Some recent developments in single transverse-spin asymmetry

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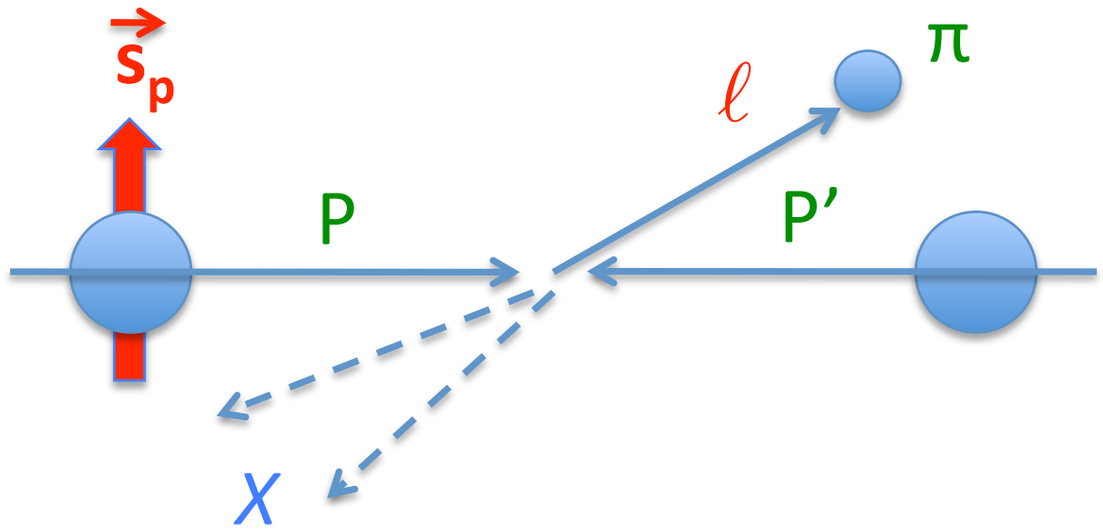
based on work with J. -W. Qiu, Sterman, Vogelsang, and Yuan

Outline

- Introduction
- Collinear factorization approach:
  - Basic formalism (LO)
  - Evolution of twist-3 correlations (beyond LO)
  - Physical meaning of twist-3 correlations
- Phenomenology for future experimental measurements:
  - open charm
  - pT dependence
  - test of universality of Sivers function: W program
- Summary

Single transverse-spin asymmetry: definition

- Consider scattering of a transversely-polarized spin-1/2 hadron ($\vec{s}_p$, p) with another hadron (or photon), observing a particle of momentum ℓ



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

- Spin-avg cross section: $\sigma(\ell) = \frac{1}{2}\left[\sigma(\ell, \vec{s}) + \sigma(\ell, -\vec{s})\right]$

  Spin-dep cross section: $\Delta\sigma(\ell, \vec{s}) = \frac{1}{2}\left[\sigma(\ell, \vec{s}) - \sigma(\ell, -\vec{s})\right]$

  Single transverse-spin asymmetry (SSA):

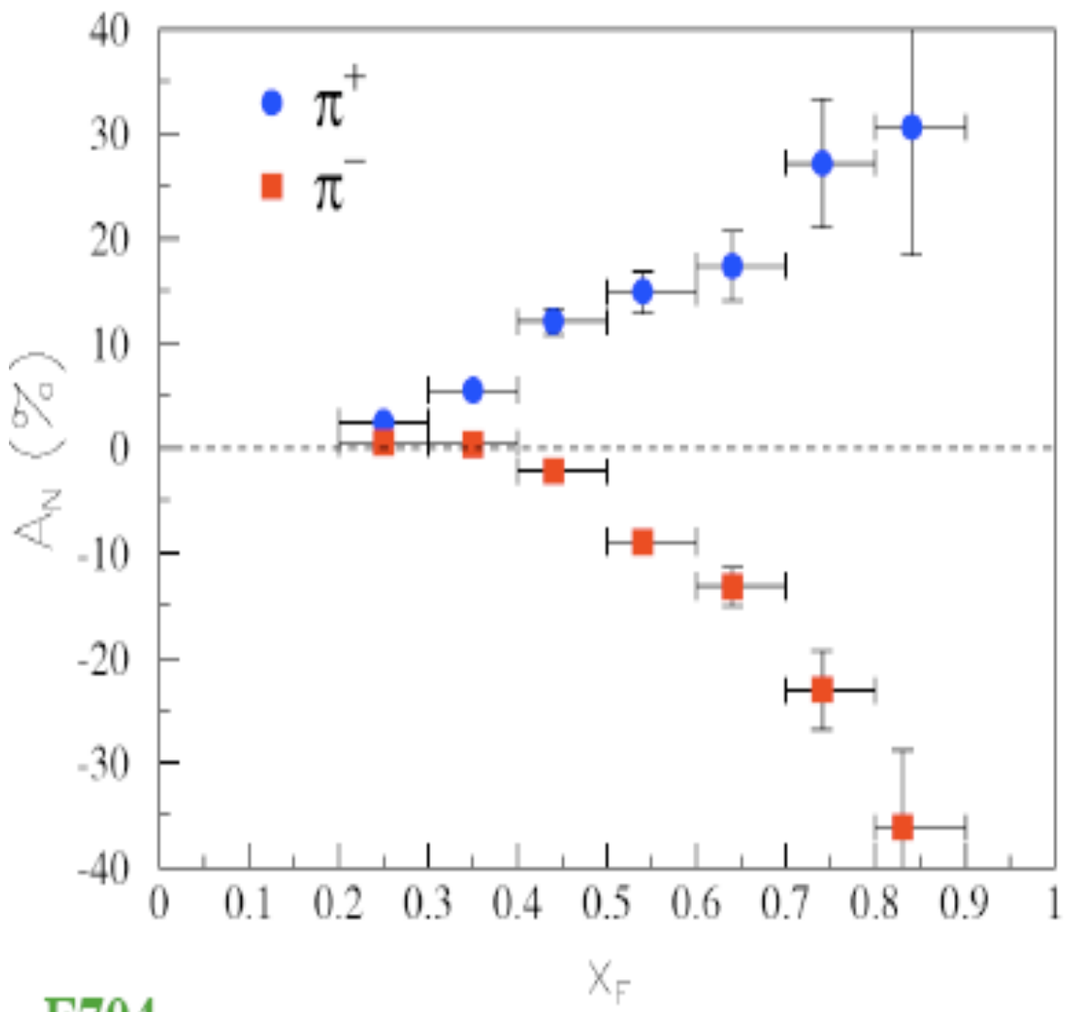
$$A_N \equiv \frac{\Delta\sigma(\ell, \vec{s})}{\sigma(\ell)} = \frac{\sigma(\ell, \vec{s}) - \sigma(\ell, -\vec{s})}{\sigma(\ell, \vec{s}) + \sigma(\ell, -\vec{s})}$$

Experimental status of Single Spin Asymmetry (SSA)

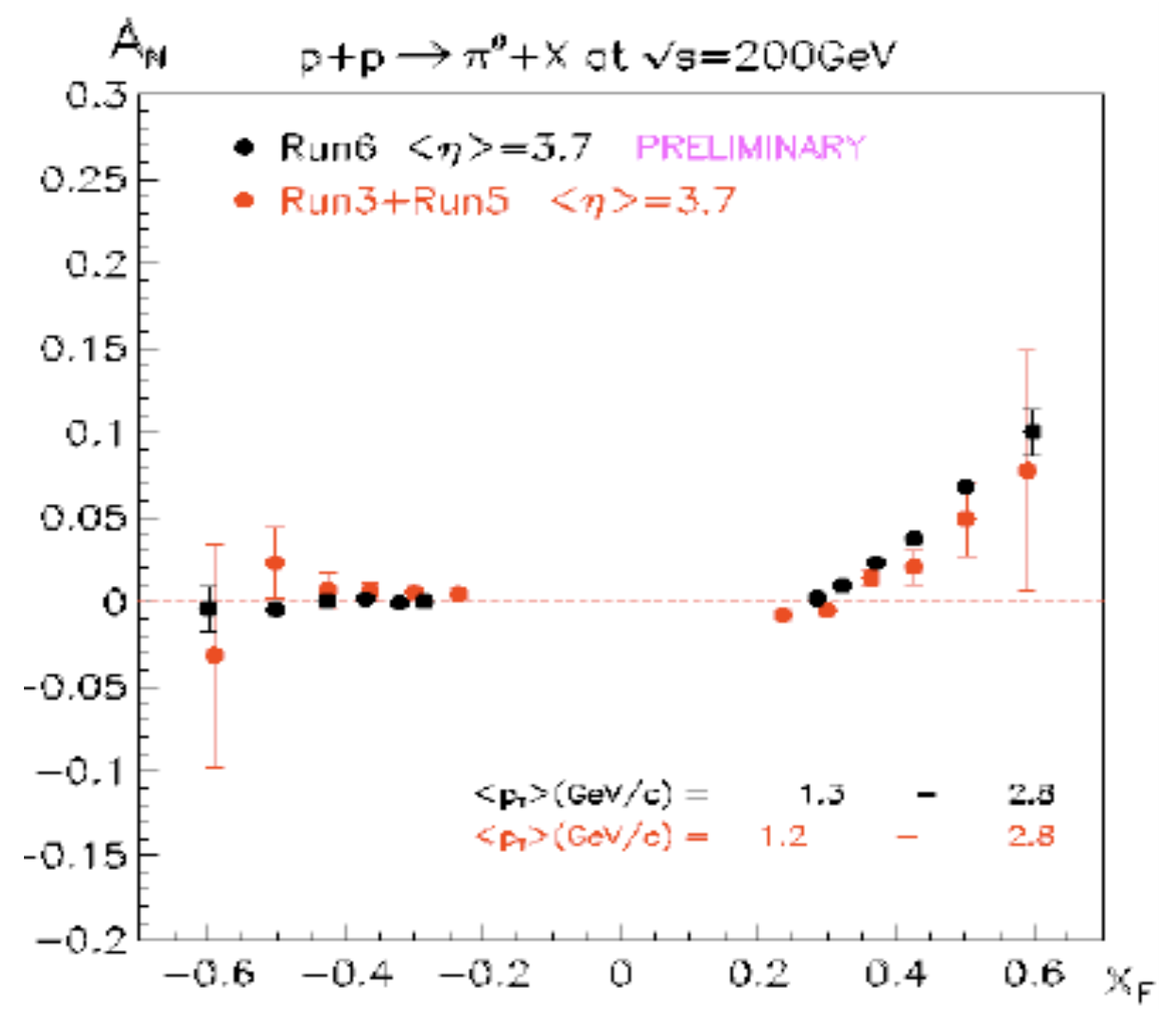
- Fermilab E704, STAR, PHENIX, BRAHMS, COMPASS, HERMES, JLab

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

SSA: $A_N = \dfrac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow}$



E704



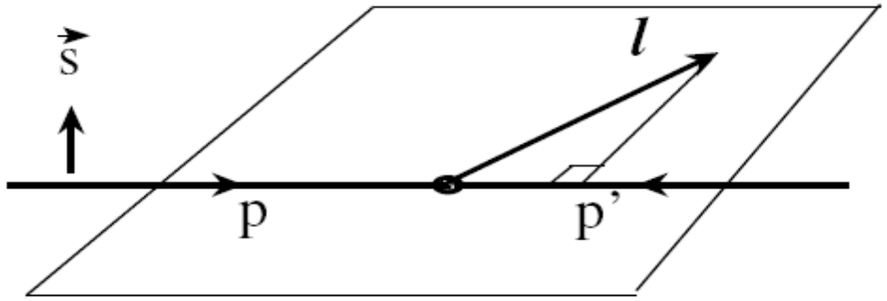
STAR (BRAHMS, too)

SSAs are observed in various experiments at different $\sqrt{s}$

SSA corresponds to a T-odd triplet product

- SSA measures the correlation between the hadron spin and the production plane, which corresponds to $\vec{s}_p \cdot (\vec{p} \times \vec{\ell})$

$$p^{\uparrow} p \to \pi(\ell) X$$



- Such a product is odd (naive) under time reversal (T-odd), and thus they can arise in a time-reversal invariant theory (eg, QCD) only when there is a phase between different spin amplitudes.

➡ $A_N \propto i\vec{s}_p \cdot (\vec{p} \times \vec{\ell})$

- the phase "i" is required by time-reversal invariance

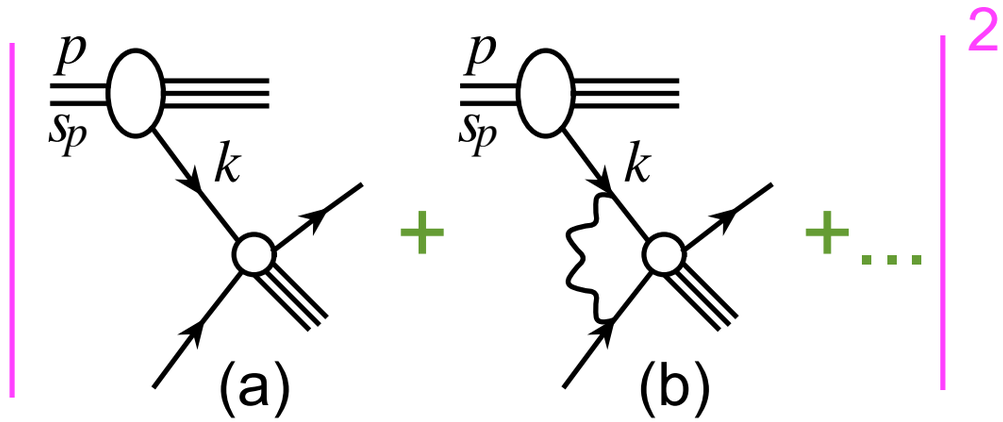
- covariant form: $A_N \propto i\epsilon^{\mu\nu\alpha\beta} p_\mu s_\nu \ell_\alpha p'_\beta$

Nonvanishing A_N requires a phase, a helicity flip, and enough vectors to fix a scattering plane

Non-vanishing SSA due to transverse motion

- If partons are purely collinear:

Kane, Pumplin, Repko, 1978

$\sigma(s_T) \sim$ 

$\Rightarrow \Delta\sigma(s_T) \sim \mathrm{Re}[(a)]\cdot\mathrm{Im}[(b)]$

- generate phase from loop diagrams, proportional to α_s
- helicity is conserved for massless partons, helicity-flip is proportional to current quark mass m_q

Therefore we have

$$A_N \sim \alpha_s \frac{m_q}{\sqrt{s}} \to 0$$

- $A_N \neq 0$: result of parton's transverse motion or correlations!

Two mechanisms to generate SSA in QCD

- TMD approach: Transverse Momentum Dependent distributions probe parton's intrinsic transverse momentum Sivers 90, Collins 93, ...

  - Sivers function: in Parton Distribution Function (PDF)
  - Collins function: in Fragmentation Function (FF)

- Collinear factorization approach: Efremov-Teryaev 82, 84, Qiu-Sterman 91, 98

  - twist-3 multiparton correlation functions

- They apply in different kinematic domain:

  - TMD approach: need TMD factorization
    Physical processes with two observed scales: Q and q (Q>>q)
    with the large Q to ensure a hard collision, while
    the $q \sim k_T$ probes parton's transverse momentum

  - Collinear factorization approach: more relevant for single scale hard process

- They generate same results in the region when they both apply

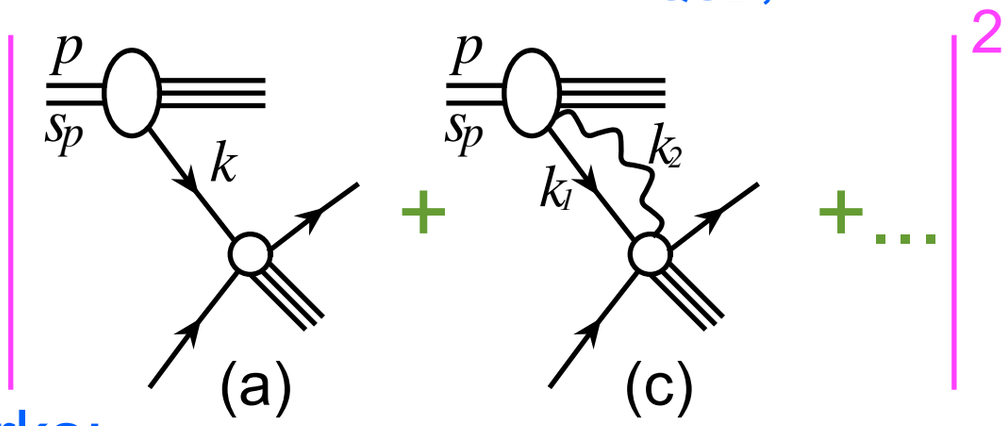
  - Ji, Qiu, Vogelsang, Yuan, 2006
  - see also, A. Bacchetta, et.al., 2008

SSA in collinear factorization approach

Efremov-Teryaev, 1982, Qiu-Sterman, 1991

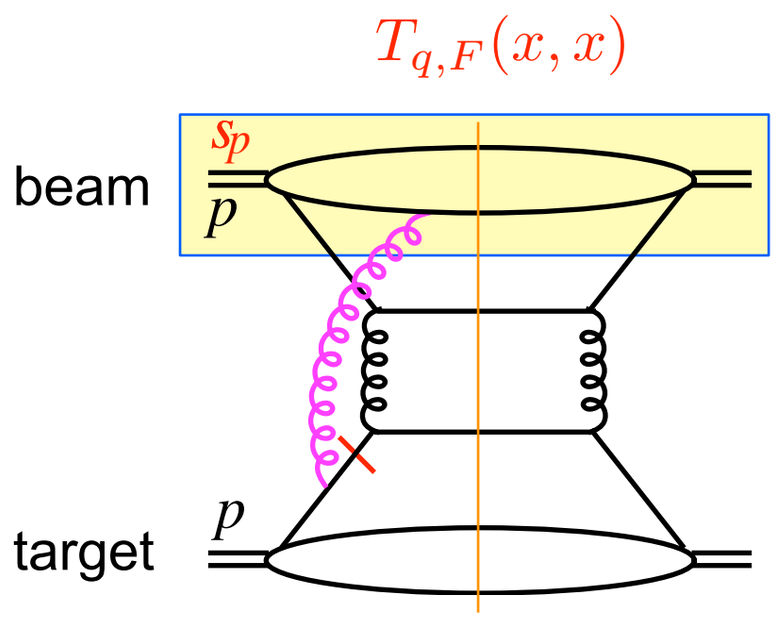
- When all observed scales >> Λ_{QCD}, collinear factorization should work:

$\sigma(s_T) \sim$



➡ $\Delta\sigma(s_T) \sim$ Re[(a)]·Im[(c)]

- How it works:



some propagators in the tree diagrams go on-shell

$$\frac{1}{k^2 - m^2 + i\epsilon} = P\frac{1}{k^2 - m^2} - i\pi\delta(k^2 - m^2)$$

- phase: from hard scattering amplitudes (unpinched pole)
- spin flip: from interference between a quark state and a quark-gluon composite state

- Twist-3 quark-gluon correlation function $T_{q,F}(x,x)$:

$$T_{q,F}(x,x) = \int \frac{dy_1^- dy_2^-}{4\pi} e^{ixP^+y_1^-} \langle P, s_T|\bar{\psi}_q(0)\gamma^+ \boxed{\left[\epsilon^{s_T\sigma n\bar{n}} F_\sigma{}^+(y_2^-)\right]} \psi_q(y_1^-)|P, s_T\rangle$$

Twist-3 approach: initial success (I)

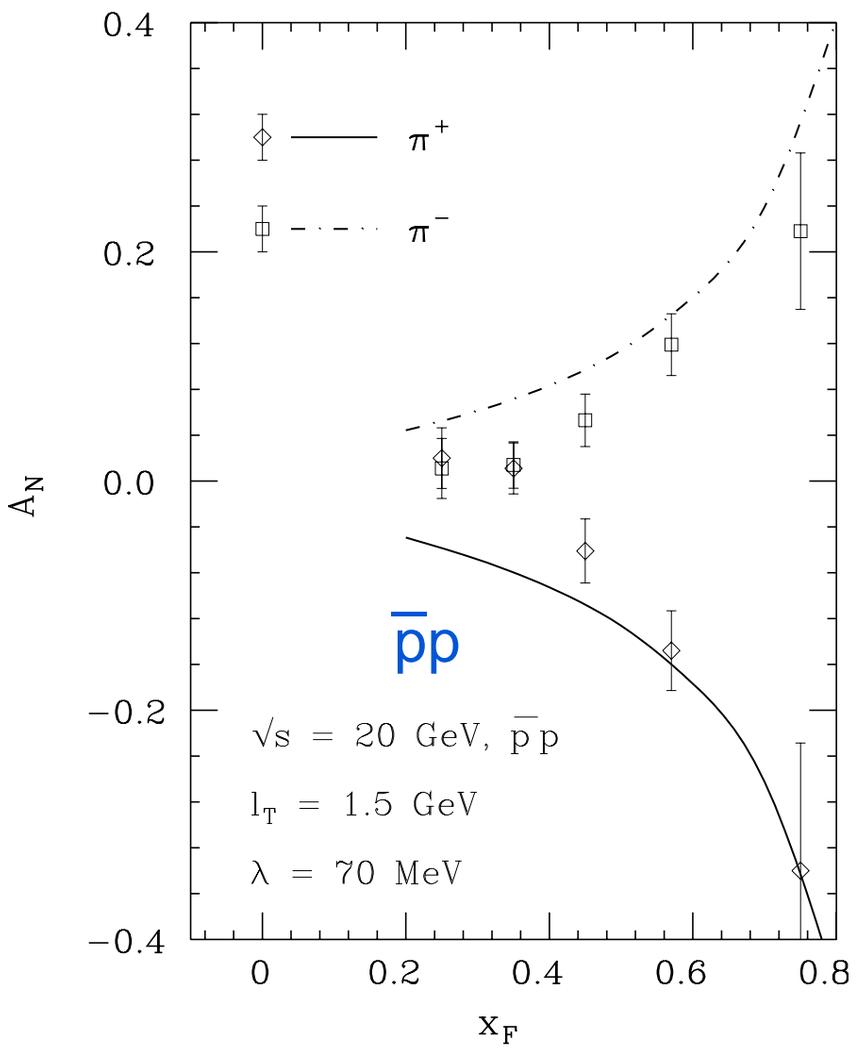
- Describe E704 data well with one parameter λ_F (valence quark approx.)

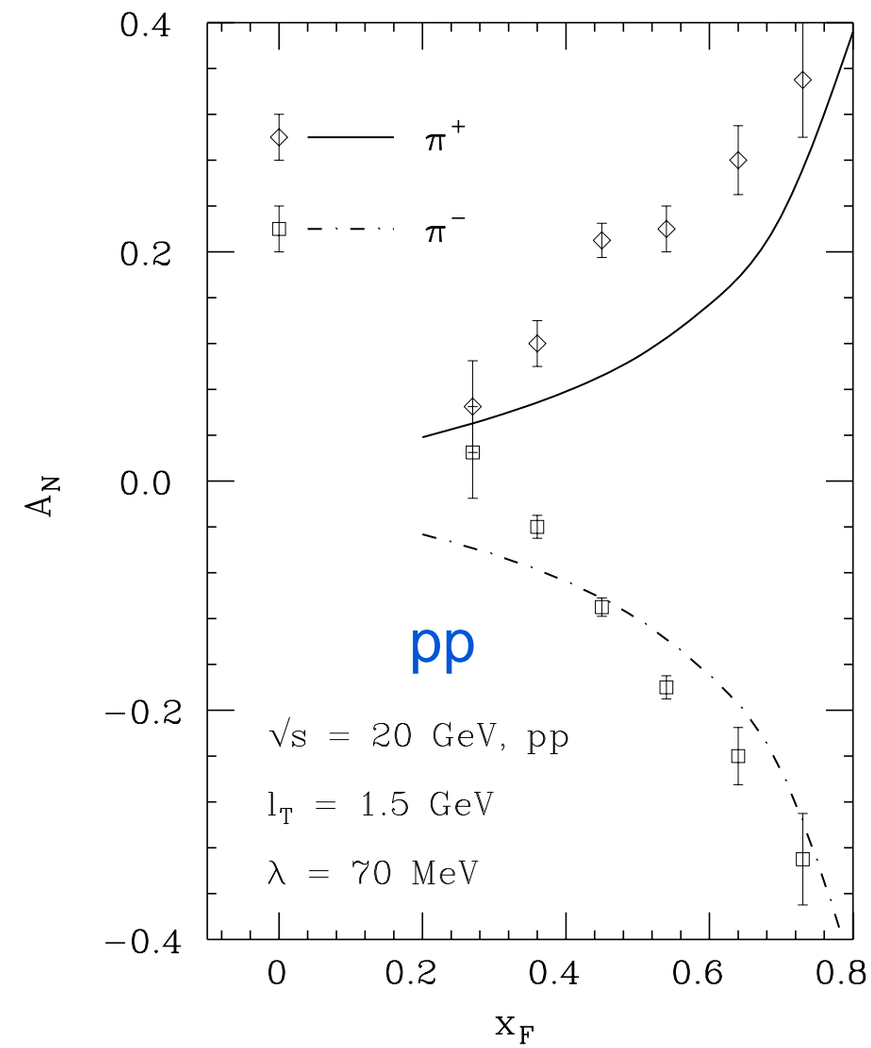
Model: $T_{u,F}(x,x) = \lambda_F \phi_u(x)$

$T_{d,F}(x,x) = -\lambda_F \phi_d(x)$

$\lambda_F = 0.07$ GeV

Qiu, Sterman 1999



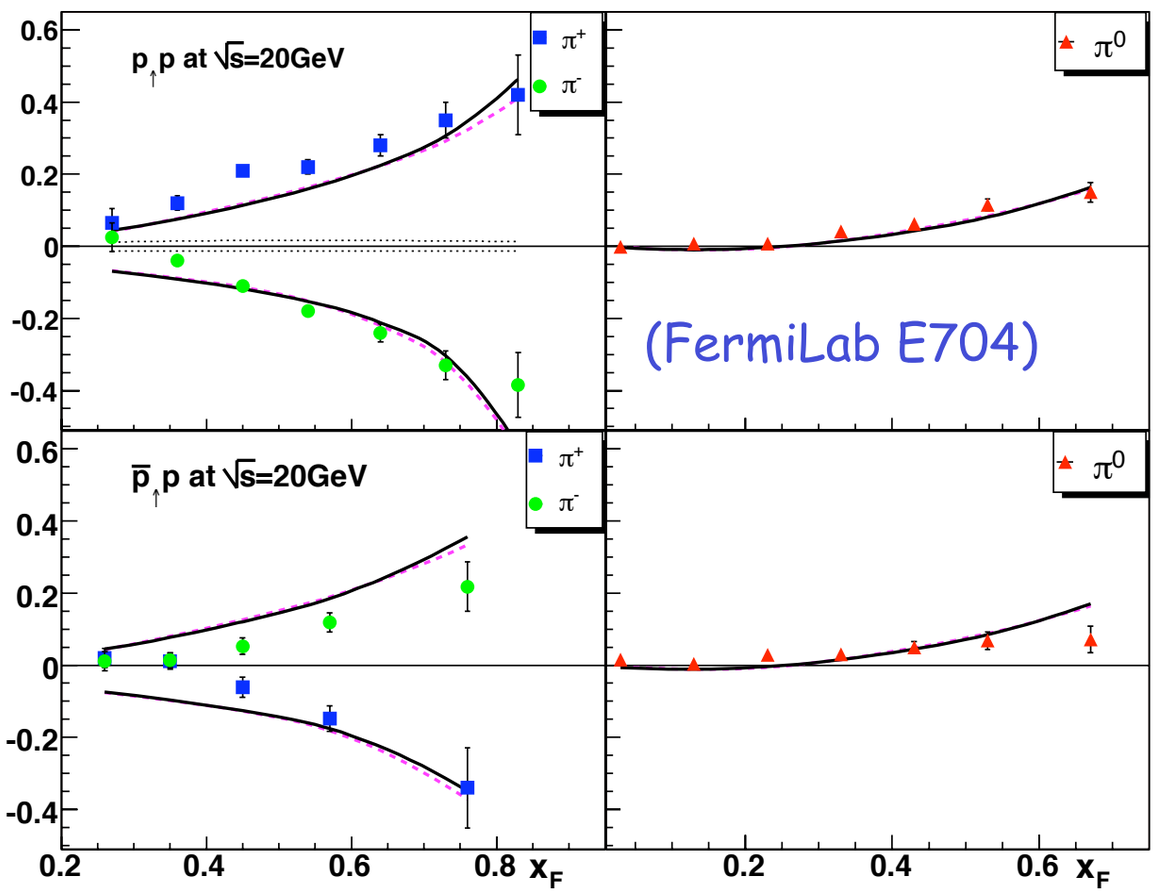


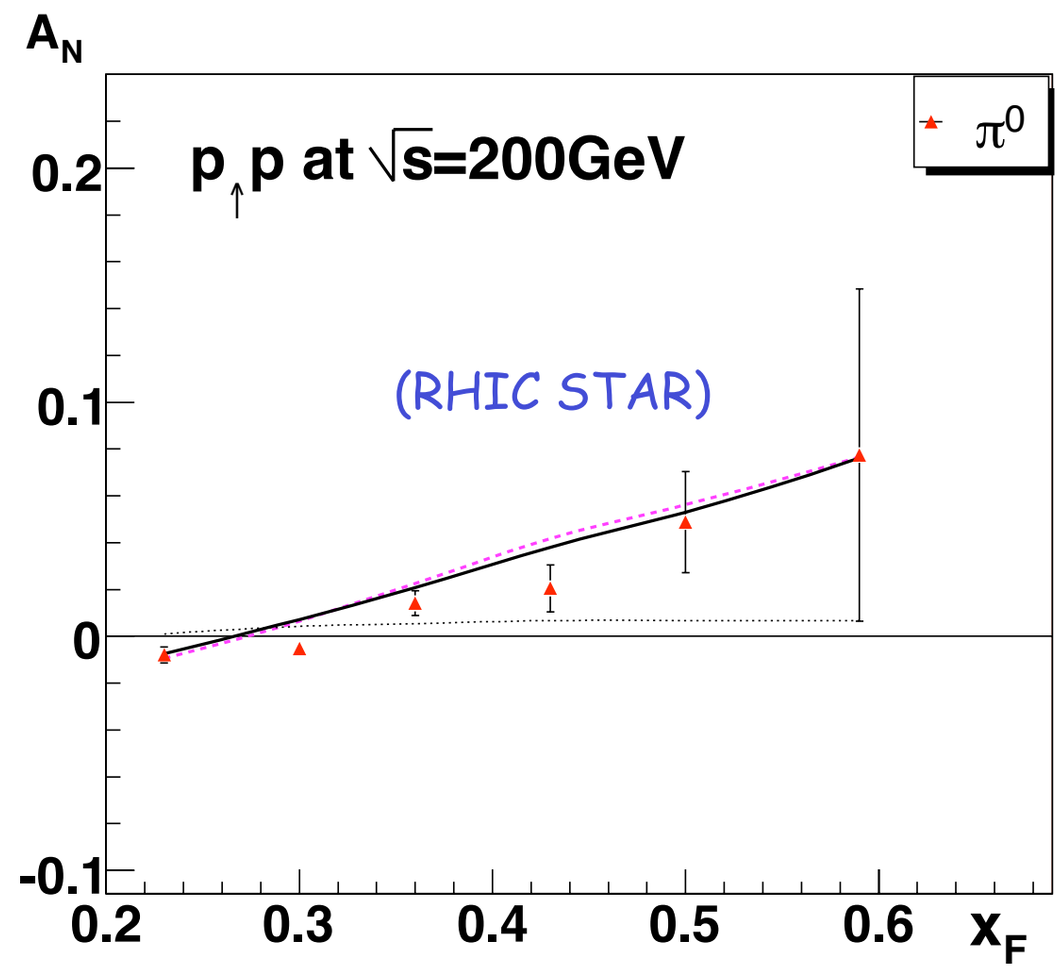
Twist-3 approach: initial success (II)

- Describe both E704 and RHIC data simultaneously with a more sophisticated $T_{q,F}(x,x)$:

Kouvaris,Qiu,Vogelsang,Yuan, 2006

$$T_{q,F}(x,x) = N_q x^{\alpha_q}(1-x)^{\beta_q}\phi_q(x)$$





$T_{q,F}(x,x)$ only in forward region

There are more than just the quark-gluon correlation.
What about the others?

Twist-3 trigluon correlation functions

Ji, 1992; Kang, Qiu, 2008

Kang, Qiu, Vogelsang, Yuan, 2008

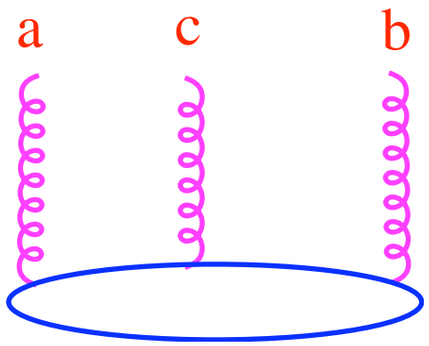
- Diagonal tri-gluon correlations:

$$T_G(x,x) = \int \frac{dy_1^- dy_2^-}{2\pi} e^{ixP^+y_1^-} \times \frac{1}{xP^+} \langle P, s_T | F^+{}_\alpha(0) \boxed{\left[\epsilon^{s_T \sigma n \bar{n}} F_\sigma{}^+(y_2^-)\right]} F^{\alpha +}(y_1^-) | P, s_T \rangle$$

- Two tri-gluon correlation functions - different color factors

$$T_G^{(f)}(x,x) \propto i f^{abc} F^a F^c F^b = F^a F^c \left[\mathcal{T}^c\right]^{ab} F^b$$

$$T_G^{(d)}(x,x) \propto d^{abc} F^a F^c F^b = F^a F^c \left[\mathcal{D}^c\right]^{ab} F^b$$



Fermionic correlation: $T_F(x,x) \propto \bar{\psi}_i F^c \left[T^c\right]_{ij} \psi_j$

- D-meson production in Semi Inclusive Deep Inelastic Scattering (SIDIS):
  - ❖ Clean probe for twist-3 tri-gluon correlation functions

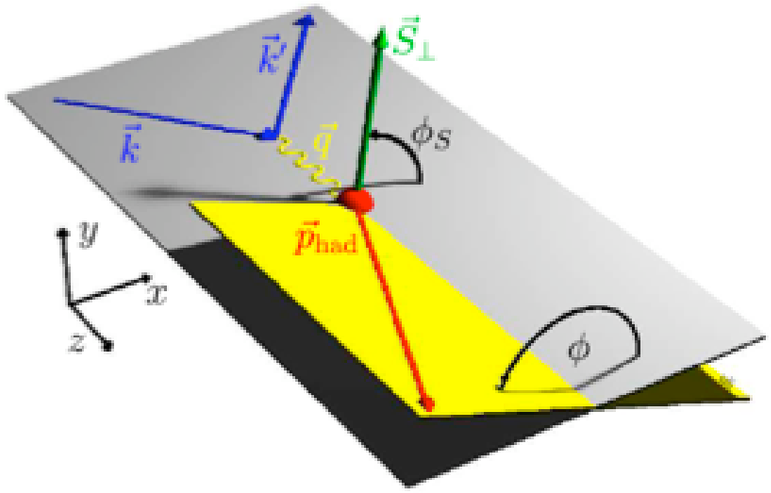
D-meson production in SIDIS: $ep^{\uparrow} \to e + D + X$

- Frame for SIDIS:

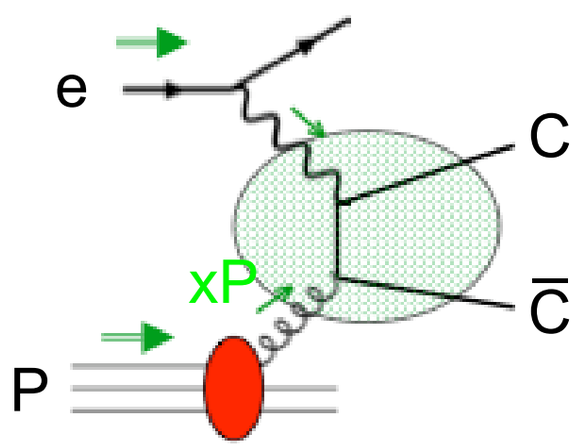
Kang, Qiu, PRD78, 034005 (2008)

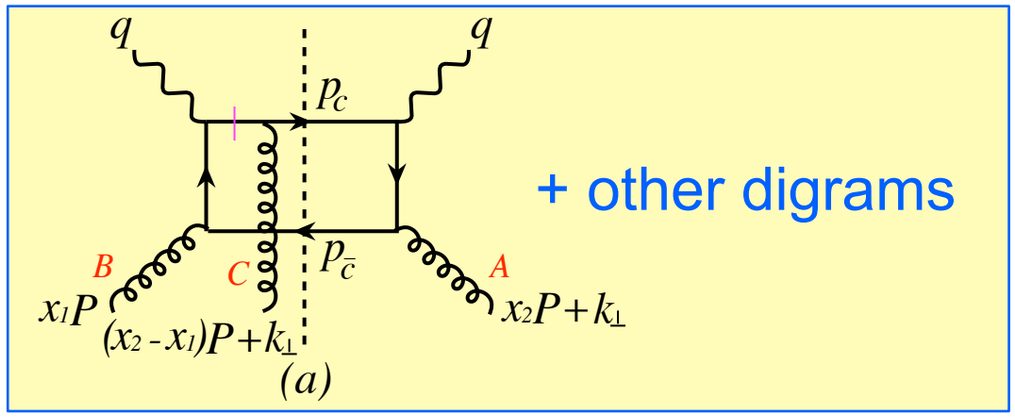
$$e(k) + p^{\uparrow}(P) \to e(k') + D(P_h) + X$$

$$q = k - k' \qquad z_h = \frac{P \cdot P_h}{P \cdot q} = E_h/\nu$$



- Dominated by the contribution from trigluon correlations





- Single transverse-spin asymmetry:

$$A_N = \frac{\sigma(s_\perp) - \sigma(-s_\perp)}{\sigma(s_\perp) + \sigma(-s_\perp)} = \frac{d\Delta\sigma(s_\perp)}{dx_B dy dz_h dP_{h\perp}^2 d\phi} \Bigg/ \frac{d\sigma}{dx_B dy dz_h dP_{h\perp}^2 d\phi}$$

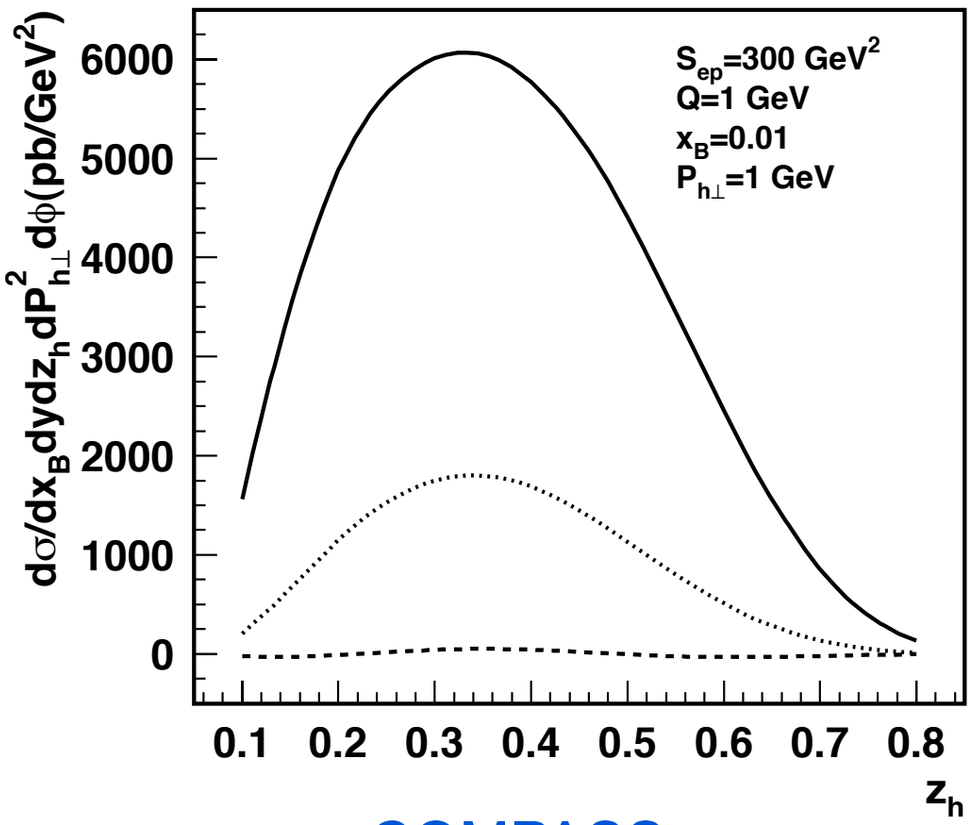
Production rate of D-meson in SIDIS

- Production rate (spin averaged):

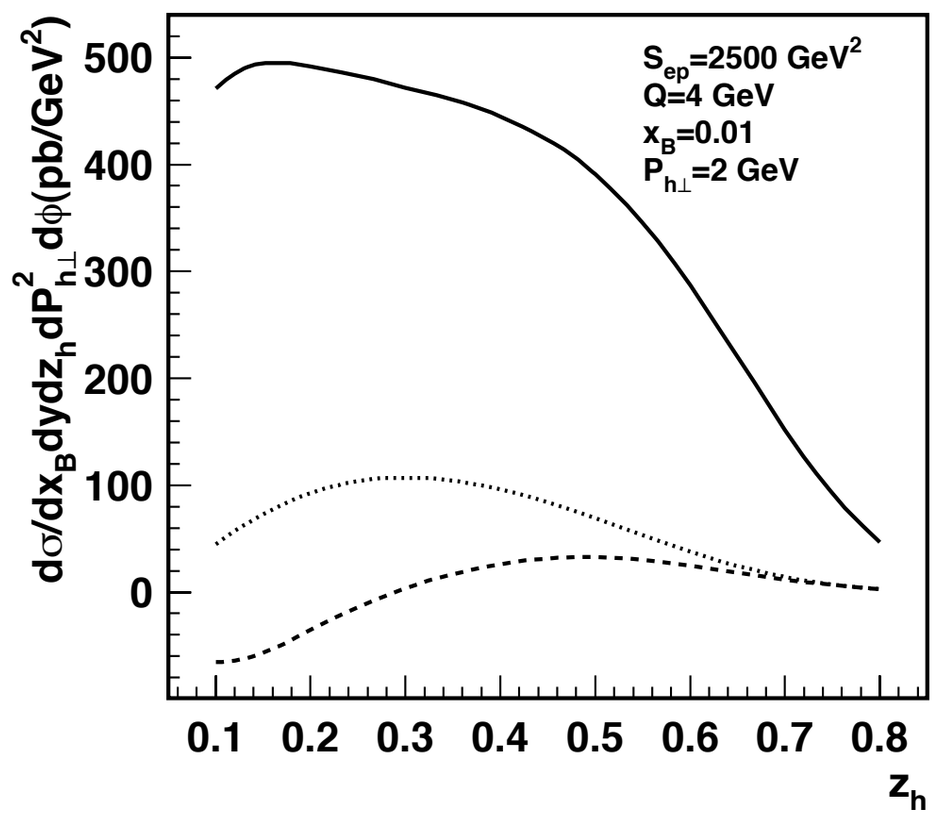
$$\frac{d\sigma}{dx_B dy dz_h dP_{h\perp}^2 d\phi} = \sigma_0^U + \sigma_1^U \cos\phi + \sigma_2^U \cos 2\phi$$

$$z_h = \frac{P \cdot P_h}{P \cdot q} = E_h/\nu$$

z_h: Energy fraction of photon carried by D-meson



COMPASS



EIC

reasonable production rate, small ϕ dependence

Features of the SSA in SIDIS

- Dependence of tri-gluon correlation functions:

$$D-\text{meson} \;\propto\; T_G^{(f)} + T_G^{(d)} \qquad\qquad \overline{D}-\text{meson} \;\propto\; T_G^{(f)} - T_G^{(d)}$$

Separate $T_G^{(f)}$ and $T_G^{(d)}$ by the difference between D and $\bar{D}$

- A_N depends on $T_G(x,x)$ and its derivative:

$$A_N \quad\propto\quad \epsilon^{P_h s_T n \bar{n}} \frac{1}{t} \frac{-x \frac{d}{dx} T_G(x,x)}{G(x)} \to 1/(1-x)$$

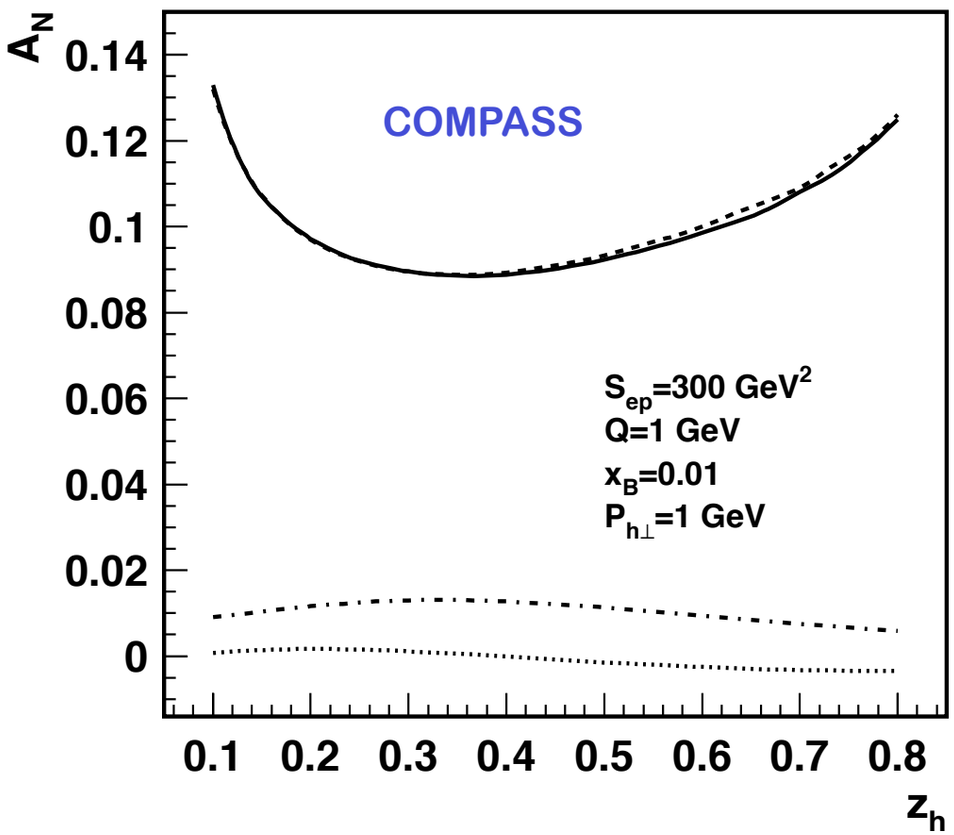
Since x has a minimum at $z_h \sim 0.5$ (from kinematics constrain), SSA should have a minimum if the derivative term dominates

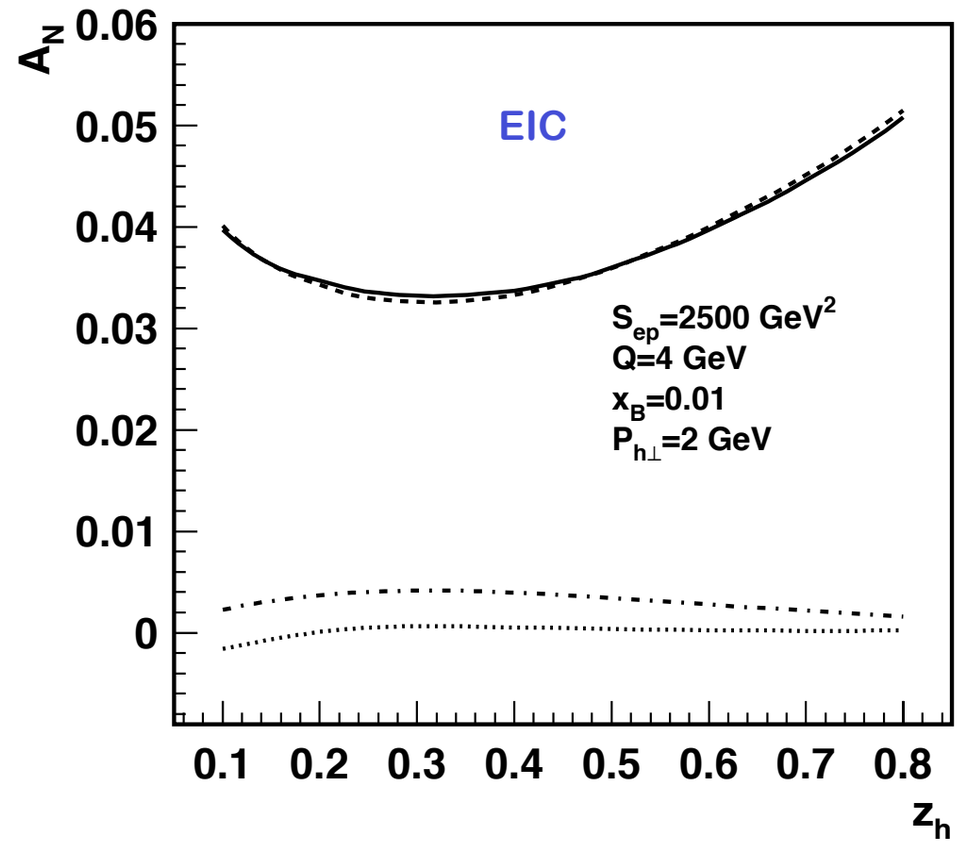
- Model for tri-gluon correlation functions:

$$T_G^{(f,d)}(x,x) = \lambda_{f,d} G(x) \qquad\qquad \lambda_{f,d} = \pm\lambda_F = \pm 0.07 \text{ GeV}$$

Estimation of SSA in D-meson production in SIDIS

- SSA for D^0 production ($T_G^{(f)}$ only)





- Derivative term dominates, and small φ dependence
- Asymmetry is twice if $T_G^{(d)} = +T_G^{(f)}$, or zero if $T_G^{(d)} = -T_G^{(f)}$
- Opposite for the $\bar{D}$ meson
- Asymmetry has a minimum ~ z_h ~ 0.5

Measure the SSAs ⇒ extract tri-gluon correlations

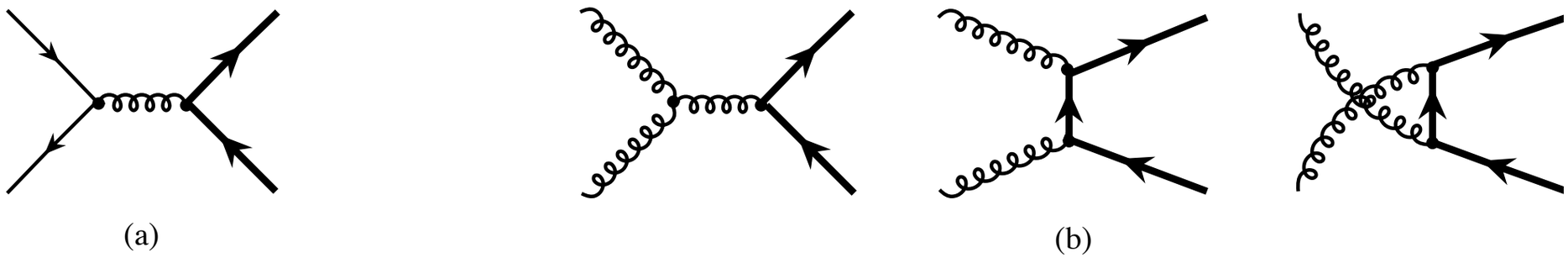
Test QCD: universality of tri-gluon correlations?

D-meson production in hadronic collisions: $p^{\uparrow}p \to D + X$

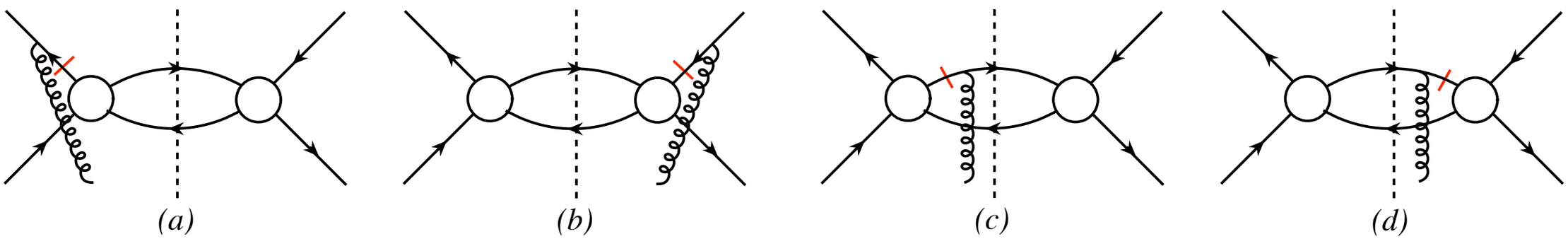
Kang, Qiu, Vogelsang, Yuan, PRD78, 114013 (2008)

- Two partonic subprocesses:

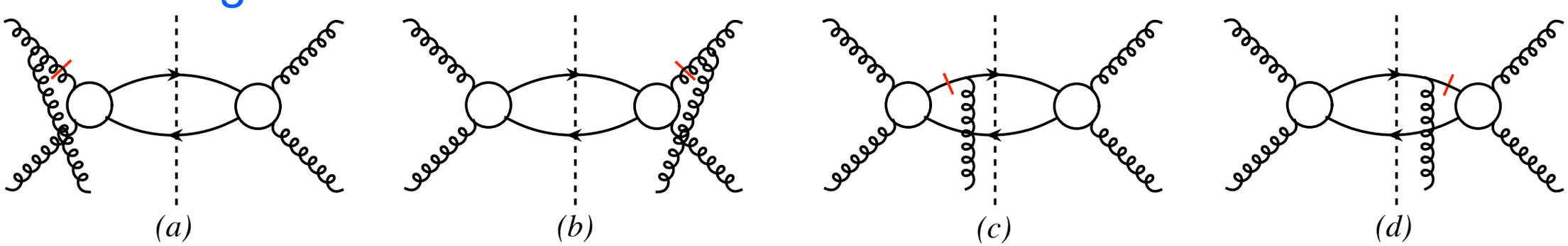
$p^{\uparrow}p \to D + X$



- Quark-antiquark annihilation:



- Gluon-gluon fusion:



Spin-dependent cross section for D-meson production

- SSA from both quark-gluon correlation $T_{q,F}(x,x)$ and tri-gluon correlation $T_G(x,x)$

$$E_{P_h}\frac{d\Delta\sigma}{d^3P_h}\bigg|_{gg\to c\bar{c}} = \frac{\alpha_s^2}{S}\sum_{i=f,d}\int\frac{dz}{z^2}D_{c\to h}(z)\int\frac{dx'}{x'}\phi_{g/B}(x')\int\frac{dx}{x}\sqrt{4\pi\alpha_s}\left(\frac{\epsilon^{P_h s_T n\bar{n}}}{z\tilde{u}}\right)\delta\left(\tilde{s}+\tilde{t}+\tilde{u}\right)$$
$$\times\left[\left(T_G^{(i)}(x,x)-x\frac{d}{dx}T_G^{(i)}(x,x)\right)H^{(i)}_{gg\to c}(\tilde{s},\tilde{t},\tilde{u})+T_G^{(i)}(x,x)\mathcal{H}^{(i)}_{gg\to c}(\tilde{s},\tilde{t},\tilde{u})\right]$$

- depends on correlation and its derivative
- same factorized form for $q\bar{q}$ subprocess

- Features of SSA:

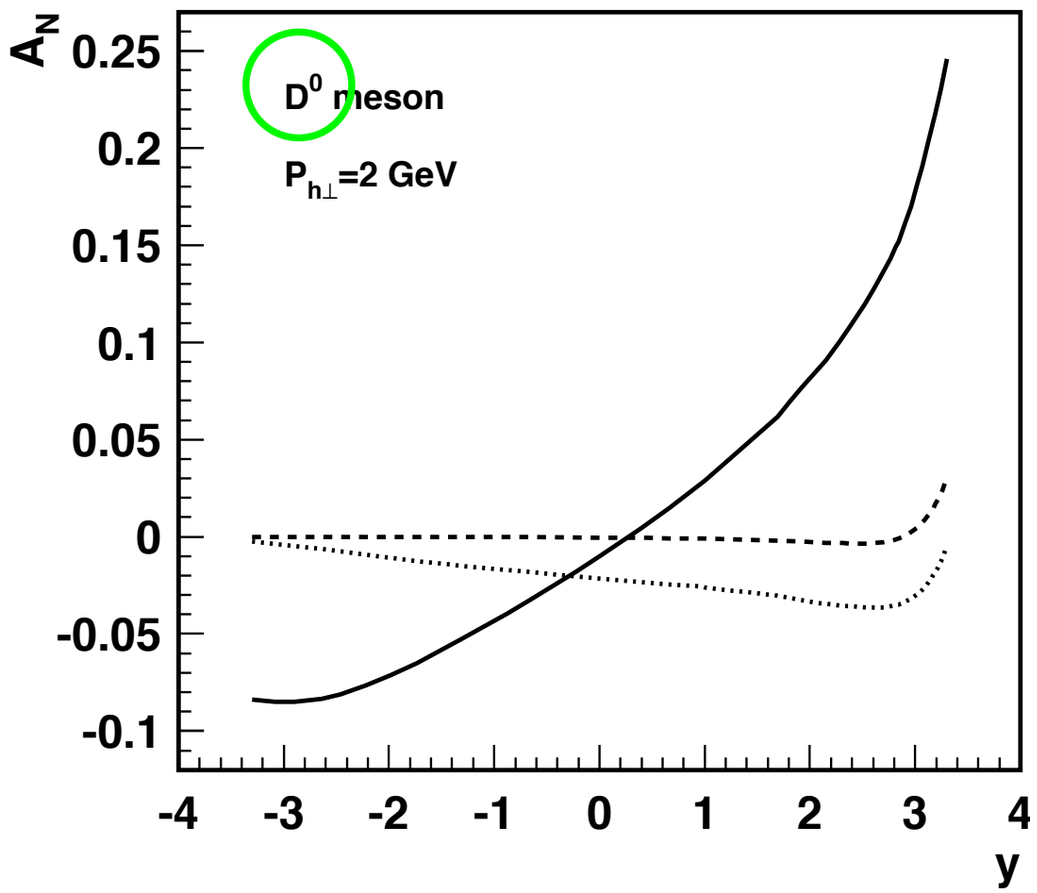
When $c\to\bar{c}$

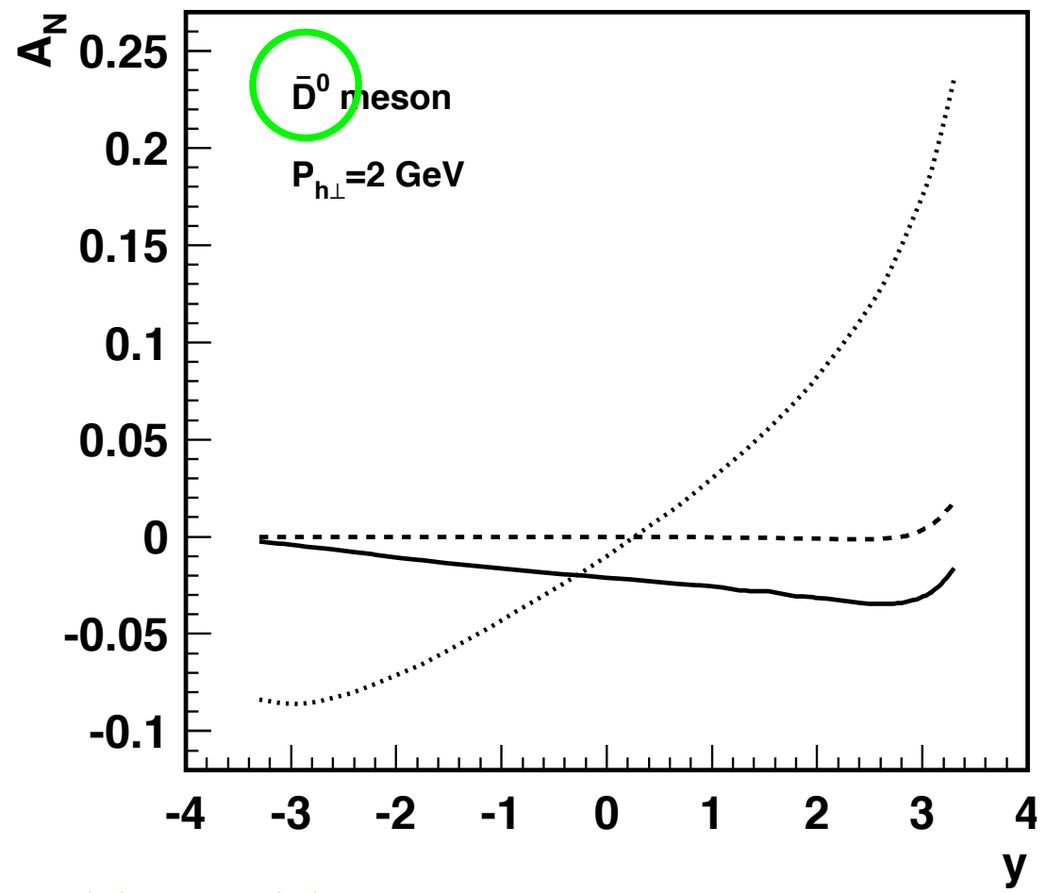
- hard parts do NOT change sign for $T_{q,F}$ and $T_G^{(f)}$
- hard parts change sign for $T_G^{(d)}$

➡ SSA will be very different for D and $\bar{D}$ if $T_G^{(d)}\neq 0$
SSA will be very similar for D and $\bar{D}$ if $T_G^{(d)}=0$

Rapidity dependence of D-meson production

- SSA at RHIC: $\sqrt{s} = 200$ GeV $\quad \mu = \sqrt{m_c^2 + P_{h\perp}^2} \quad m_c = 1.3$ GeV





Solid: $(1)\lambda_f = \lambda_d = 0.07$ GeV $\quad T_G^{(d)} = T_G^{(f)}$

Dotted: $(2)\lambda_f = -\lambda_d = 0.07$ GeV $\quad T_G^{(d)} = -T_G^{(f)}$

Dashed: $(3)\lambda_f = \lambda_d = 0 \quad T_G^{(d)} = T_G^{(f)} = 0$

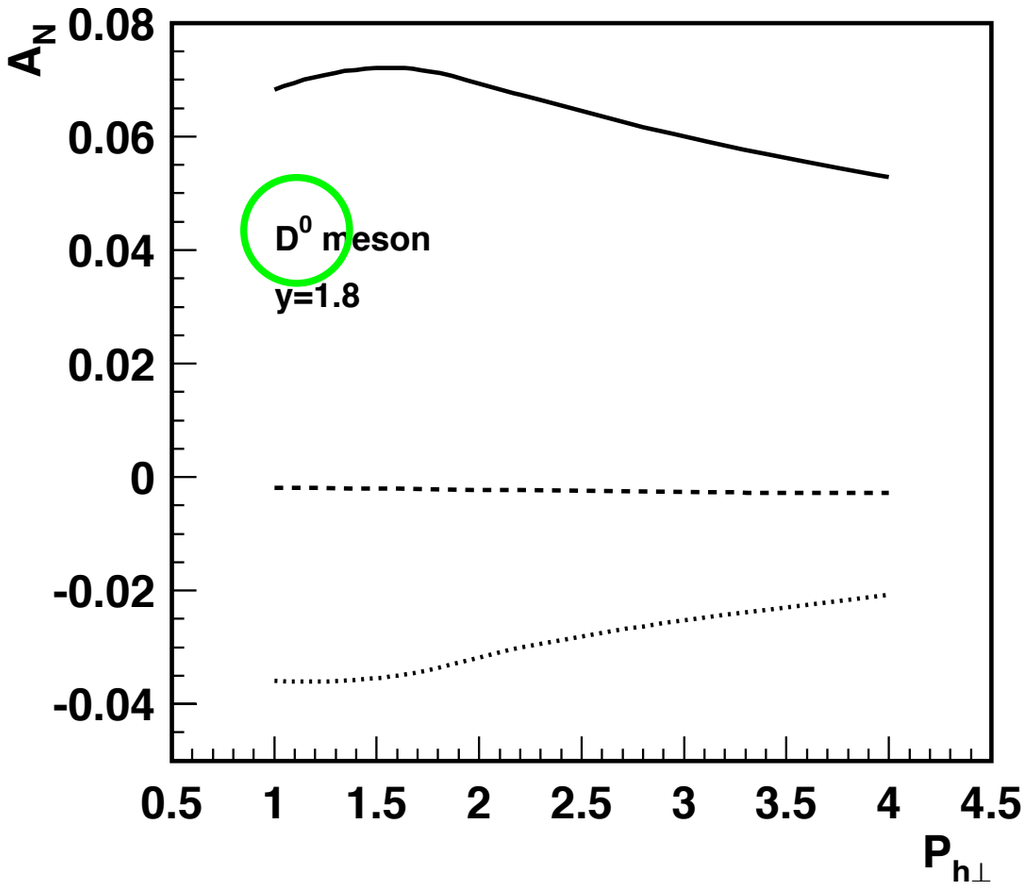
D meson : Largest A_N happens when $T_G^{(d)} = +T_G^{(f)}$

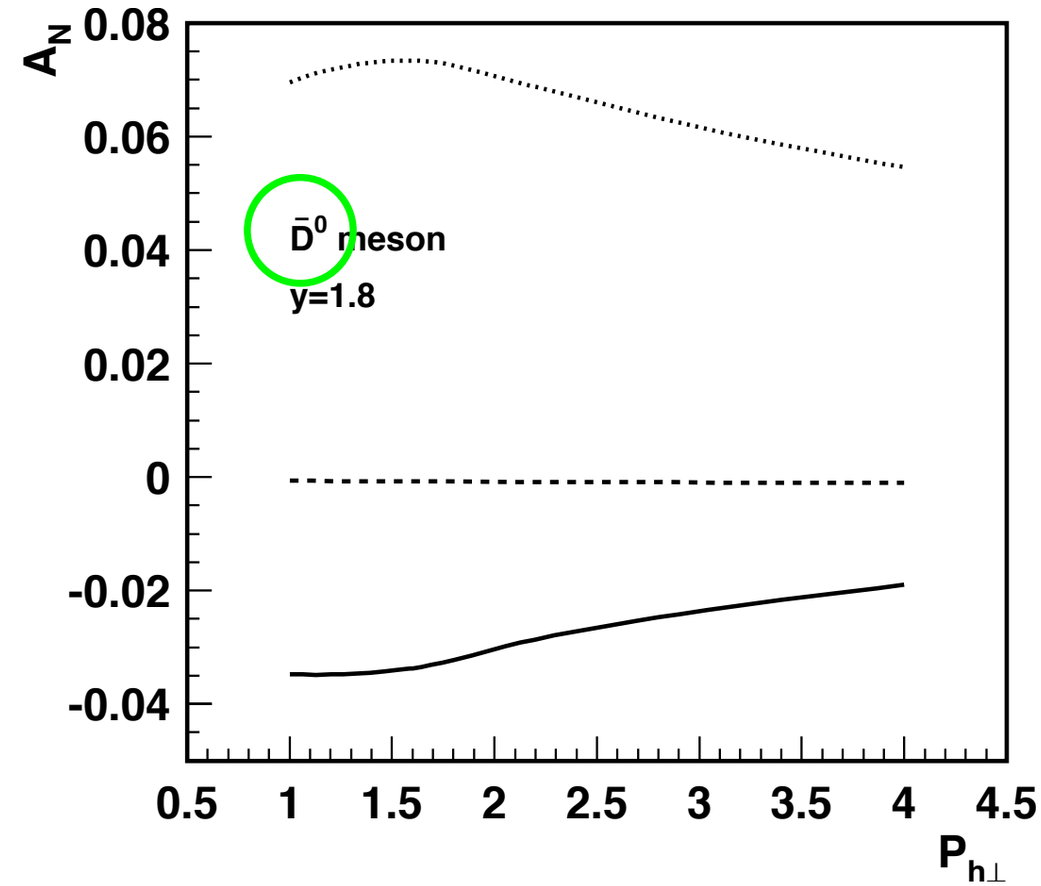
$\bar{D}$ meson : Largest A_N happens when $T_G^{(d)} = -T_G^{(f)}$

P_T-dependence of D-meson production

- SSA at RHIC

$\sqrt{s} = 200$ GeV $\quad \mu = \sqrt{m_c^2 + P_{h\perp}^2} \quad m_c = 1.3$ GeV





Solid: $(1)\lambda_f = \lambda_d = 0.07$ GeV $\quad T_G^{(d)} = T_G^{(f)}$

Dotted: $(2)\lambda_f = -\lambda_d = 0.07$ GeV $\quad T_G^{(d)} = -T_G^{(f)}$

Dashed: $(3)\lambda_f = \lambda_d = 0 \quad T_G^{(d)} = T_G^{(f)} = 0$

- Without tri-gluon correlation, SSA is too small to be observed
- As a twist-3 effect, the SSAs fall off as $1/P_T$ when $P_T >> m_c$

Recent progress on tri-gluon correlation

Kang, Qiu, Vogelsang, Yuan, 2009

- Tri-gluon correlation contribution to the following processes have been studied
  - Drell-Yan: $p^{\uparrow}p \to [\gamma^* \to \ell\bar{\ell}] + X$
  - Single inclusive hadron: $p^{\uparrow}p \to \pi + X$
  - Direct photon: $p^{\uparrow}p \to \gamma + X$

- A new global fitting with both $T_{q,F}(x,x)$ and $T_G(x,x)$ is on the way

  Comparing with SSA for single inclusive pion data from:
  - E704
  - STAR
  - PHENIX

Strong scale dependence of SSA

- So far, all the calculations for SSA are at leading order (LO)

$$\Delta\sigma(Q, s_T) = \frac{1}{Q} H_1(Q/\mu_F, \alpha_s) \otimes f_2(\mu_F) \otimes f_3(\mu_F) + \mathcal{O}\left(\frac{1}{Q^2}\right)$$

- LO result has a strong scale dependence

  - Evolution of correlation function (long-distance distributions)
  - NLO correction (short-distance contribution beyond LO)

- Question: what are the complete set of correlation functions?

Recall: Leading twist (DGLAP evolution equation)

- unpolarized PDFs: $q(x)$, $G(x)$
- helicity distributions: $\Delta q(x)$, $\Delta G(x)$

twist-3 spin dependent correlations:

two sets of correlation functions

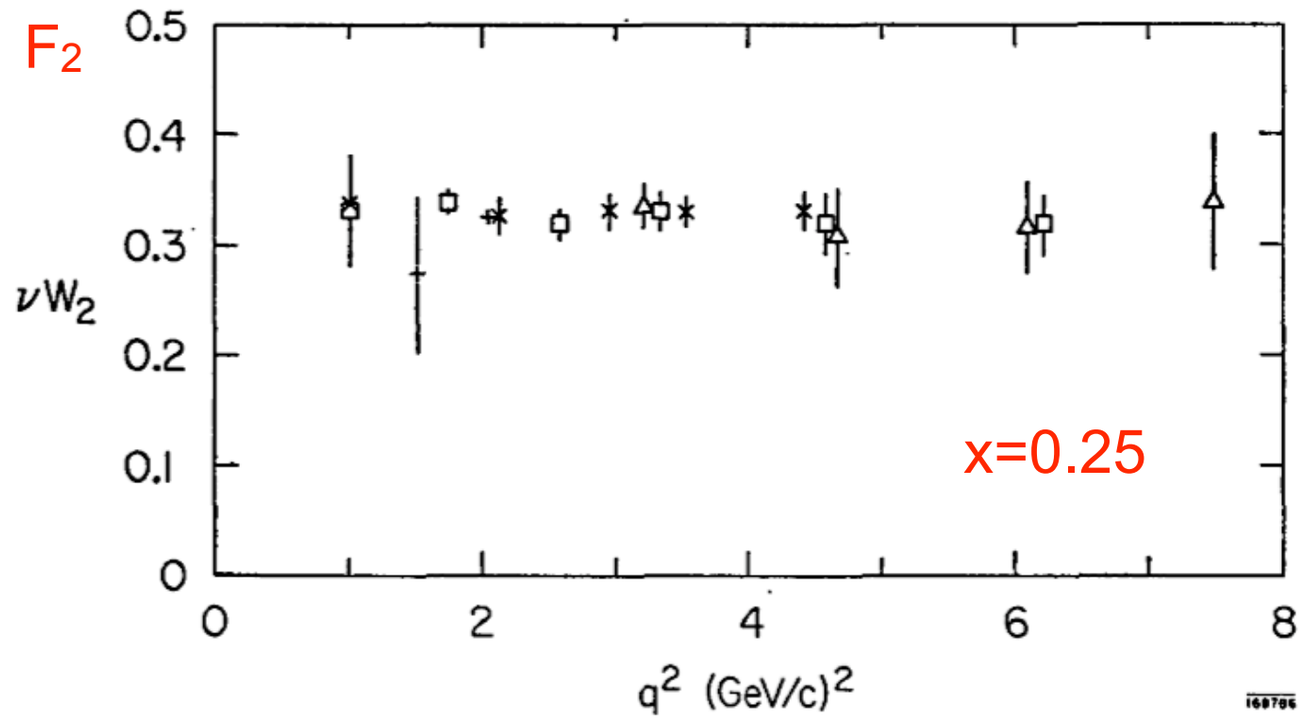
Evolution distinguishes QCD from parton model

- Parton model: Bjorken scaling (point particles)

Friedman, Kendall, 1972

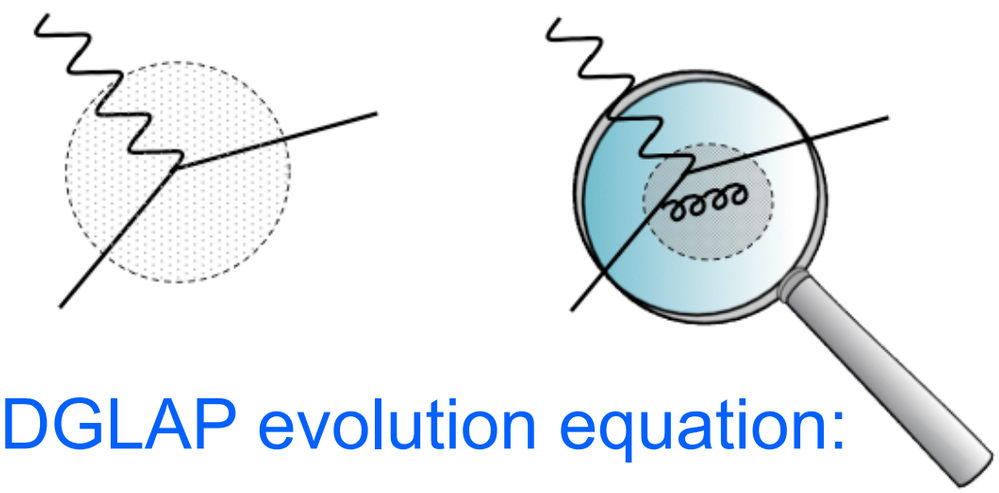
$$F_2(x) = \sum_q e_q^2 \, x \, \phi_q(x)$$

confirmed in the 1970s at SLAC

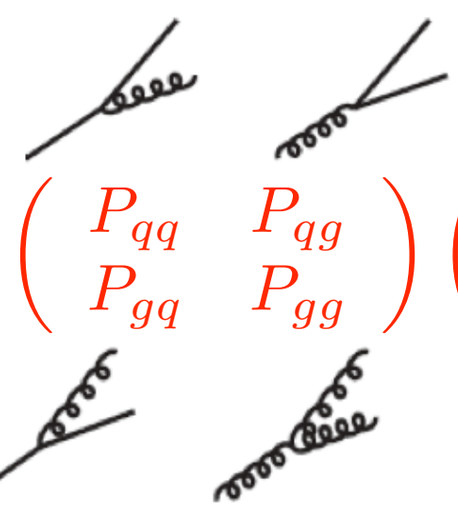


- QCD is much richer:

Q_0^2 $\qquad$ $Q^2 > Q_0^2$



- DGLAP evolution equation:

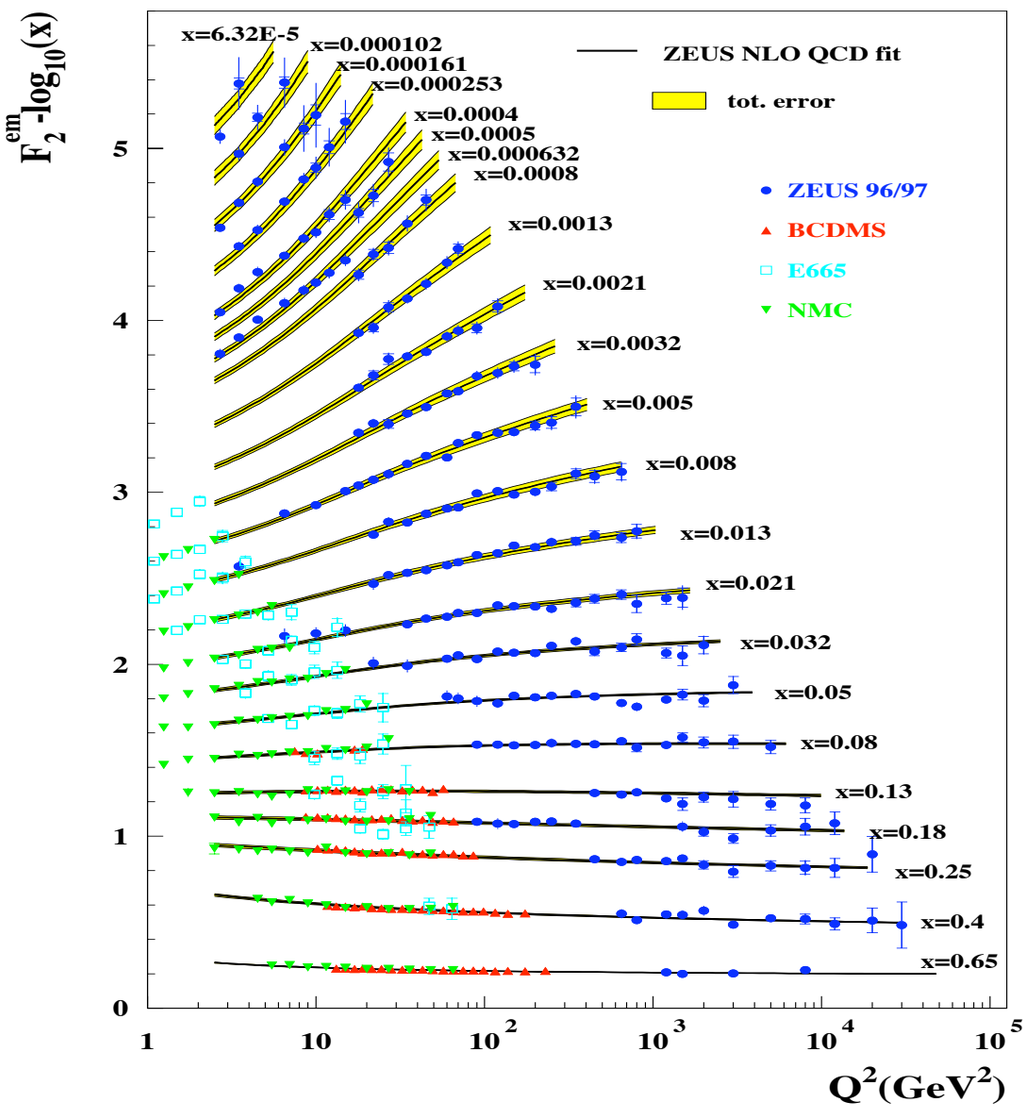


$$\frac{\partial}{\partial \ln \mu^2} \begin{pmatrix} q(x,\mu^2) \\ g(x,\mu^2) \end{pmatrix} = \frac{\alpha_s(\mu^2)}{2\pi} \int_x^1 \frac{dy}{y} \begin{pmatrix} P_{qq} & P_{qg} \\ P_{gq} & P_{gg} \end{pmatrix} \begin{pmatrix} q \\ g \end{pmatrix} \left(\frac{x}{y}, \mu^2 \right)$$

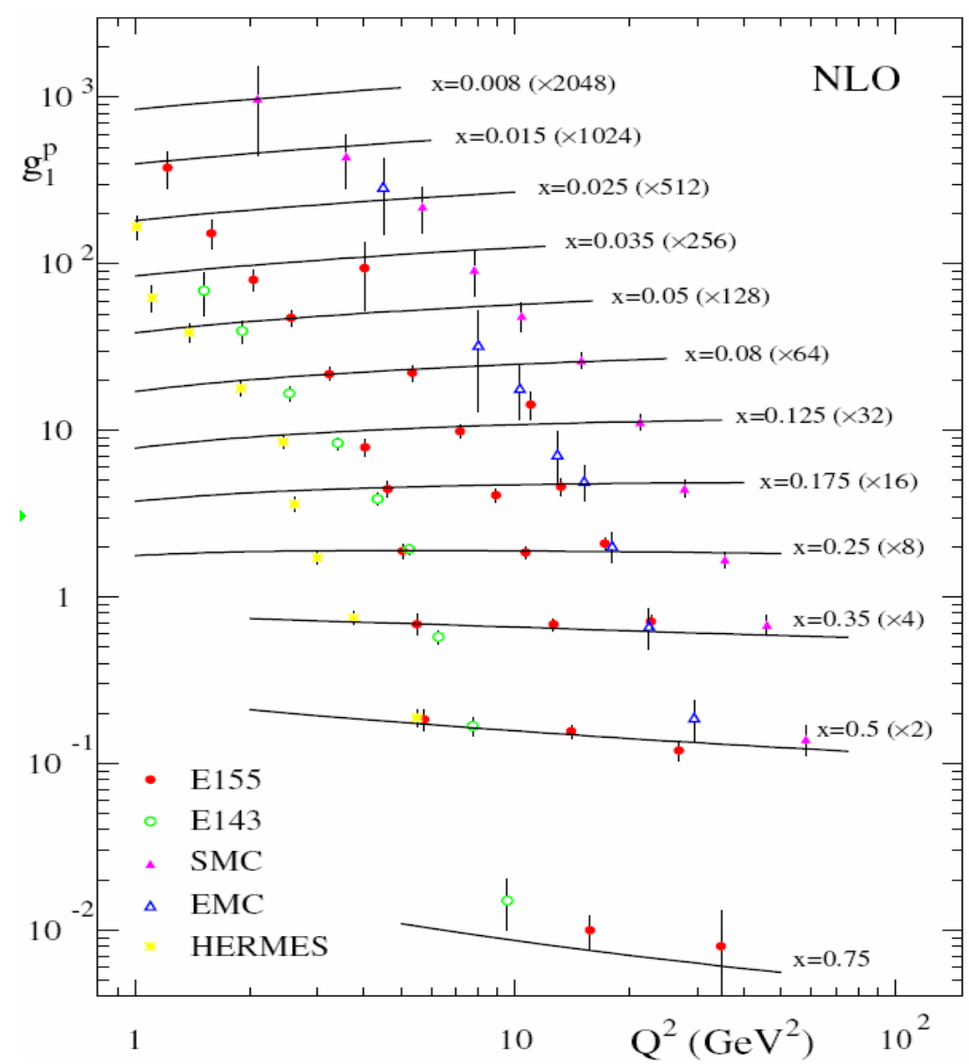
Scaling violation and evolution has been confirmed

- NLO DGLAP (scale dependence) for both PDF and Helicity Distribution Function (HDF) describes data very well

unpolarized structure function F_2



polarized structure function g_1



Twist-3 three-parton correlations

Qiu, Sterman, 1991, 1998

- Set I: **spin-averaged twist-2 PDFs + an operator Insertion** Ji, 1992, Kang, Qiu, 2008

$$\widetilde{\mathcal{T}}_{q,F} = \int \frac{dy_1^- dy_2^-}{(2\pi)^2} e^{ixP^+y_1^-} e^{ix_2P^+y_2^-} \langle P, s_T|\overline{\psi}_q(0) \frac{\gamma^+}{2} \left[\epsilon^{s_T\sigma n\bar{n}} F_\sigma{}^+(y_2^-)\right] \psi_q(y_1^-)|P, s_T\rangle \qquad q(x)$$

$$\widetilde{\mathcal{T}}_{G,F}^{(f,d)} = \int \frac{dy_1^- dy_2^-}{(2\pi)^2} e^{ixP^+y_1^-} e^{ix_2P^+y_2^-} \frac{1}{P^+} \langle P, s_T|F^{+\rho}(0) \left[\epsilon^{s_T\sigma n\bar{n}} F_\sigma{}^+(y_2^-)\right] F^{+\lambda}(y_1^-)|P, s_T\rangle (-g_{\rho\lambda}) \qquad G(x)$$

- Set II: **spin-dependent twist-2 HDFs + an operator Insertion**

$$\widetilde{\mathcal{T}}_{\Delta q,F} = \int \frac{dy_1^- dy_2^-}{(2\pi)^2} e^{ixP^+y_1^-} e^{ix_2P^+y_2^-} \langle P, s_T|\overline{\psi}_q(0) \frac{\gamma^+\gamma^5}{2} \left[i\, s_T^\sigma\, F_\sigma{}^+(y_2^-)\right] \psi_q(y_1^-)|P, s_T\rangle \qquad \Delta q(x)$$

$$\widetilde{\mathcal{T}}_{\Delta G,F}^{(f,d)} = \int \frac{dy_1^- dy_2^-}{(2\pi)^2} e^{ixP^+y_1^-} e^{ix_2P^+y_2^-} \frac{1}{P^+} \langle P, s_T|F^{+\rho}(0) \left[i\, s_T^\sigma\, F_\sigma{}^+(y_2^-)\right] F^{+\lambda}(y_1^-)|P, s_T\rangle (i\epsilon_{\perp\rho\lambda}) \qquad \Delta G(x)$$

Two possible color contractions: if_{abc}, d_{abc}

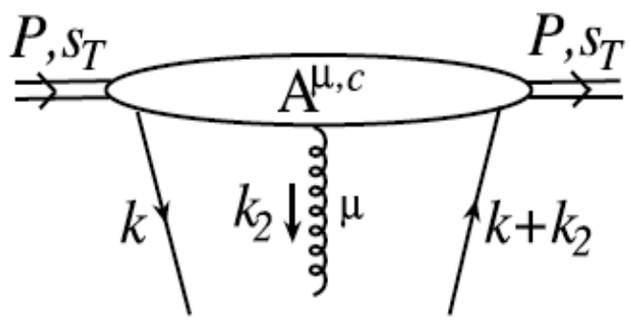
⇒Two tri-gluon correlation functions

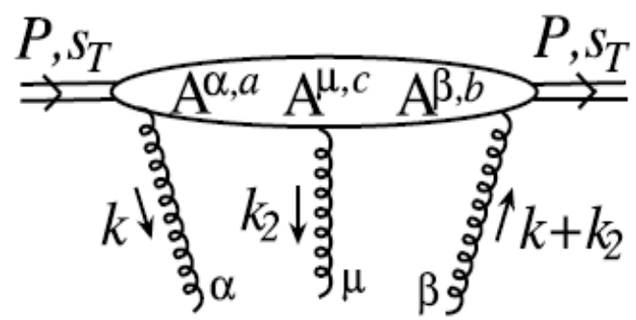
- **$T^{(f)}$ connects to gluon Sivers function**
- **$T^{(d)}$ has no connections to TMD distribution**

Feynman diagram reperesentation

Diagrams:

Kang, Qiu, PRD79: 016003, 2009





$A^{\mu} \leftrightarrow F^{+\mu}$

Lagrangian →	Feynman rules	
	↓	
Cross section ←	Feynman diagrams	

→

Operator definition →	Cut vertices	
	↓	
Perturbative change ←	Feynman diagrams	

Same diagram can represent different correlation functions depending on cut vertices

Cut vertices in the light-cone gauge:

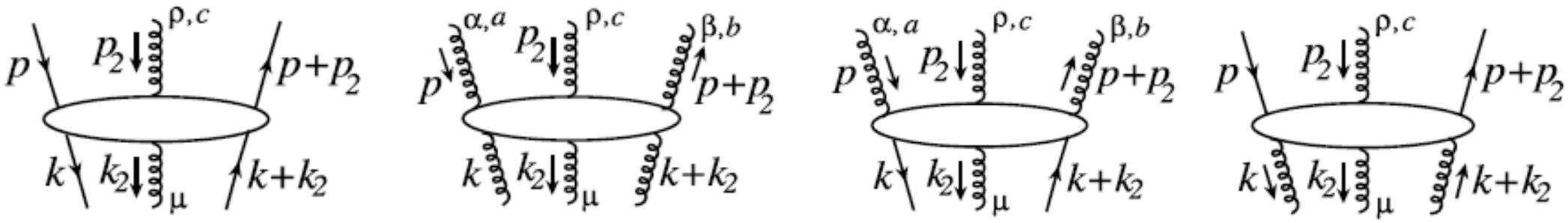
$$\mathcal{V}^{\rm LC}_{q,F} = \frac{\gamma^+}{2P^+}\,\delta\left(x-\frac{k^+}{P^+}\right) x_2\,\delta\left(x_2-\frac{k_2^+}{P^+}\right)\left(i\,\epsilon^{s_T\sigma n\bar{n}}\right)\left[-g_{\sigma\mu}\right]\mathcal{C}_q\,,$$

$$\mathcal{V}^{\rm LC}_{G,F} = x(x+x_2)\left(-g_{\alpha\beta}\right)\delta\left(x-\frac{k^+}{P^+}\right) x_2\,\delta\left(x_2-\frac{k_2^+}{P^+}\right)\left(i\,\epsilon^{s_T\sigma n\bar{n}}\right)\left[-g_{\sigma\mu}\right]\mathcal{C}_g^{(f,d)}\,,$$

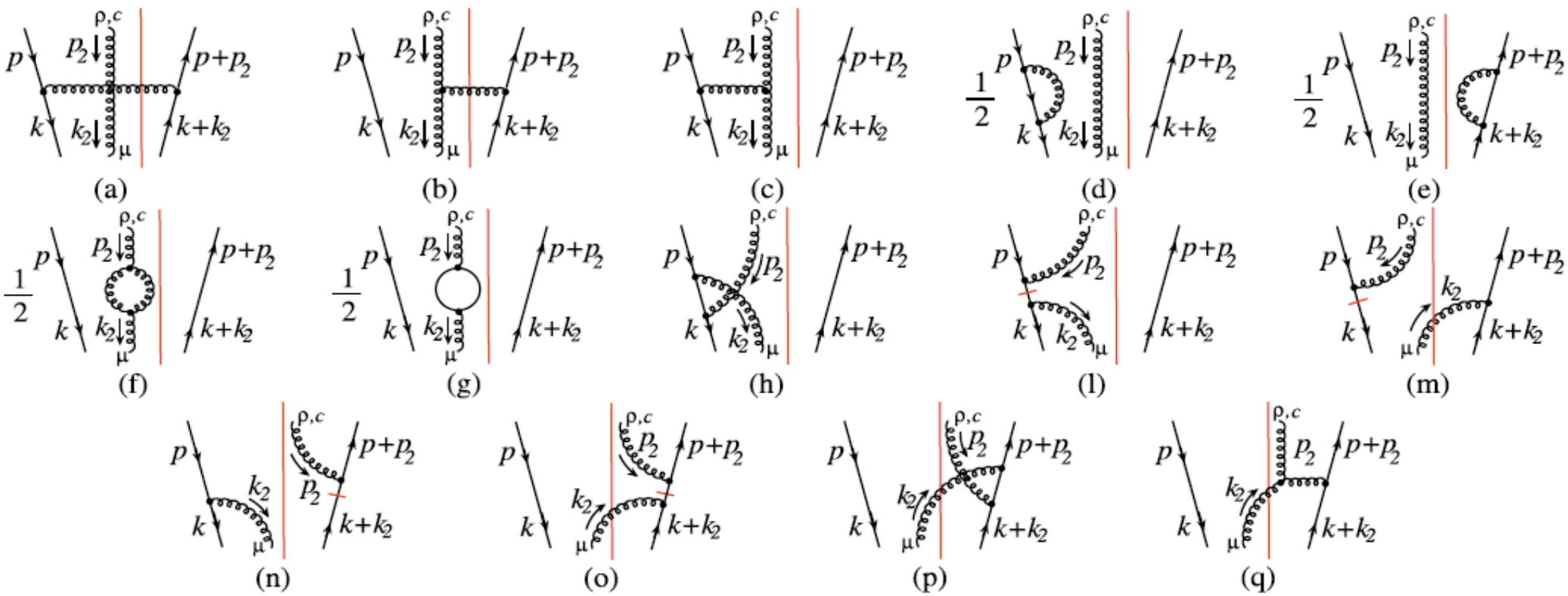
likewise for: $\mathcal{V}^{\rm LC}_{\Delta q,F}$ $\mathcal{V}^{\rm LC}_{\Delta G,F}$

Evolution kernels

- Feynman diagrams:



- Leading order for flavor non-singlet channel:



LO evolution equations - I

Diagonal contribution - Quarks:

relevant to single hadron production

$$\frac{\partial T_{q,F}(x,x,\mu_F)}{\partial \ln \mu_F^2} = \frac{\alpha_s}{2\pi}\int_x^1 \frac{d\xi}{\xi}\Bigg\{ P_{qq}(z)\, T_{q,F}(\xi,\xi,\mu_F)$$
$$+\frac{C_A}{2}\left[\frac{1+z^2}{1-z}\left[T_{q,F}(\xi,x,\mu_F)-T_{q,F}(\xi,\xi,\mu_F)\right]+z\,T_{q,F}(\xi,x,\mu_F)\right]+\frac{C_A}{2}\left[T_{\Delta q,F}(x,\xi,\mu_F)\right]$$
$$+P_{qg}(z)\left(\frac{1}{2}\right)\left[T^{(d)}_{G,F}(\xi,\xi,\mu_F)+T^{(f)}_{G,F}(\xi,\xi,\mu_F)\right]\Bigg\}$$

Diagonal contribution - Anti-quarks:

$$\frac{\partial T_{\bar q,F}(x,x,\mu_F)}{\partial \ln \mu_F^2} = \frac{\alpha_s}{2\pi}\int_x^1 \frac{d\xi}{\xi}\Bigg\{ P_{qq}(z)\, T_{\bar q,F}(\xi,\xi,\mu_F)$$
$$+\frac{C_A}{2}\left[\frac{1+z^2}{1-z}\left[T_{\bar q,F}(\xi,x,\mu_F)-T_{\bar q,F}(\xi,\xi,\mu_F)\right]+z\,T_{\bar q,F}(\xi,x,\mu_F)\right]+\frac{C_A}{2}\left[T_{\Delta \bar q,F}(x,\xi,\mu_F)\right]$$
$$+P_{qg}(z)\left(\frac{1}{2}\right)\left[T^{(d)}_{G,F}(\xi,\xi,\mu_F)-T^{(f)}_{G,F}(\xi,\xi,\mu_F)\right]\Bigg\}$$

1. All kernels are Infared safe

2. Diagonal term is the same as DGLAP

3. Singlet terms are different for quark and anti-quark

$\Rightarrow$ they evolve differently (from tri-gluon correlations)

LO evolution equations - II

Diagonal contribution - Gluons:

$$\frac{\partial T^{(d)}_{G,F}(x,x,\mu_F)}{\partial \ln \mu_F^2} = \frac{\alpha_s}{2\pi}\int_x^1 \frac{d\xi}{\xi}\Bigg\{ P_{gg}(z)\, T^{(d)}_{G,F}(\xi,\xi,\mu_F)$$
$$+\frac{C_A}{2}\Bigg[2\left(\frac{z}{1-z}+\frac{1-z}{z}+z(1-z)\right)\left[T^{(d)}_{G,F}(\xi,x,\mu_F)-T^{(d)}_{G,F}(\xi,\xi,\mu_F)\right]$$
$$+2\left(1-\frac{1-z}{2z}-z(1-z)\right)T^{(d)}_{G,F}(\xi,x,\mu_F)+(1+z)\,T^{(d)}_{\Delta G,F}(x,\xi,\mu_F)\Bigg]$$
$$+P_{gq}(z)\left(\frac{N_c^2-4}{N_c^2-1}\right)\sum_q\left[T_{q,F}(\xi,\xi,\mu_F)+T_{\bar{q},F}(\xi,\xi,\mu_F)\right]\Bigg\}$$

likewise for $T^{(f)}_{G,F}(x,x,\mu_F)$

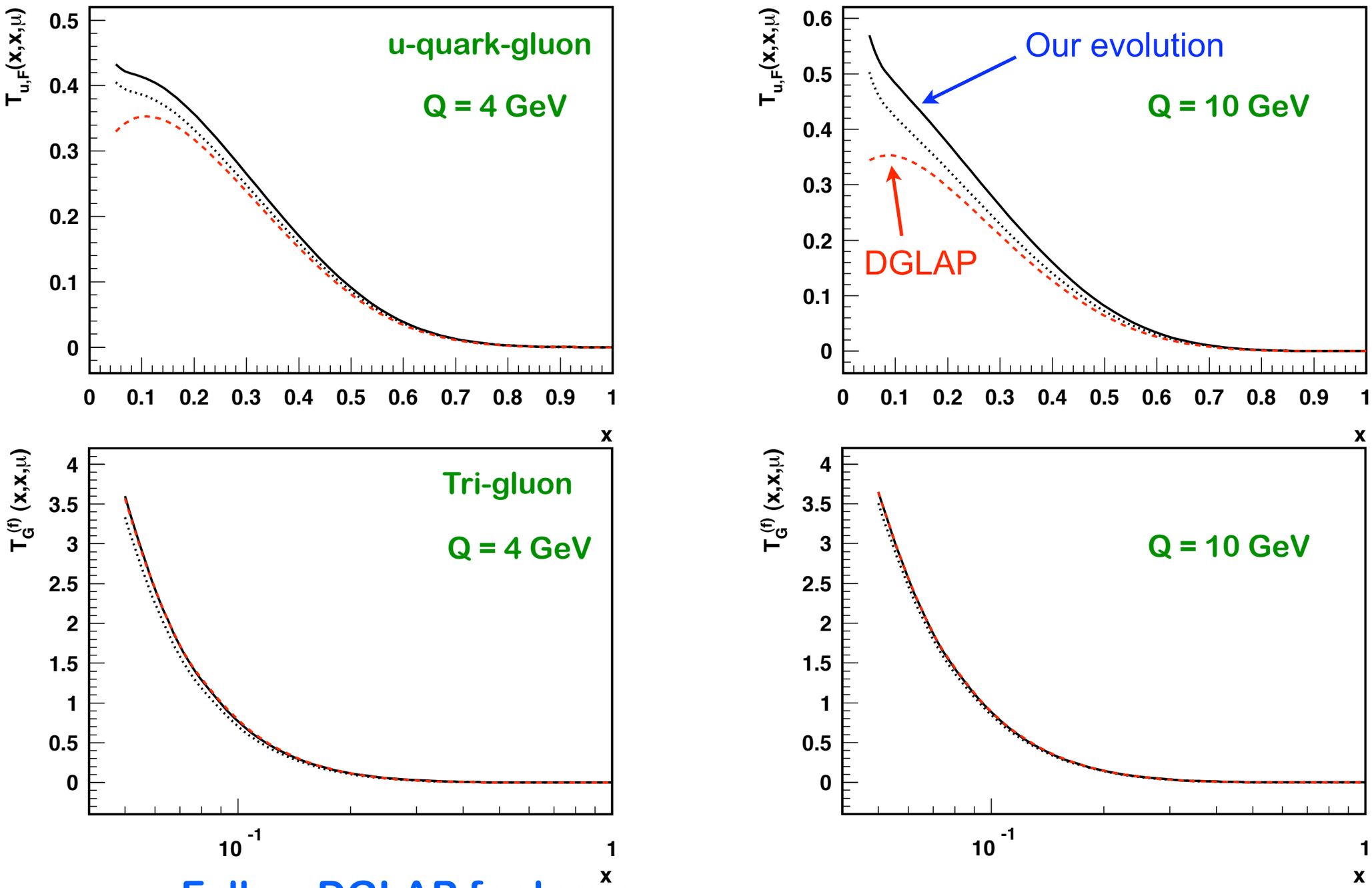
1. Similar features as in quark case:

IR safe, diagonal term same as DGLAP

2. $T^{(d)}_G$ **has no connection to TMD distribution. One may argue that** $T^{(d)}_G = 0$ **, however,**

Evolution can generate $T^{(d)}_G$ **as long as** $\sum_q [T_{q,F}+T_{\bar{q},F}] \neq 0$

Q^2 - Dependence of correlation functions



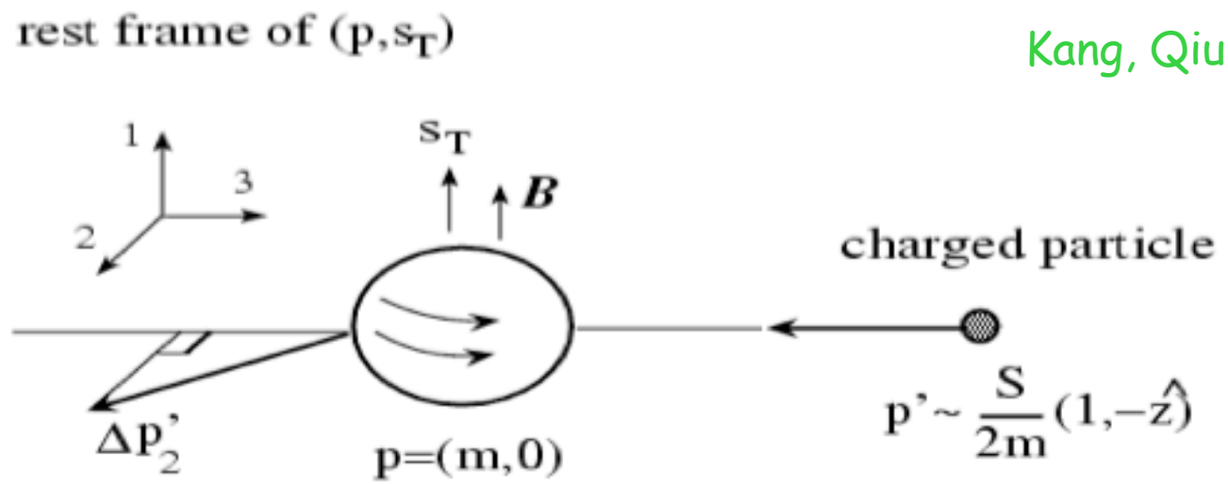
- Follow DGLAP for large x
- Large deviation in small x region (large coherence)

What can we learn from twist-3 correlation functions?

Set I: $\int dy^- \epsilon^{s_T \sigma n \bar{n}} F_\sigma{}^+(y^-)$ Set II: $\int dy_2^- e^{ix_2 P^+ y_2^-} \left[i s_T^\sigma F_\sigma{}^+(y_2^-) \right]$

Kang, Qiu, Sterman, in preparation

- Consider a classical (Abelian) situation:



– change of transverse momentum

$$\frac{d}{dt} p_2' = e(\vec{v}' \times \vec{B})_2 = -e v_3 B_1 = e v_3 F_{23}$$

– in the c.m. frame

$$(m, \vec{0}) \to \bar{n} = (1, 0, 0_T), \quad (1, -\hat{z}) \to n = (0, 1, 0_T)$$

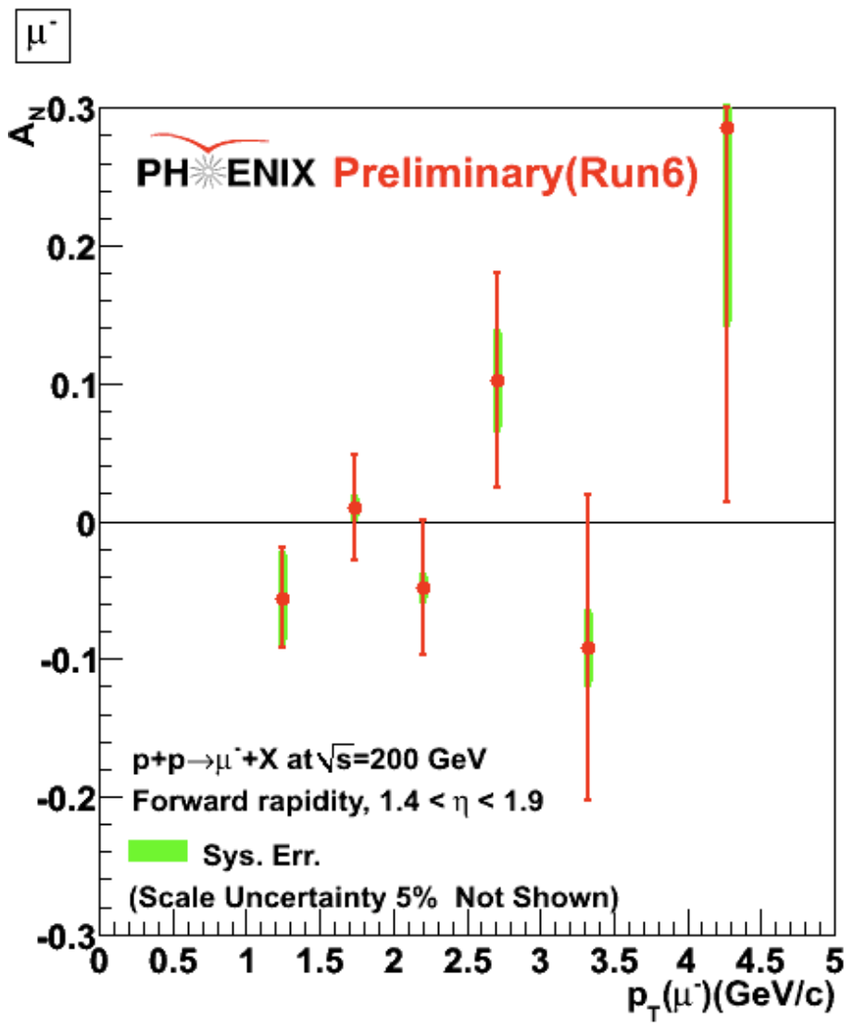
$$\Longrightarrow \frac{d}{dt} p_2' = e\, \epsilon^{s_T \sigma n \bar{n}} F_\sigma{}^+$$

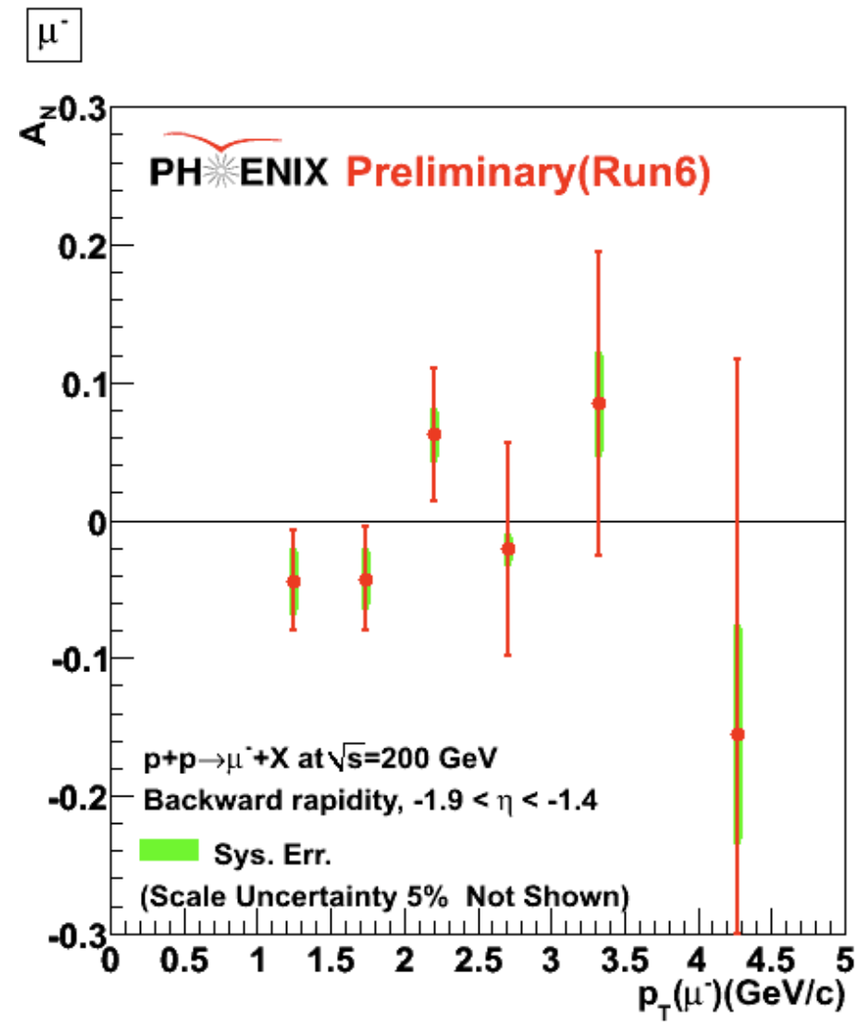
– total change: $\Delta p_2' = e \int dy^- \epsilon^{s_T \sigma n \bar{n}} F_\sigma{}^+(y^-)$ → Set I

Set II: $\int dy_2^- e^{ix_2 P^+ y_2^-} \left[s_T^\sigma F_\sigma{}^+(y_2^-) \right] \propto \mu \cdot B$

New experimental data: heavy flavor production

- Asymmetry for muon decay from open charm:



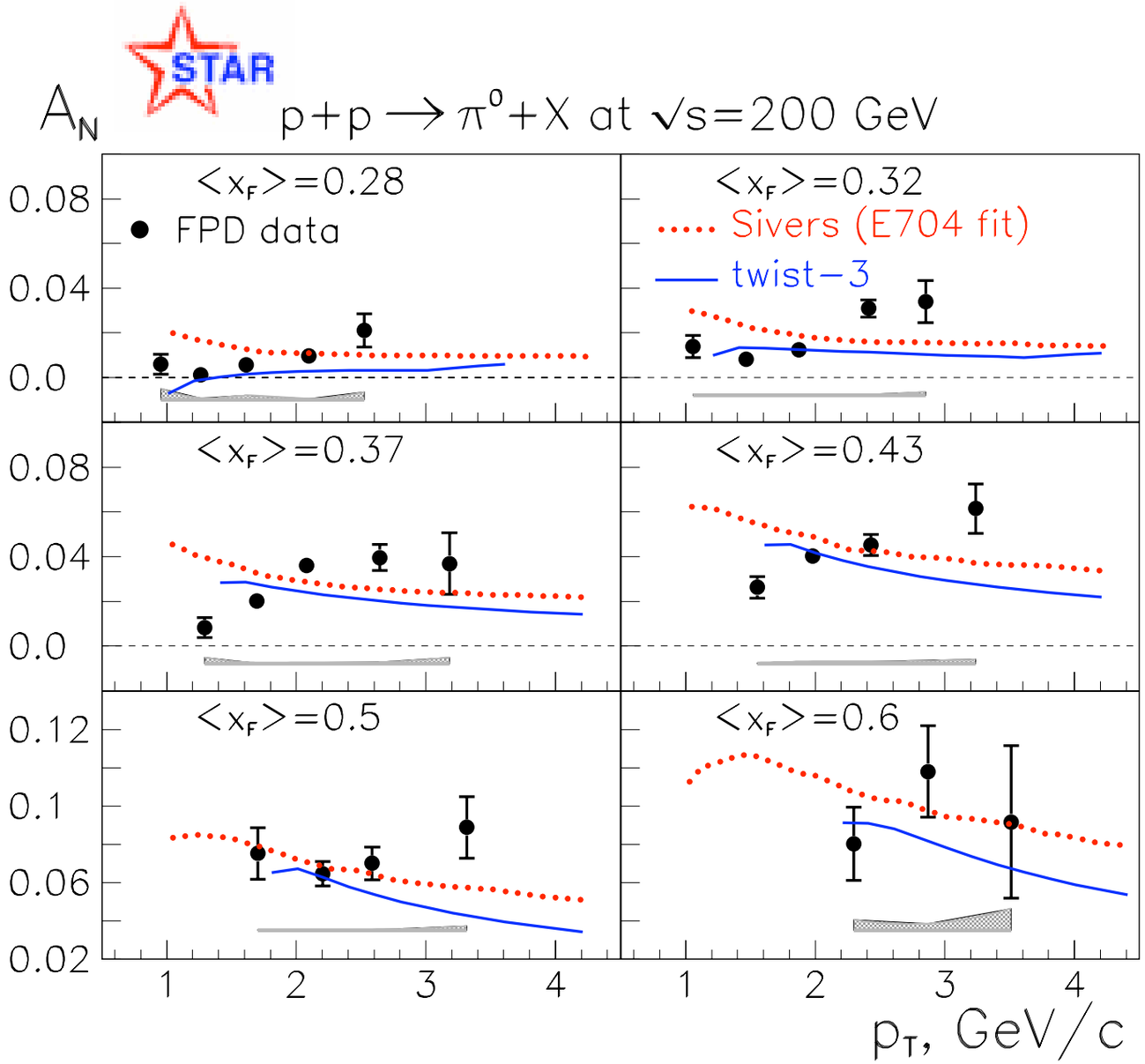


- Too large error bar
- Not able to constrain tri-gluon correlations

New experimental data: pT dependence, puzzle?

pT dependence of asymmetry for pion production

Kang, Qiu, in preparation



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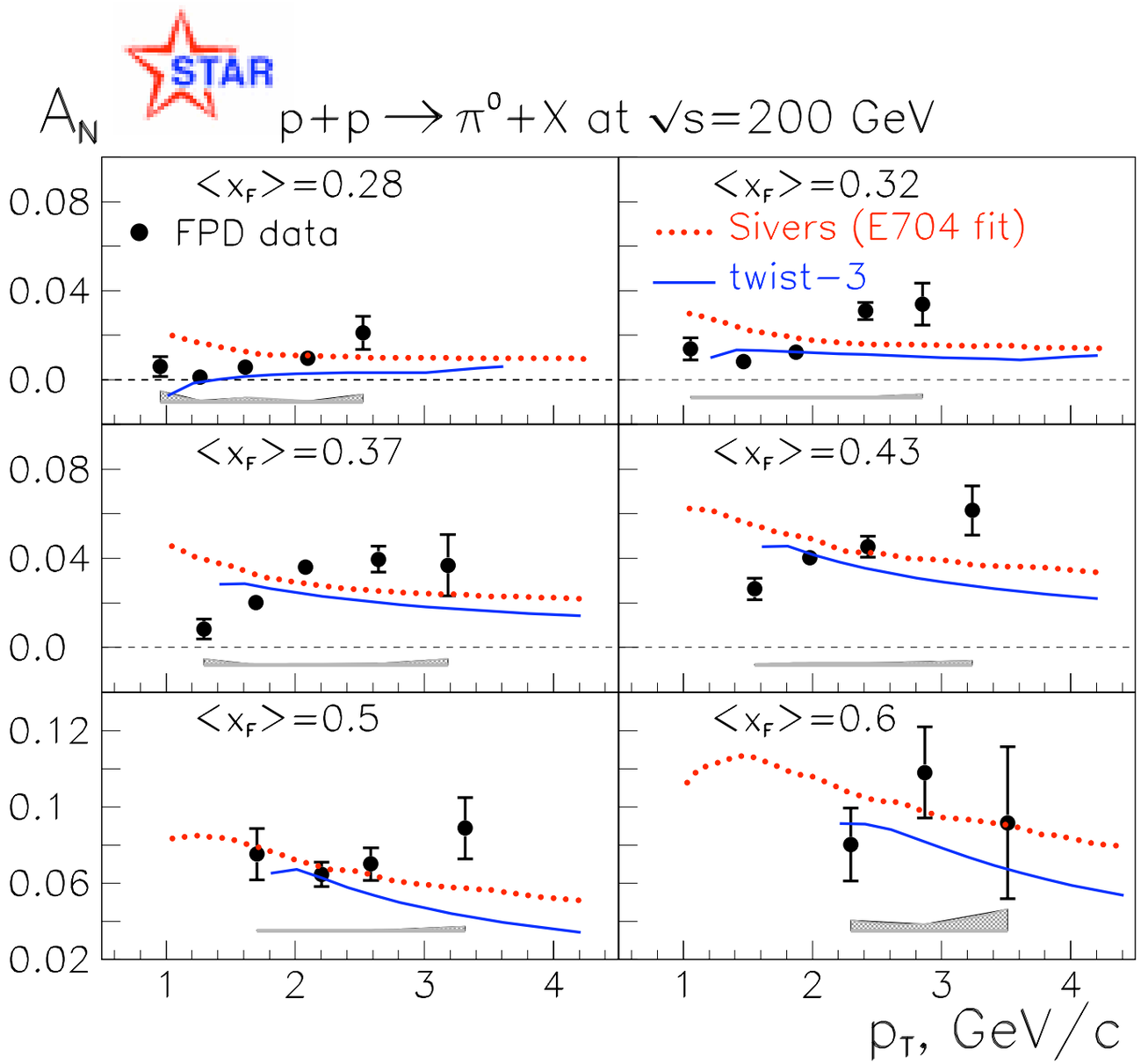
Kang, Qiu, in preparation



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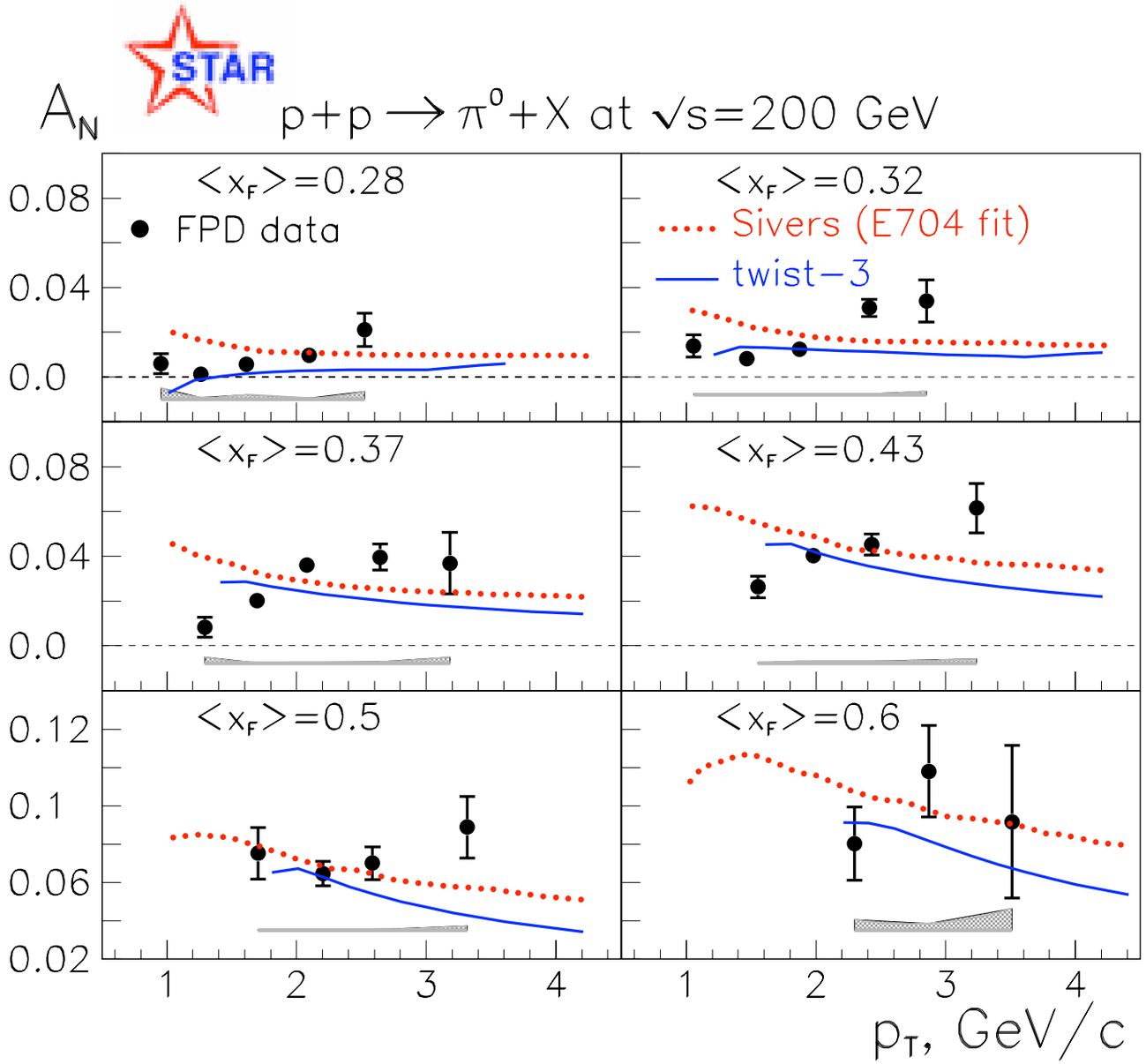
Kang, Qiu, in preparation



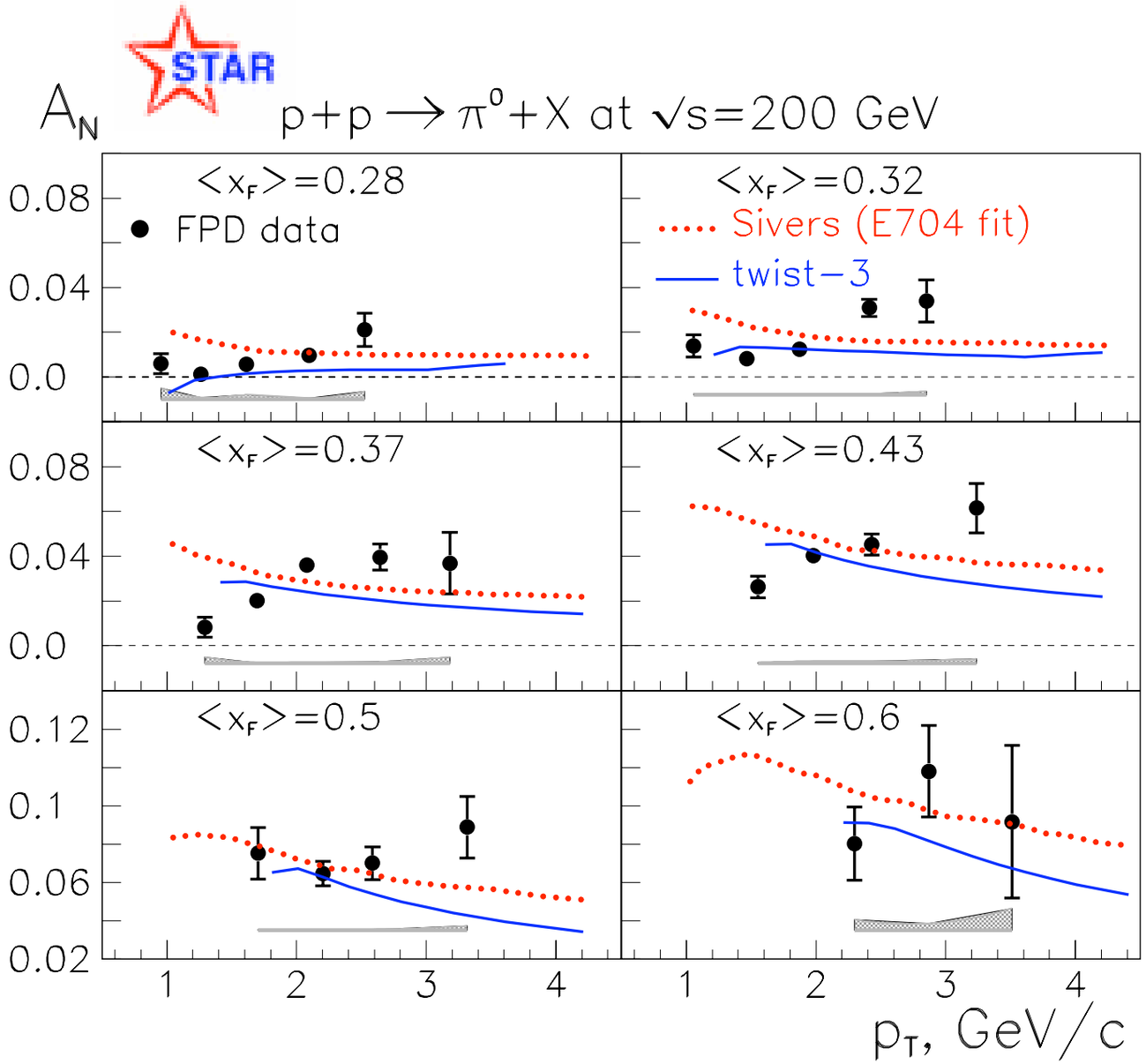
- pT=0: A_N=0

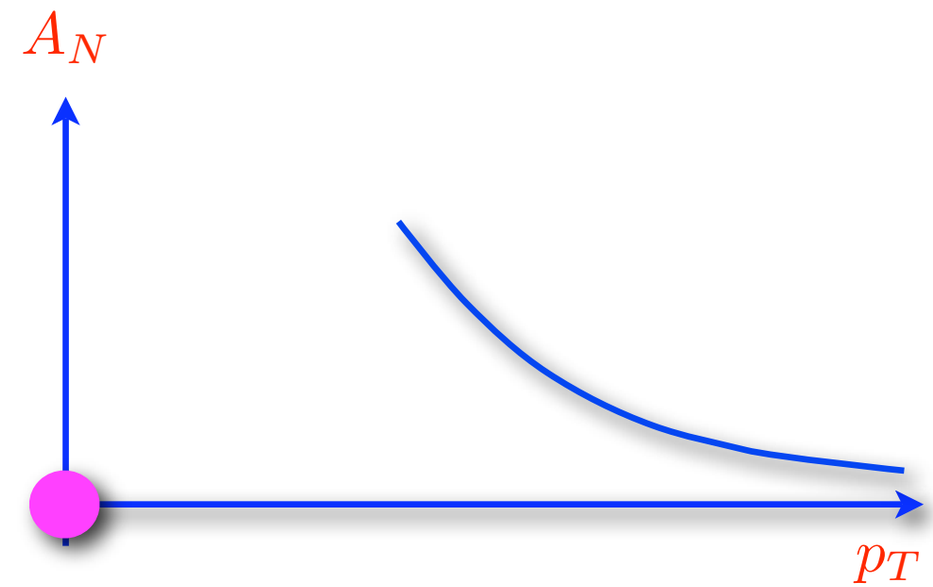
  no plane any more

New experimental data: pT dependence, puzzle?

pT dependence of asymmetry for pion production

Kang, Qiu, in preparation





- pT=0: A_N=0

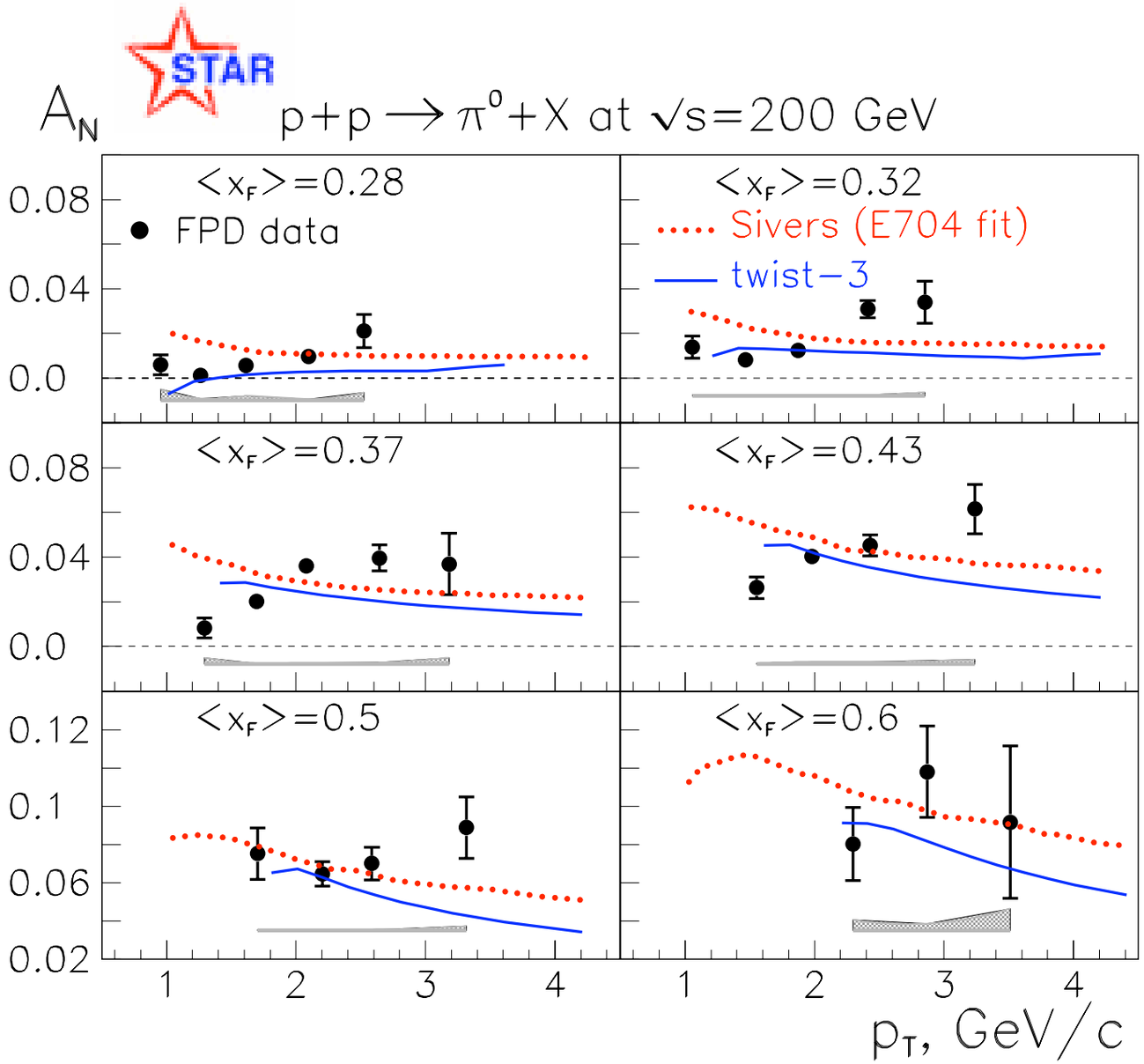
  no plane any more
- very large pT: approach to 0

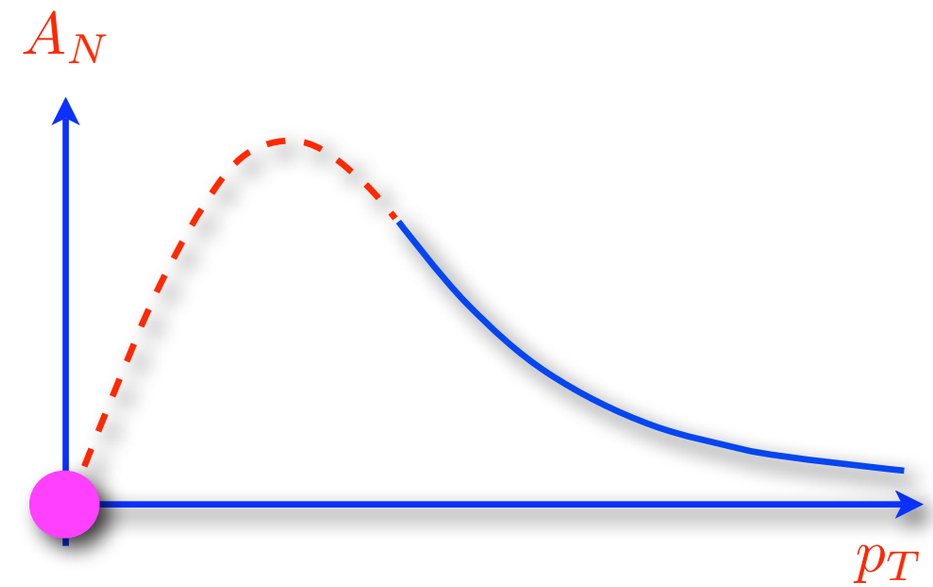
  higher-twist, suppressed by $1/p_T$

New experimental data: pT dependence, puzzle?

pT dependence of asymmetry for pion production

Kang, Qiu, in preparation



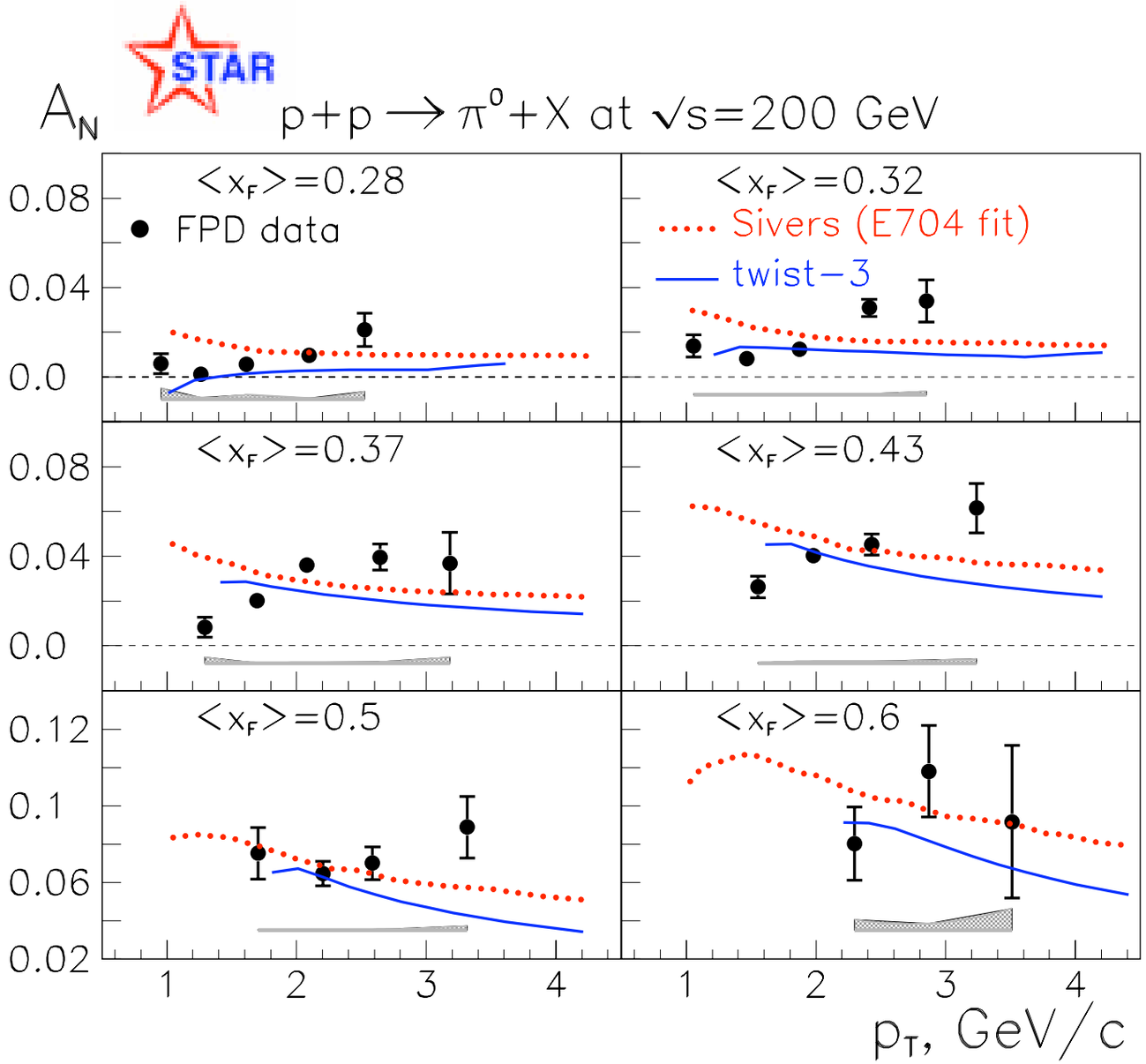


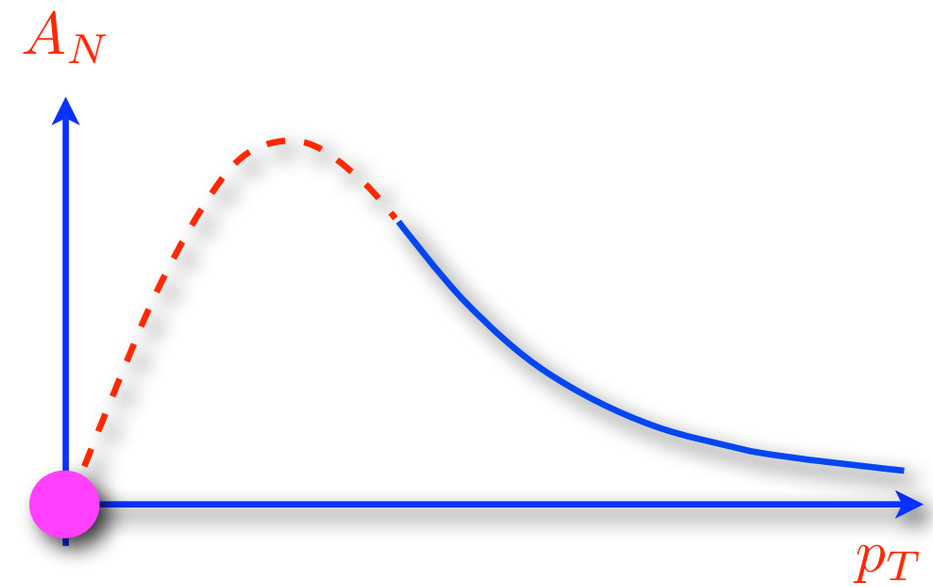
- pT=0: A_N=0
  no plane any more
- very large pT: approach to 0
  higher-twist, suppressed by $1/p_T$
- natural connection
  all power resummation?

New experimental data: pT dependence, puzzle?

- pT dependence of asymmetry for pion production

Kang, Qiu, in preparation





- pT=0: A_N=0

  no plane any more
- very large pT: approach to 0

  higher-twist, suppressed by $1/p_T$
- natural connection

  all power resummation?

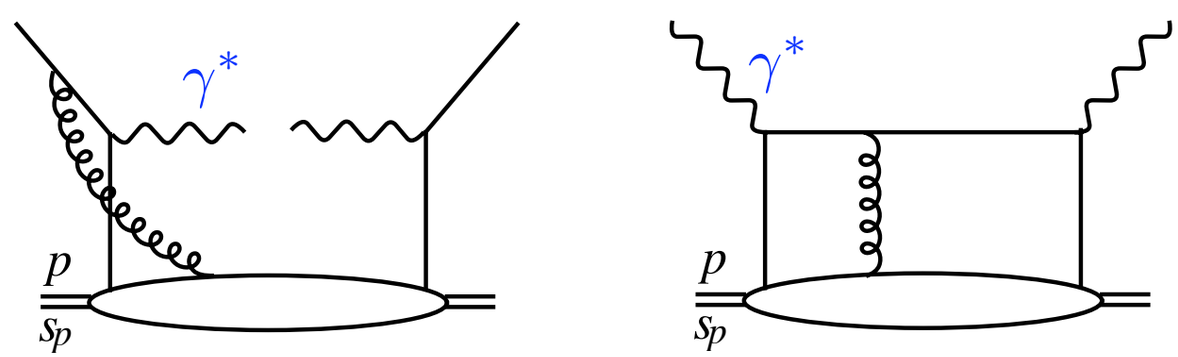
- STAR future measurements: test high pT part

TMD approach

- TMD factorization applies for the process with two observed momentum scales:

$$Q_1 \gg Q_2 \begin{cases} Q_1 & \text{necessary for pQCD factorization to have a chance} \\ Q_2 & \text{sensitive to parton's transverse momentum} \end{cases}$$

- Very limited processes with valid TMD factorization
  - Drell-Yan transverse momentum distribution: Q, q_T
  - Semi-inclusive DIS: Q, p_T (eg, JLab, HERMES, ...)
- How it works:
  - TMD: the quark orbital angular momentum leads to helicity flip
  - The factorizable initial (final) state interactions -- the gauge link provides the phase

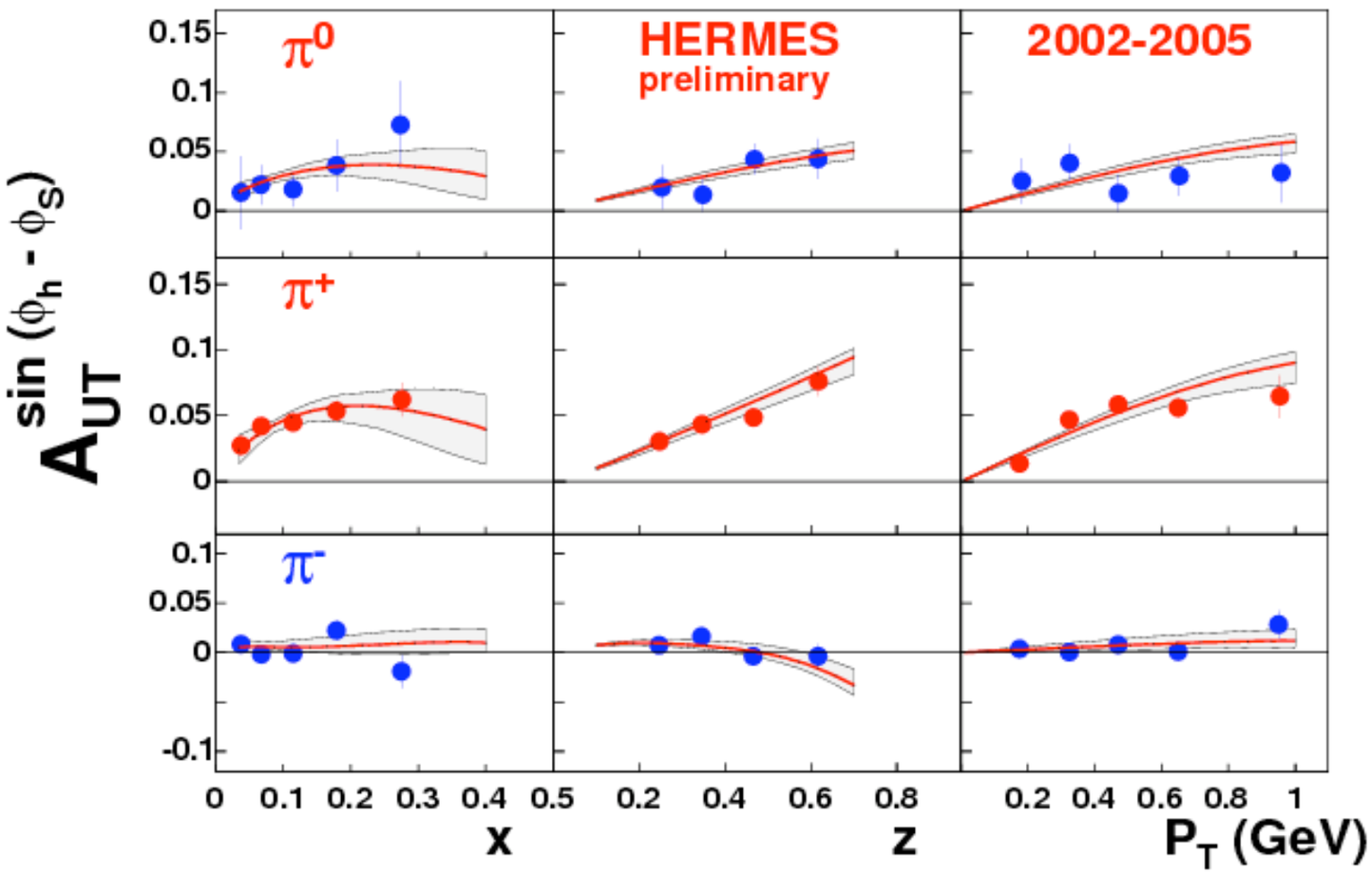


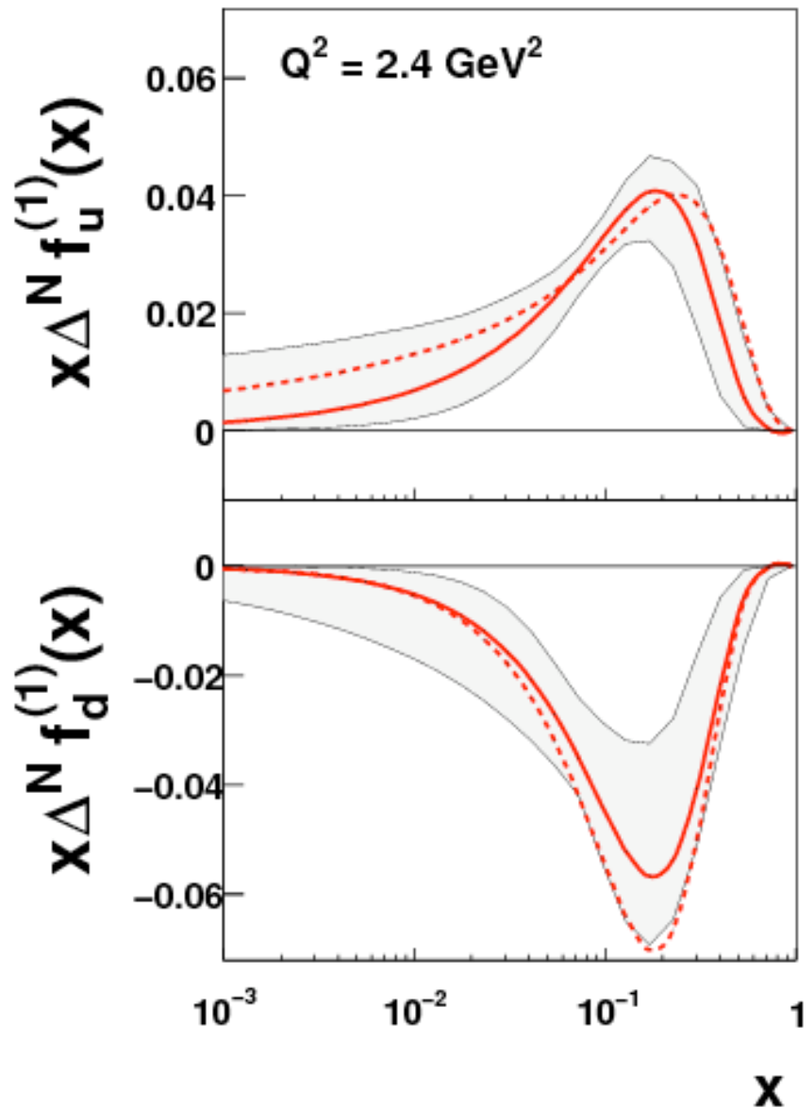
Most critical test: $\mathbf{Sivers}|_{\mathbf{DY}} = -\,\mathbf{Sivers}|_{\mathbf{DIS}}$

Sivers function from SIDIS

- Extract Sivers function from SIDIS

Anselmino, et.al., 2009





SIDIS	QCD ➡	DY
$\text{Sivers}_{\text{u-quark}} > 0$		$\text{Sivers}_{\text{u-quark}} < 0$
$\text{Sivers}_{\text{d-quark}} < 0$		$\text{Sivers}_{\text{d-quark}} > 0$

- large uncertainty
- Improvement expected from JLab

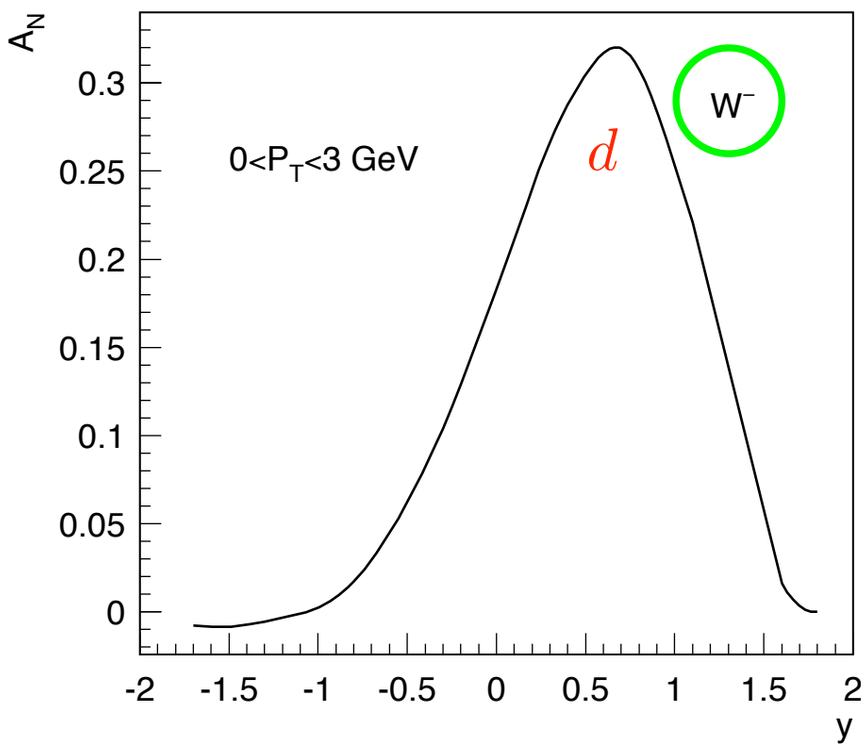
Test of "universality": W production at RHIC (I)

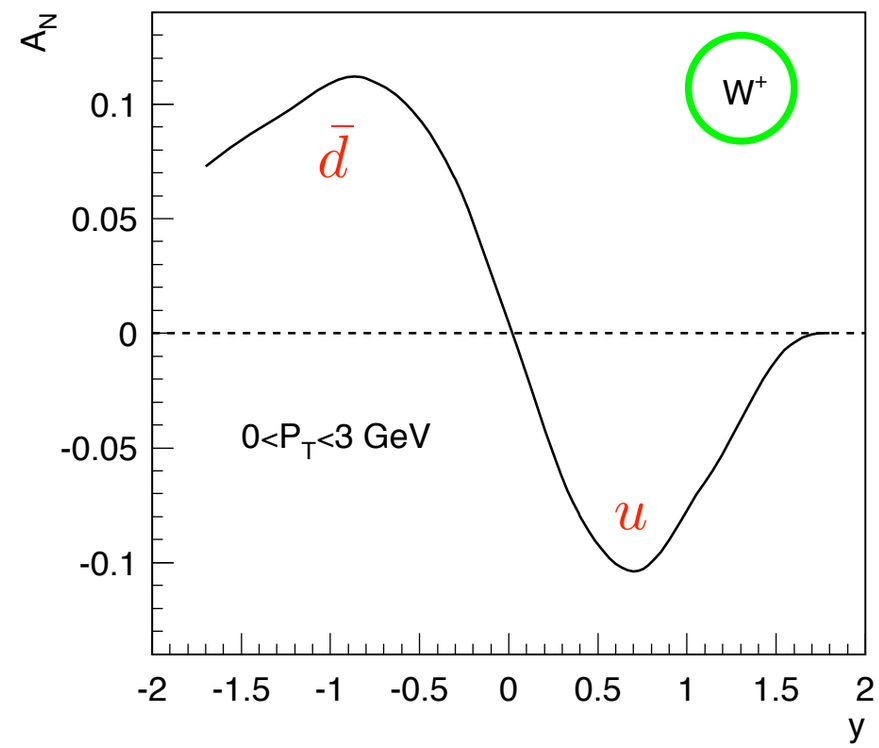
Kang, Qiu, 2009

Take advantage of RHIC W program, do transverse spin physics

- If one reconstructs W boson:

  Sivers function same as DY, different from SIDIS by a sign





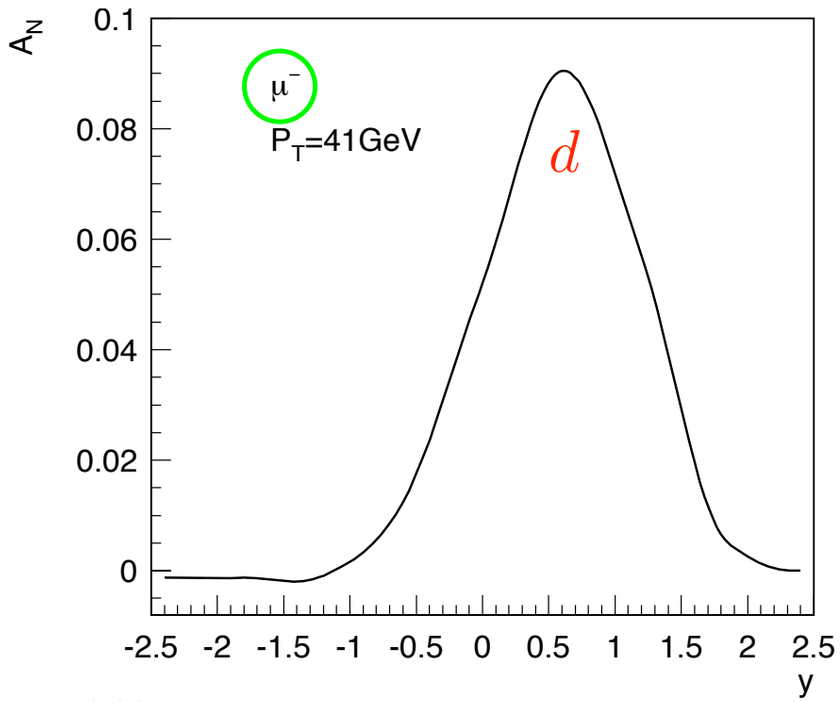
  - flavor separation
  - large asymmetry: should be able to see sign change

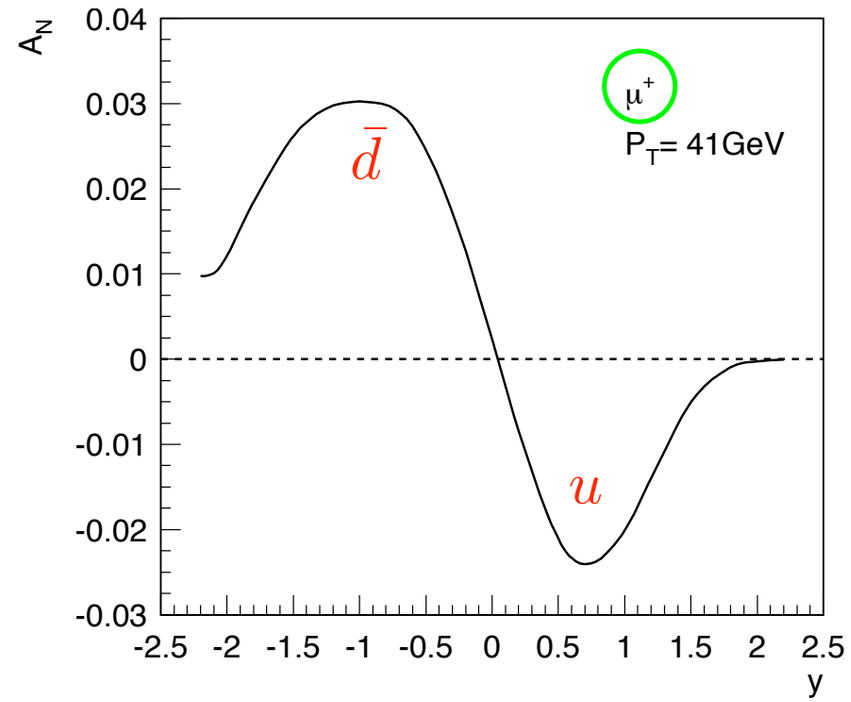
- The only problem is that RHIC does NOT reconstruct W boson:

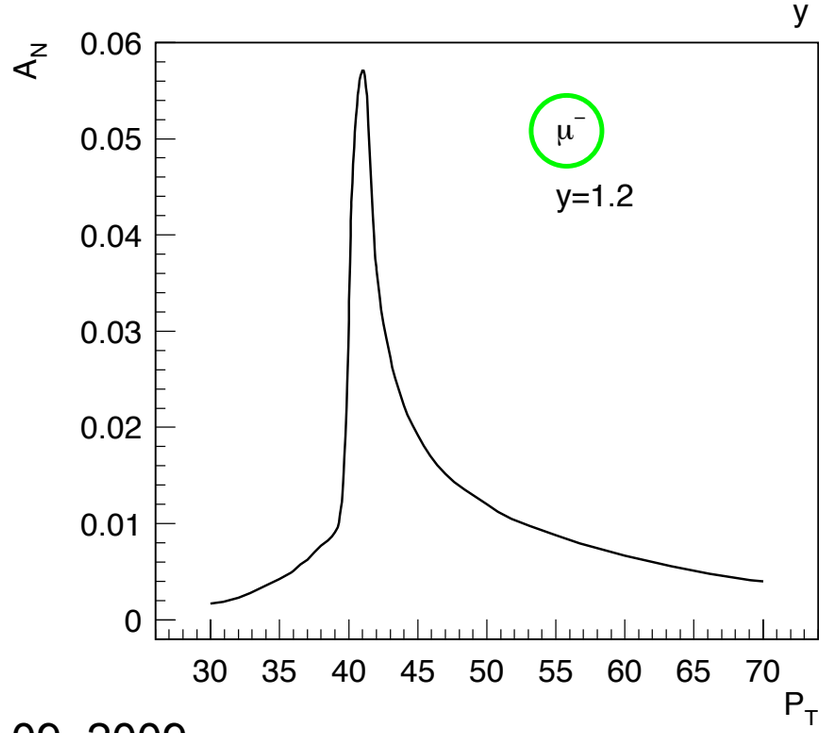
Test of “universality”: W production at RHIC (II)

Kang, Qiu, 2009

- RHIC measures leptons decay from W boson:







- flavor separation
- asymmetry gets smaller due to dilution should still be measurable by current RHIC sensitivity

Summary

- Single transverse-spin asymmetry is directly connected to the parton's transverse motion
  - an excellent probe for the parton's transverse motion
- Two complementary approaches:
  - TMD: direct kT information (two-scale observables)
  - Collinear: net spin-dependence of all kT (single-scale observables)
- For the first time, we derive the evolution equations of the twist-3 correlation functions that are responsible for generating the SSAs in the QCD collinear factorization approach
  - Consistent calculations beyond LO are now possible
- A very exciting era of transverse spin physics is coming, and the future RHIC, JLAB, JPARC, EIC and etc. experiments will play very important roles

Summary

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Thank you!

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