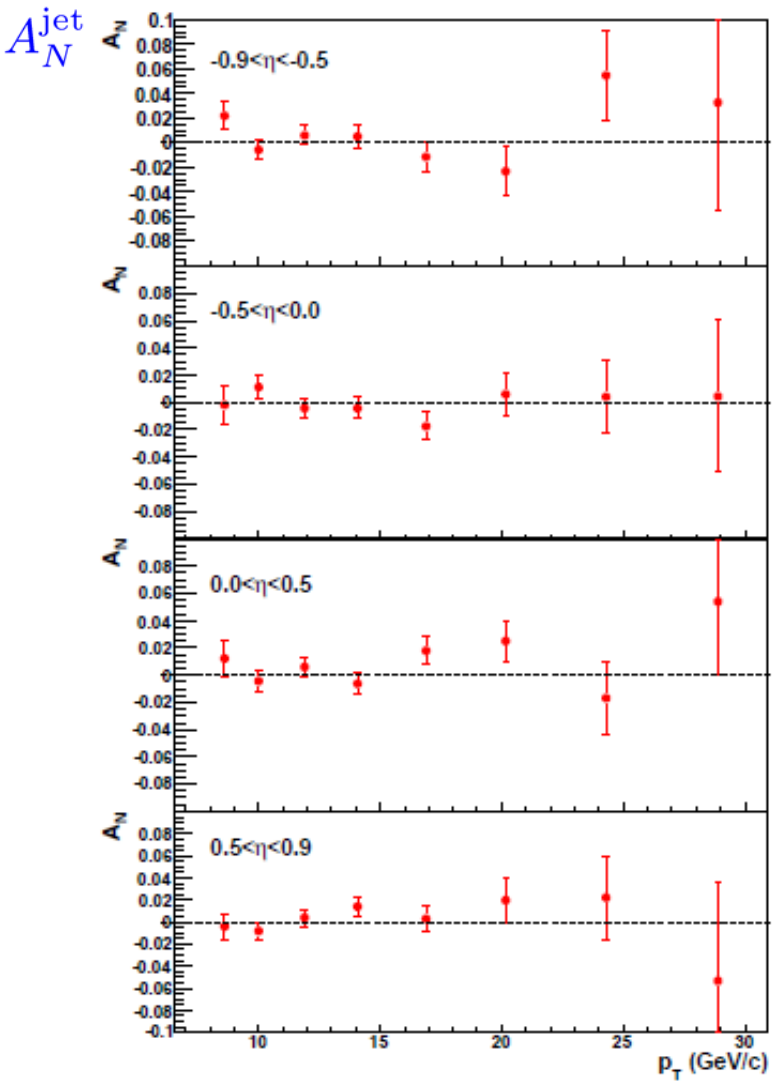
$\Rightarrow$ Different behaviors for A_N^{γ} and $A_N^{\text{jet},\pi}$.

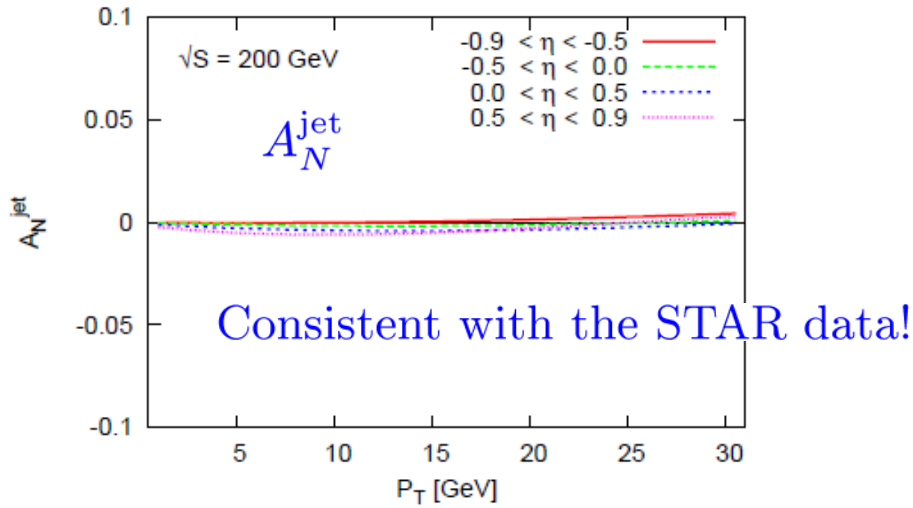
· Quark-gluon correlations give $A_N^{\gamma,\text{jet},\pi} \simeq 0$ at $x_F < 0$.

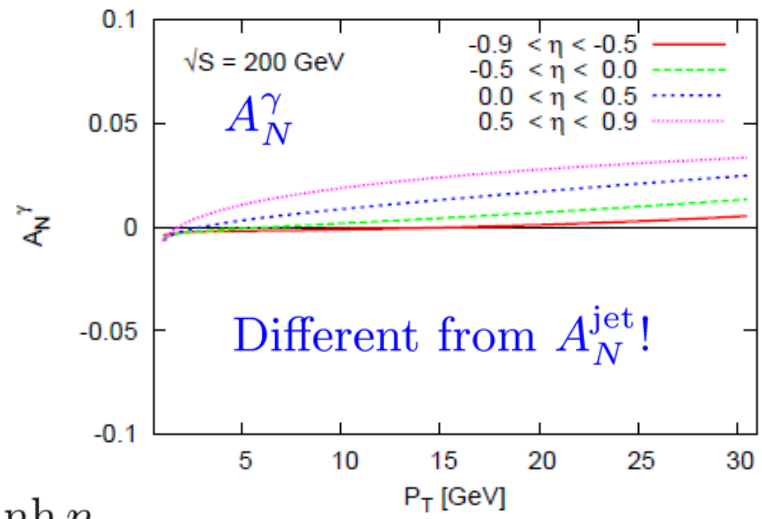
$\Rightarrow$ 3-gluon correlation can be the only source of $A_N^{\text{jet},\gamma}$ at $x_F < 0$. (See next)

⋆ P_T-dependence of $A_N^{\mathrm{jet},\gamma}$ (η-integrated)

RHIC-STAR, arXiv:1205.2735[nucl-ex]

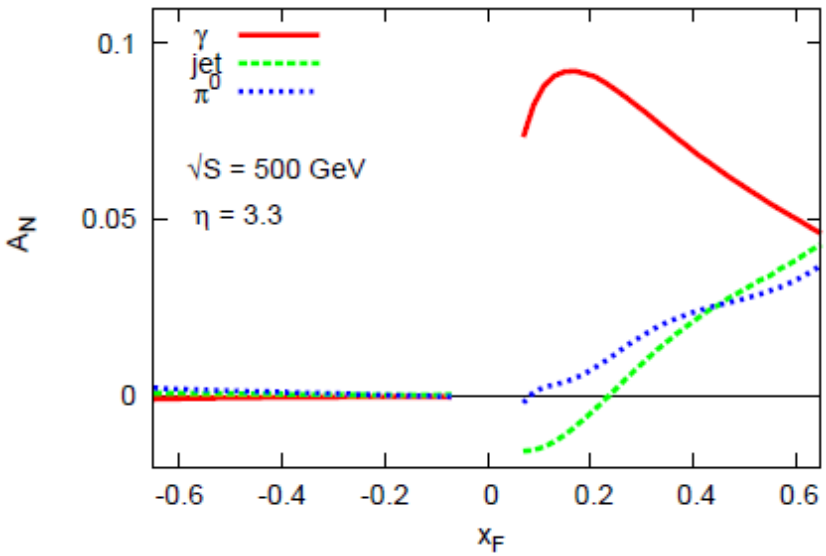


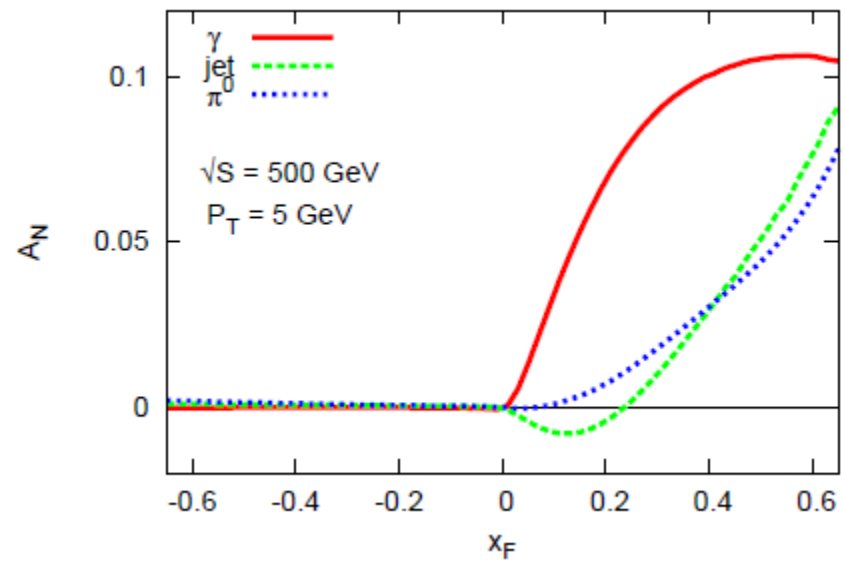


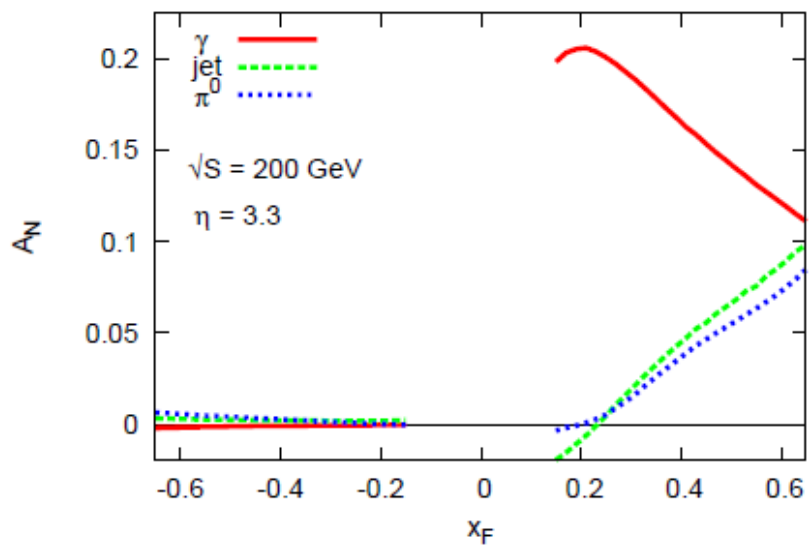


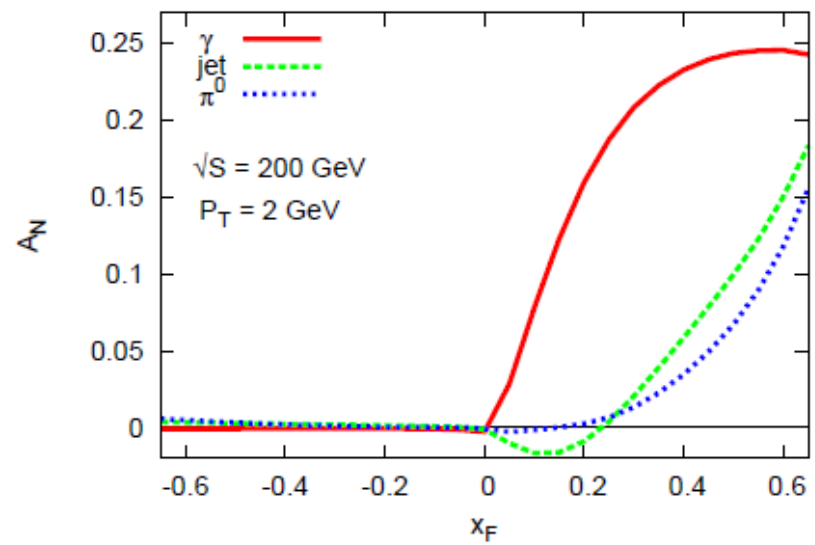
$$x_F = \frac{2P_T}{\sqrt{S}} \sinh \eta$$

$\star$ A_N for $\sqrt{S} = 500$ GeV vs. $\sqrt{S} = 200$ GeV $\quad A_N(500\,\text{GeV}) \simeq 0.5 A_N(200\,\text{GeV})$









3. Multi-gluon contribution to SSA.

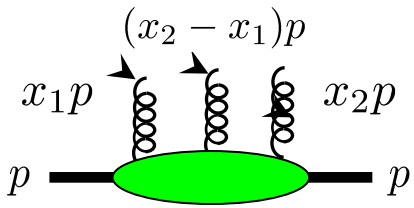
· See the impact of the 3-gluon correlation function on $p^{\uparrow}p \to (\gamma, \pi)X$ using the parametrization for $p^{\uparrow}p \to DX$.

For the formalism, see (for $ep^{\uparrow} \to eDX$):
H.Beppu, YK, T. Tanaka, S. Yoshida, PRD 82(2010)054005,(arXiv:1007.2034)
YK, T. Tanaka, S.Yoshida, PRD 83(2011)114014 (arXiv:1104.0798) .

For earlier works, see

Kang-Qiu (PRD 78('08)034005), Kang-Qiu-Vogelsang-Yuan (PRD 78('08)114013)

⋆ Twist-3 "three-gluon" correlation functions



Beppu-Koike-Tanaka-Yoshida (PRD 82('10)054005)

See also, Belitsky-Ji-Lu-Osborne, PRD63,094012(2001)
Braun-Manashov-Pirnay, PRD80,114002(2009).

-Two independent correlation functions $O(x_1, x_2)$ and $N(x_1, x_2)$ due to Hermiticity, PT-invariance and Permutation symmetry

$$O^{\alpha\beta\gamma}(x_1, x_2) = -gi^3 \int \frac{d\lambda}{2\pi} \int \frac{d\mu}{2\pi} e^{i\lambda x_1} e^{i\mu(x_2 - x_1)} \langle pS | d^{bca} F_b^{\beta n}(0) F_c^{\gamma n}(\mu n) F_a^{\alpha n}(\lambda n) | pS \rangle$$

$$= 2iM_N \left[O(x_1, x_2) g^{\alpha\beta} \epsilon^{\gamma pnS} + O(x_2, x_2 - x_1) g^{\beta\gamma} \epsilon^{\alpha pnS} + O(x_1, x_1 - x_2) g^{\gamma\alpha} \epsilon^{\beta pnS} \right]$$

$$N^{\alpha\beta\gamma}(x_1, x_2) = -gi^3 \int \frac{d\lambda}{2\pi} \int \frac{d\mu}{2\pi} e^{i\lambda x_1} e^{i\mu(x_2 - x_1)} \langle pS | i f^{bca} F_b^{\beta n}(0) F_c^{\gamma n}(\mu n) F_a^{\alpha n}(\lambda n) | pS \rangle$$

$$= 2iM_N \left[N(x_1, x_2) g^{\alpha\beta} \epsilon^{\gamma pnS} - N(x_2, x_2 - x_1) g^{\beta\gamma} \epsilon^{\alpha pnS} - N(x_1, x_1 - x_2) g^{\gamma\alpha} \epsilon^{\beta pnS} \right].$$

$F_a^{\alpha n} \equiv F_a^{\alpha\mu} n_\mu$ $\quad$ n: lightlike vector satisfying $p \cdot n = 1$.

$\epsilon^{\gamma pnS} \equiv \epsilon^{\gamma\mu\nu\lambda} p_\mu n_\nu S_\lambda$ etc. $\quad$ Gauge-links suppressed above.

$p^{\uparrow}p \to DX$

YK, S.Yoshida, PRD84(2011)014026 (arXiv:1104.3943 [hep-ph]).

$\star$ Three-gluon contribution to $p^{\uparrow}(p) + p(p') \to D(P_h) + X$

$$P_h^0 \frac{d\sigma^{3\text{gluon}}}{d^3 P_h} = \frac{\alpha_s^2 M_N \pi}{S} \epsilon^{P_h p n S_\perp} \sum_{f=c\bar{c}} \int \frac{dx'}{x'} G(x') \int \frac{dz}{z^3} D_a(z) \int \frac{dx}{x} \delta\left(\tilde{s} + \tilde{t} + \tilde{u}\right) \frac{1}{\tilde{u}}$$

$$\times \left[\delta_f \left\{ \left(\frac{d}{dx} O(x,x) - \frac{2O(x,x)}{x} \right) \hat{\sigma}^{O1} + \left(\frac{d}{dx} O(x,0) - \frac{2O(x,0)}{x} \right) \hat{\sigma}^{O2} + \frac{O(x,x)}{x} \hat{\sigma}^{O3} + \frac{O(x,0)}{x} \hat{\sigma}^{O4} \right\} \right.$$

$$\left. + \left\{ \left(\frac{d}{dx} N(x,x) - \frac{2N(x,x)}{x} \right) \hat{\sigma}^{N1} + \left(\frac{d}{dx} N(x,0) - \frac{2N(x,0)}{x} \right) \hat{\sigma}^{N2} + \frac{N(x,x)}{x} \hat{\sigma}^{N3} + \frac{N(x,0)}{x} \hat{\sigma}^{N4} \right\} \right].$$

$$\tilde{s} = (xp + x'p')^2 \qquad \tilde{t} = (p_c - xp)^2 - m_c^2 \qquad \tilde{u} = (p_c - x'p')^2 - m_c^2,$$

$\delta_c = 1$ (D-meson) and $\delta_{\bar{c}} = -1$ ($\bar{D}$-meson) $\qquad p_c = \frac{P_h}{z}$

· Receives derivative contributions from $O(x,x), O(x,0), N(x,x), N(x,0)$.

· O-function contributes to D and $\bar{D}$ with opposite signs.

· 4 hard cross sections for the derivative terms are dominant and have similar magnitude (at RHIC energy): $\hat{\sigma}^{O1} \simeq \hat{\sigma}^{O2} \sim \hat{\sigma}^{N1} \simeq -\hat{\sigma}^{N2}$ ($\gg \hat{\sigma}^{O3}, \hat{\sigma}^{N3}, \hat{\sigma}^{O4}, \hat{\sigma}^{N4}$).

· At $m_c \to 0$, one has $\hat{\sigma}^{O1} = \hat{\sigma}^{O2}$ and $\hat{\sigma}^{N1} = -\hat{\sigma}^{N2}$ and $\hat{\sigma}^{O3,O4,N3,N4} = 0$.

At the RHIC energy the cross section can be approximated as

$$P_h^0 \frac{d\sigma^{3\text{gluon}}}{d^3 P_h} \simeq \frac{\alpha_s^2 M_N \pi}{S} \epsilon^{P_h p n S_\perp} \sum_{f=c\bar{c}} \int \frac{dx'}{x'} G(x') \int \frac{dz}{z^3} D_a(z) \int \frac{dx}{x} \delta\left(\tilde{s} + \tilde{t} + \tilde{u}\right) \frac{1}{\tilde{u}}$$
$$\times \left[\delta_f \left(\frac{d}{dx} O(x) - \frac{2O(x)}{x} \right) \hat{\sigma}^{O1} + \left(\frac{d}{dx} N(x) - \frac{2N(x)}{x} \right) \hat{\sigma}^{N1} \right].$$

where $O(x) \equiv O(x,x) + O(x,0)$, $N(x) \equiv N(x,x) - N(x,0)$.

NB. For Drell-Yan and SIDIS (with large Q^2), the results are not simplied like this.

⋆ Model calculation of A_N^D

Ansatz: $O(x) = \pm N(x)$

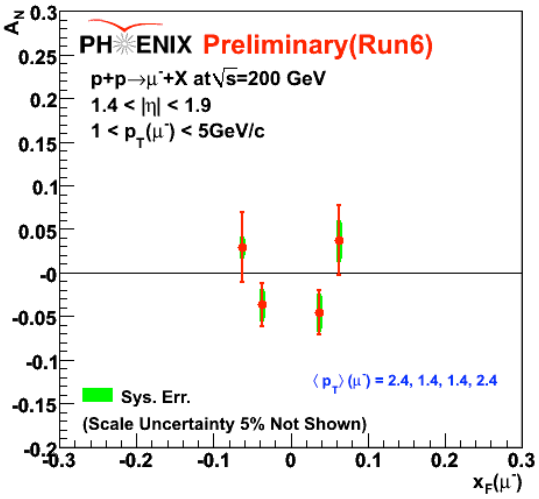
Two models for the functions with constant K_G, K'_G.

$$\begin{cases} \text{Model 1: } O(x) = K_G \times x\,G(x) \\ \text{Model 2: } O(x) = K'_G \times \sqrt{x}\,G(x) \end{cases}$$

· $G(x)$:unpolarized gluon distribution function
Gluck, Jimenez-Delgado, Reya Eur.phys.J.C53(2008)

· D-meson fragmentation function by
KKKS (Kneesh *et al.* NPB799('08)34)

A_N for $p^{\uparrow}p \to \bar{D}X$

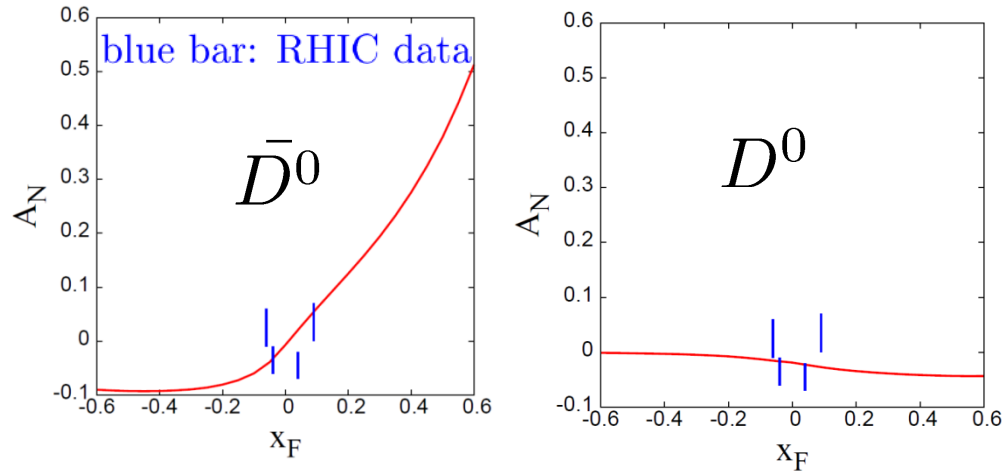


⋆ We determine K_G, K'_G so that A_N is consistent with the RHIC preliminary data.

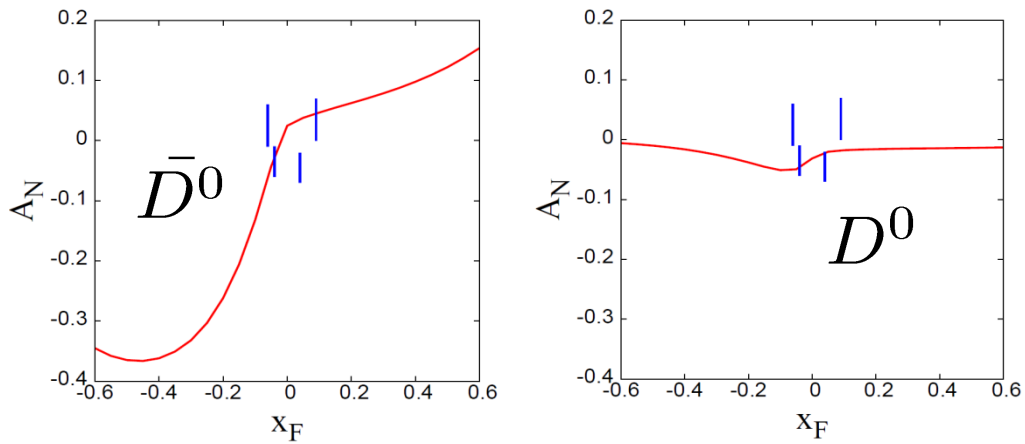
$\star$ $O(x) = -N(x)$ case @ $\sqrt{S} = 200$ GeV, $P_T = 2$ GeV

Cancellation between $O(x)$ and $N(x)$ for D!

Model 1:
$O(x) = 0.004xG(x)$



Model 2:
$O(x) = 0.001\sqrt{x}G(x)$



· If $O(x)$ and $N(x)$ do not cancel, A_N rises at large x_F by the derivative contribution.

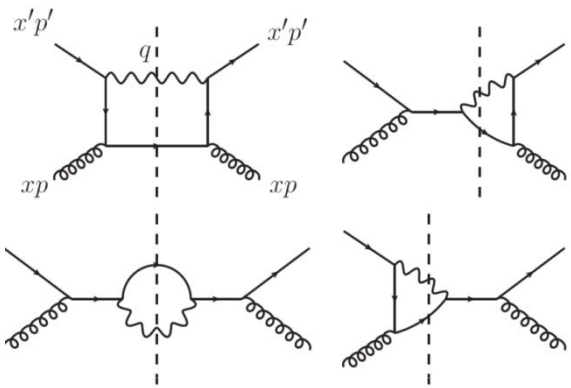
· A_N at $x_F < 0$ strongly depends on the small-x behavior of 3-gluon correlation function.

Direct photon production: $p^{\uparrow}p \to \gamma X$

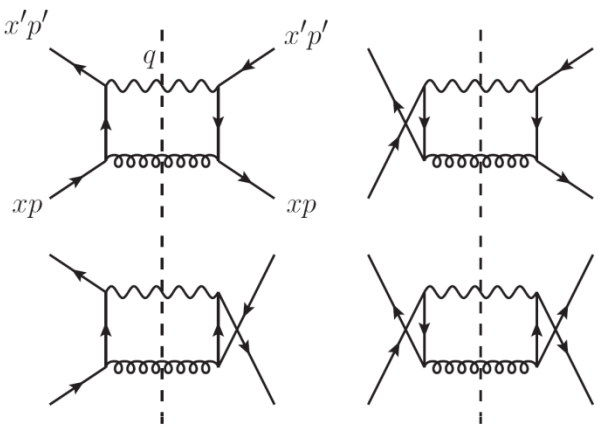
YK and Yoshida, Phys. Rev. D **85** (2012) 034030

⋆ LO diagrams for $p^{\uparrow}(p,S) + p(p') \to \gamma(q) + X$

Twist-2(unpolarized cross section)



$gq \to \gamma q$

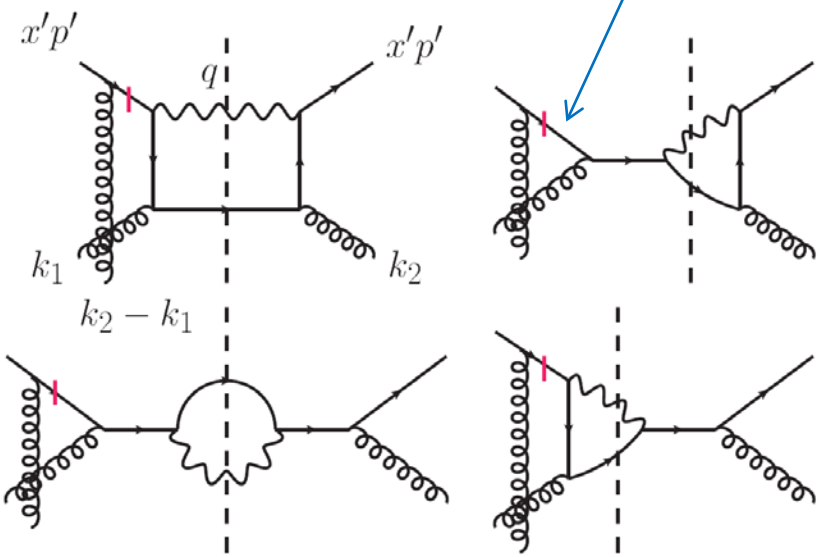


$q\bar{q} \to \gamma g$

Twist-3(polarized cross section)

initial state interaction

pole at $x_1 = x_2$



+ mirrors

⋆ Three-gluon contribution to $p^{\uparrow}(p) + p(p') \to \gamma(q) + X$.

$\hat{s} = (xp + x'p')^2$,
$\hat{t} = (xp - q)^2$,
$\hat{u} = (x'p' - q)^2$

$$E_\gamma \frac{d\sigma}{d^3q} = \frac{4\alpha_{em}\alpha_s M_N \pi}{S} \sum_a e_a^2 \int \frac{dx'}{x'} f_a(x') \int \frac{dx}{x} \delta(\hat{s} + \hat{t} + \hat{u}) \epsilon^{qpnS_\perp} \frac{1}{\hat{u}}$$

$$\times \left[\delta_a \left(\frac{d}{dx} O(x) - \frac{2O(x)}{x} \right) - \left(\frac{d}{dx} N(x) - \frac{2N(x)}{x} \right) \right] \left(\frac{1}{N} \left(\frac{\hat{s}}{\hat{u}} + \frac{\hat{u}}{\hat{s}} \right) \right)$$

$$O(x) \equiv O(x,x) + O(x,0)$$
$$N(x) \equiv N(x,x) - N(x,0)$$

The same as twist-2 cross section
(also from master formula!)
(YK,Tanaka,Yoshida,('11))

$\delta_a = 1$ for a =quark, $\delta_a = -1$ for a =anti-quark.

$\hat{s} = (xp + x'p')^2$, $\hat{t} = (xp - q)^2$, $\hat{u} = (x'p' - q)^2$

· This differs from the previous study (X. Ji, Phys.lett.B289 ('92)137).

· If $O(x) \simeq N(x)$, quarks in the unpolarized nucleon are NOT active. $\to$ Small A_N^γ.

· If $O(x) \simeq -N(x)$, quarks in the unpolarized nucleon are active. $\to$ Large A_N^γ.

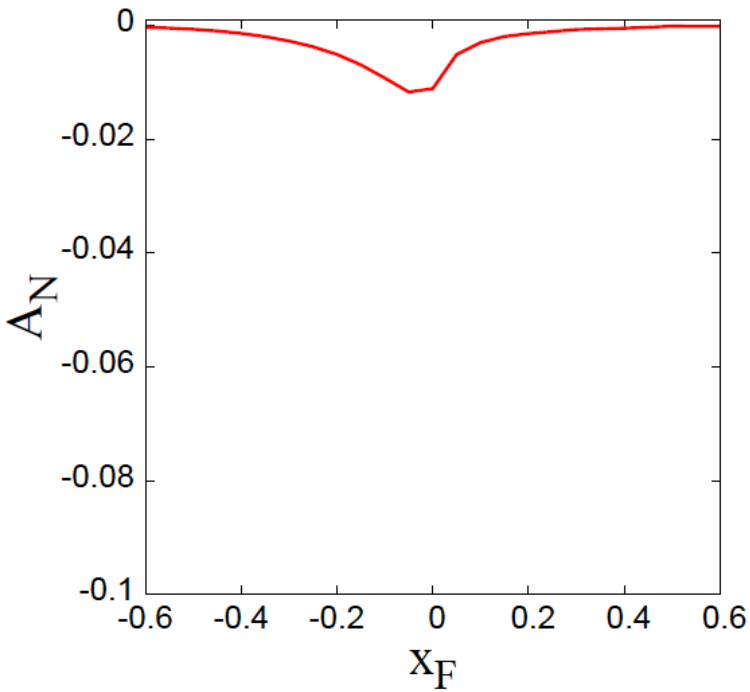
⋆ Estimate of A_N for $p^\uparrow p \to \gamma X$ by the models determined from $p^\uparrow p \to DX$.

(i) Case 1: $O(x) = N(x)$

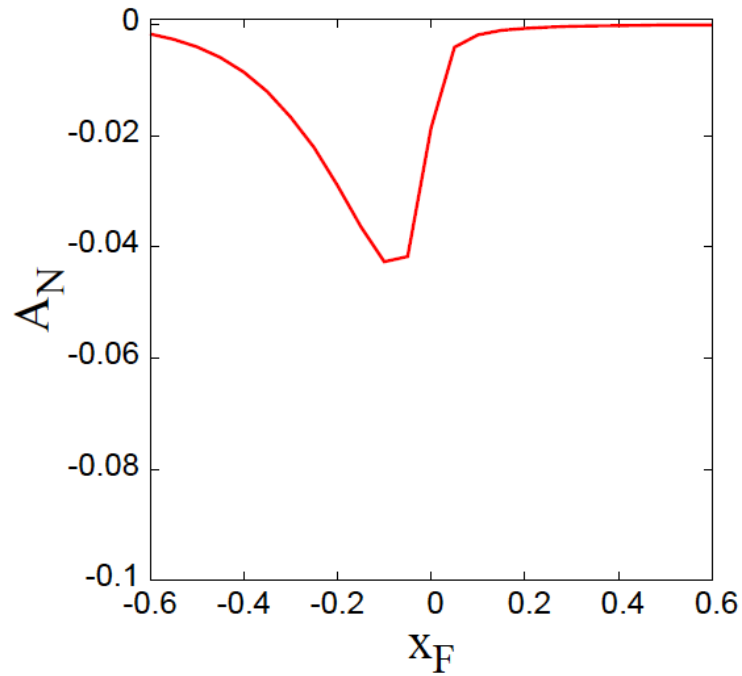
· Only anti-quark contribution from the unpolarized nucleon are active for the polarized cross section.

@ $\sqrt{S} = 200$ GeV, $P_T = 2$ GeV

Model 1: $O(x) = 0.004 \times xG(x)$



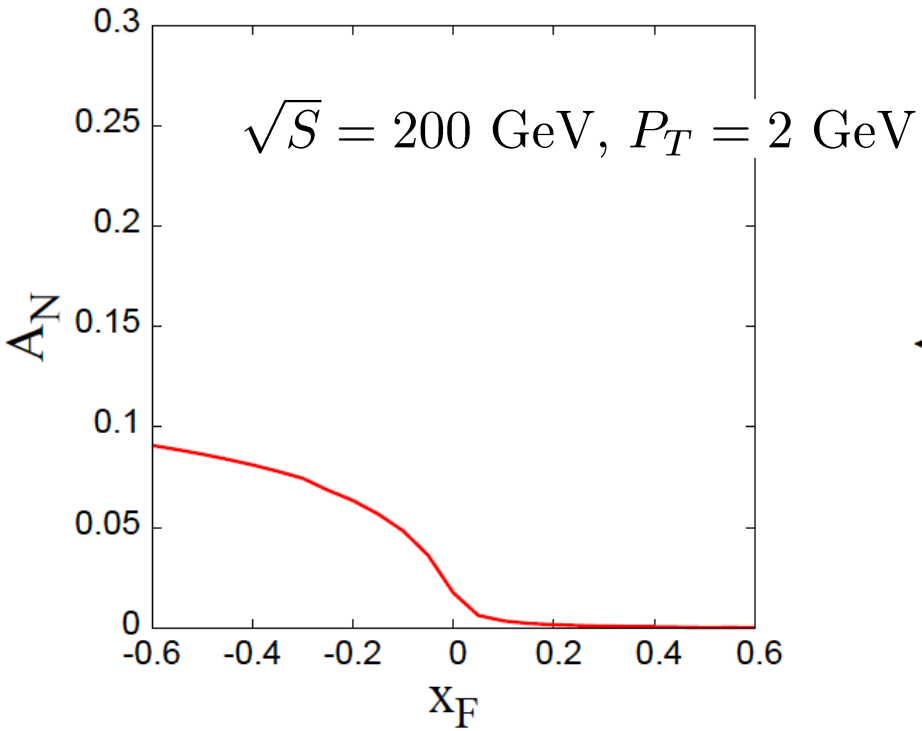
Model 2: $O(x) = 0.001\sqrt{x}G(x)$



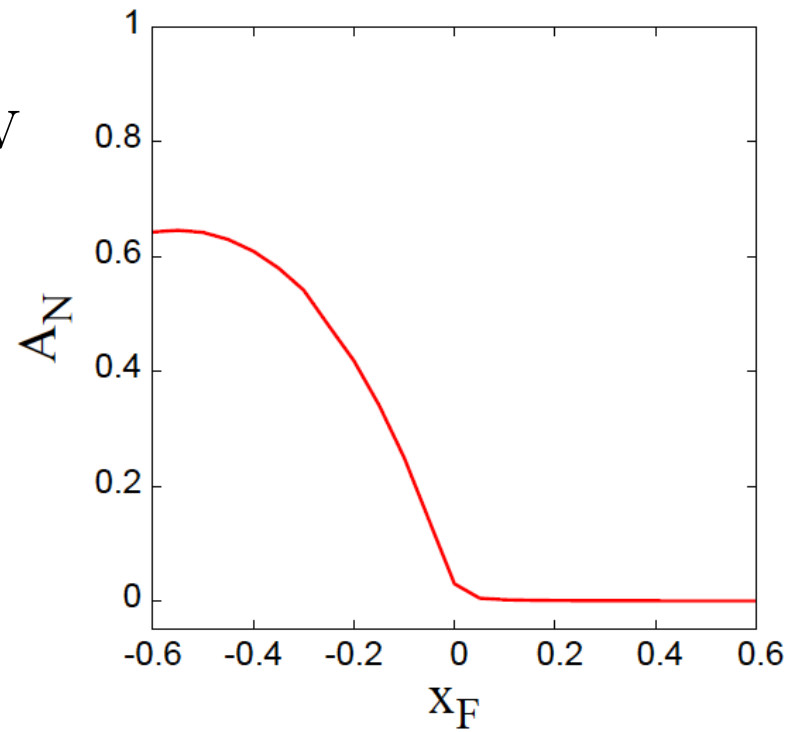
(ii) Case 2: $O(x) = -N(x)$

→ Quark contribution from the unpolarized nucleon is active, while anti-quark contribution is cancelled.

Model 1: $O(x) = 0.004 \times xG(x)$



Model 2: $O(x) = 0.001\sqrt{x}G(x)$



· $A_N \sim 0$ at $x_F > 0$ regardless of magnitude of the 3-gluon correlation functions.

· Behavior at $x_F < 0$ is sensitive to small x behavior similarly to $pp \to DX$.

Impact of the 3-gluon correlation functions on $p^{\uparrow}p \to \pi X$

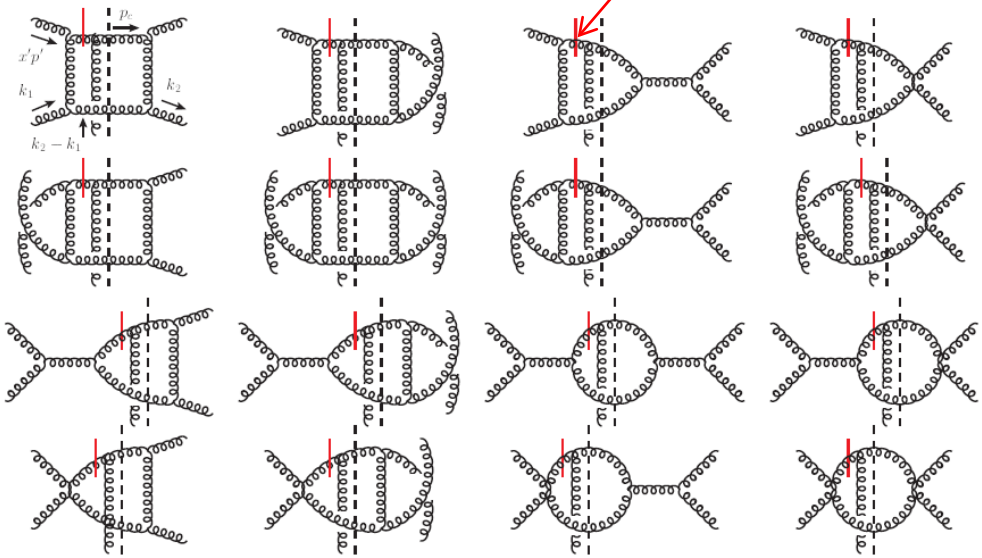
(Beppu, YK, Kanazawa, Yoshida, in preparation.)

⋆ 3-gluon contribution to $p^{\uparrow}p \to \pi X$

Ex. Purely gluonic contributions

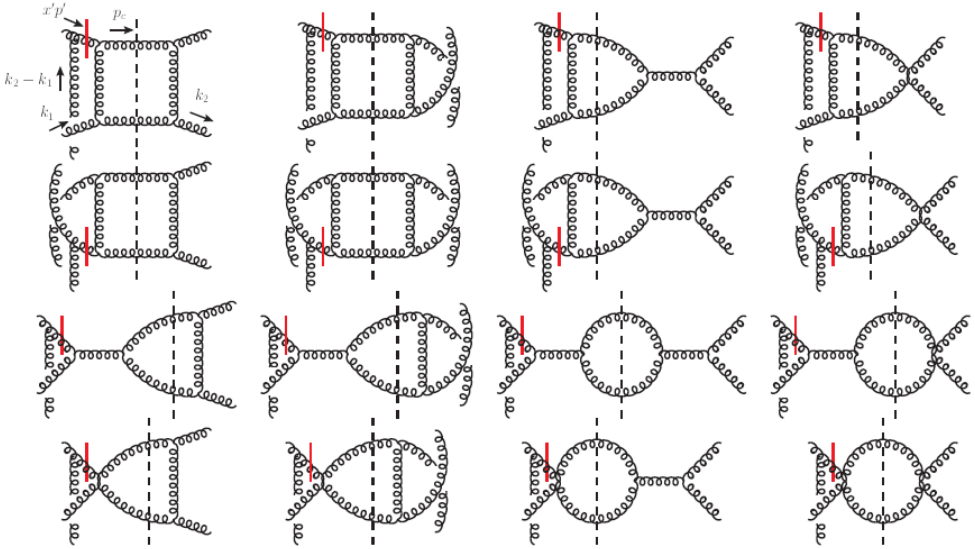
pole at $x_1 = x_2$

FSI



$+ \cdots$

ISI



$+ \cdots$

$\star$ 3-gluon contribution to the cross section for $p^{\uparrow}(p,S)+p(p')\to\pi(P_h)+X$

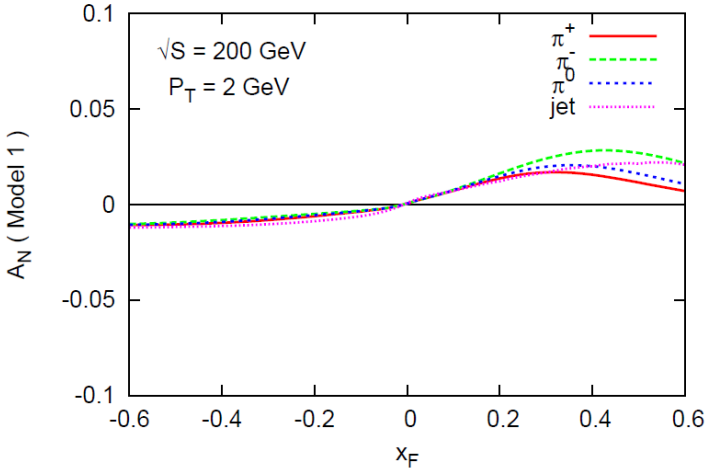
$$P_h^0\frac{d^3\Delta\sigma}{d^3P_h} = \frac{2\pi M_N\alpha_s^2}{S}\sum_{b=q,g}\sum_{c=q,g}\int\frac{dx}{x}\int\frac{dx'}{x'}f_b(x')\int\frac{dz}{z^2}D_c(z)\delta(\hat{s}+\hat{t}+\hat{u})\epsilon^{P_h pnS_\perp}\frac{1}{z\hat{u}}$$
$$\times\left[\delta_b\left(\frac{d}{dx}O(x)-\frac{2O(x)}{x}\right)\hat{\sigma}^{(O)}_{gb\to c}+\left(\frac{d}{dx}N(x)-\frac{2N(x)}{x}\right)\hat{\sigma}^{(N)}_{gb\to c}\right]$$

$$O(x)\equiv O(x,x)+O(x,0) \qquad \hat{\sigma}^{(O,N)}_{gb\to c}=\hat{\sigma}^{(O,N)I}_{gb\to c}-\frac{\hat{s}}{\hat{t}}\hat{\sigma}^{(O,N)F}_{gb\to c}$$
$$N(x)\equiv N(x,x)-N(x,0)$$

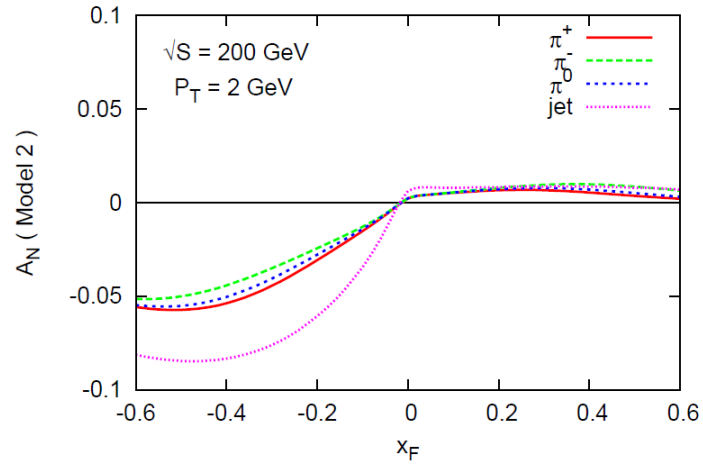
$$\hat{s}=(xp+x'p')^2,\quad \hat{t}=(xp-P_h/z)^2,\quad \hat{u}=(x'p'-P_h/z)^2.$$

(i) Case 1: $O(x) = N(x)$

Model 1: $O(x) = 0.004 \times xG(x)$

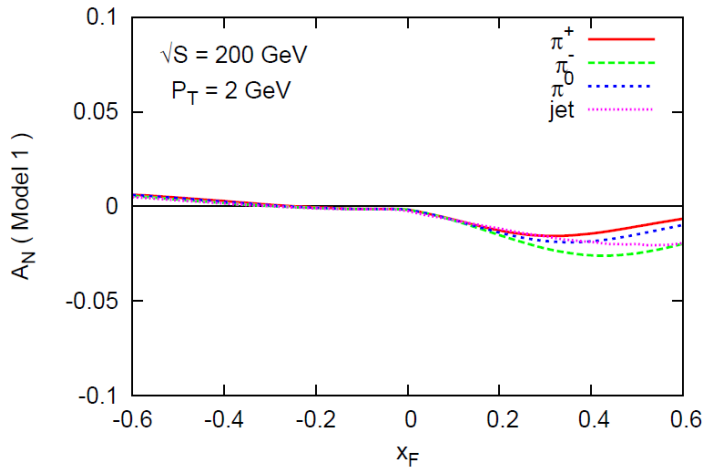


Model 2: $O(x) = 0.001\sqrt{x}G(x)$

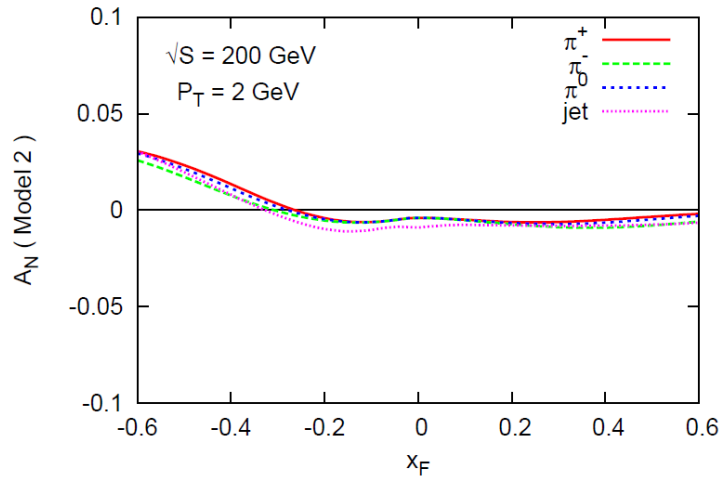


(ii) Case 2: $O(x) = -N(x)$

Model 1: $O(x) = 0.004 \times xG(x)$

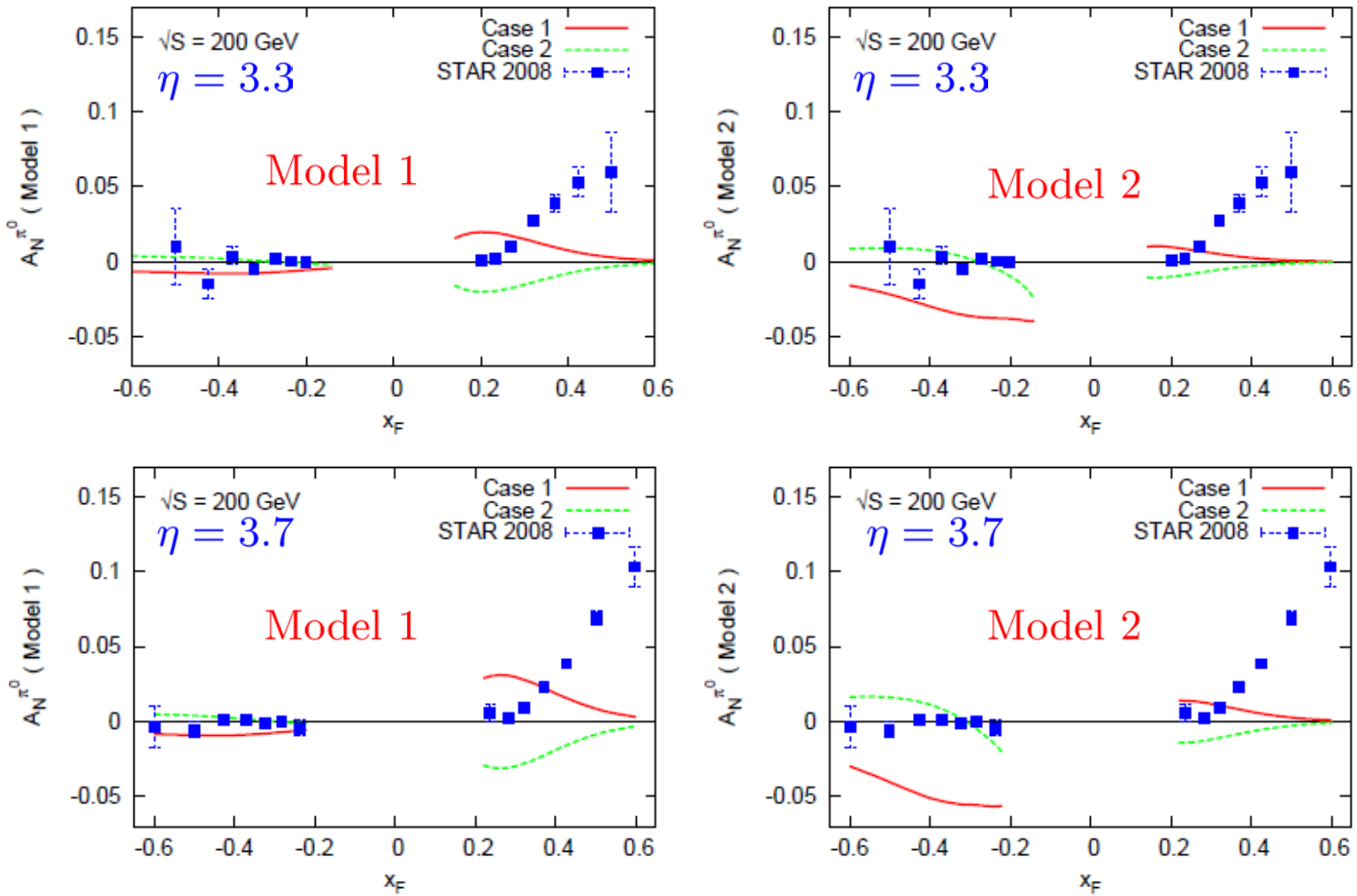


Model 2: $O(x) = 0.001\sqrt{x}G(x)$



Model 2 gives too large A_N at $x_F < 0$. $\Rightarrow$ Unlikely!

⋆ 3-gluon contribution to $A_N^{\pi^0}$ vs. STAR data.



· Model 1 disturbes the fitting of A_N at $x_F > 0$.

· Model 2 disturbes the fitting of A_N at $x_F < 0$.

$\Rightarrow$ A good constraint for the 3-gluon correlation function.

4. Summary

⋆ Characteristics of the twist-3 analysis based the quark-gluon correlation functions

· Fitting of the STAR and BRAHMS data reproduces A_N of π and K by the combination of SGP and SFP contributions.

· This analysis also reproduces the observed peculiar pattern of the P_T-dependence of $A_N^{\pi^0}$.

· Our prediction for A_N^η is approximately consistent with the STAR data. The origin of $A_N^\eta \sim 2A_N^{\pi^0}$ is the strangeness content in the η fragmentation function and the strangeness-gluon correlation in the nucleon.

· $A_N^{\mathrm{jet},\gamma} = 0$ at $x_F < 0$ in the present analysis implies that the nonzero $A_N^{\mathrm{jet},\gamma}$ at $x_F < 0$ can be ascribed to the 3-gluon correlation function.

· Peculiar pattern of the P_T-dependence of A_N^γ can be used as a test for the twist-3 mechanism.

⋆ Characteristics of the 3-gluon contribution to A_N

· Complete LO twist-3 cross section formula have been derived for $p^{\uparrow}p \to \{D, \ell^+\ell^-, \gamma, \pi, \text{jet}\}X$.

· $A_N^{\gamma} \simeq 0$ at $x_F > 0$, which is model-independent.
⇒ The roles of the quark-gluon correlation and the 3-gluon correlation are clearly separated.

· The upper bound for the 3-gluon correlations extracted from the RHIC A_N^D data already disturbes the observed A_N^{π}.
⇒ A better constraint for the 3-gluon correlations.