Single transverse spin asymmetry: progress and puzzles

Zhongbo Kang

RIKEN BNL Research Center
Brookhaven National Laboratory

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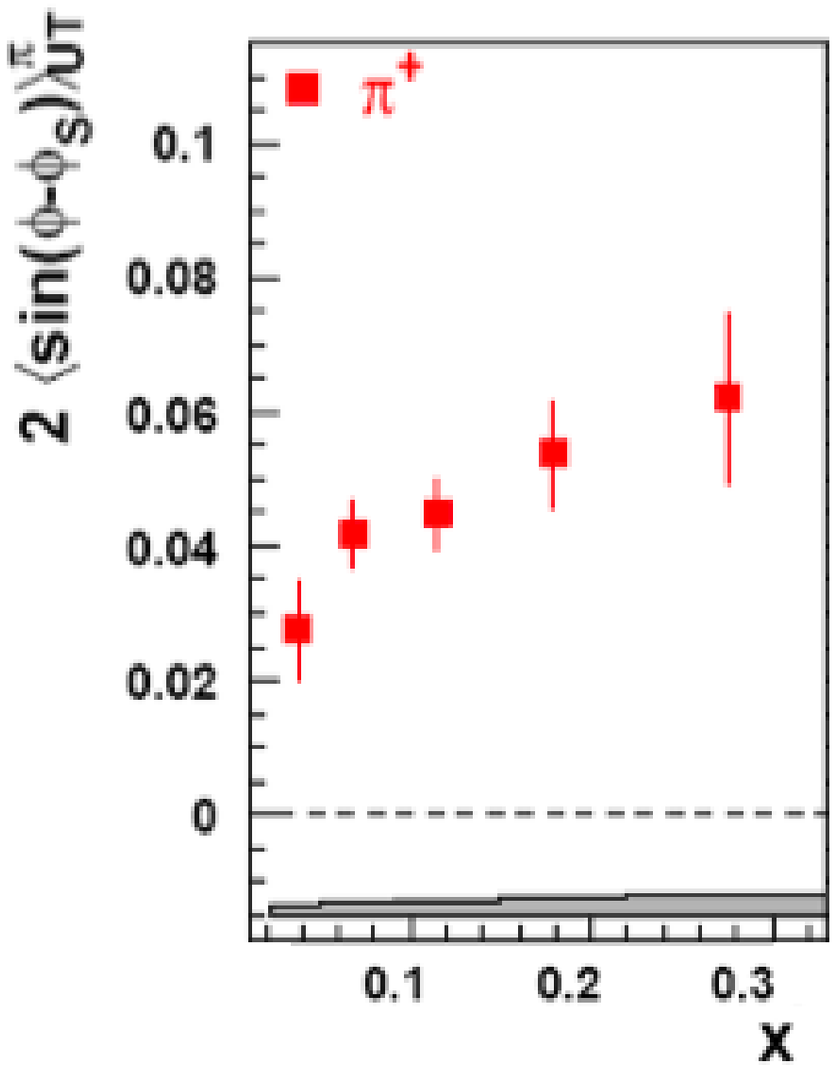
Outline

- Progress
  - Transverse momentum dependent approach
  - Collinear twist-3 factorization approach
  - Connection and evolutions
- Puzzles
  - Sivers functions extracted from SIDIS
  - ETQS twist-3 matrix element extracted from pp
  - “Sign mismatch”
  - Inconsistency?!
- Summary

Experimental data on single transverse spin asymmetry

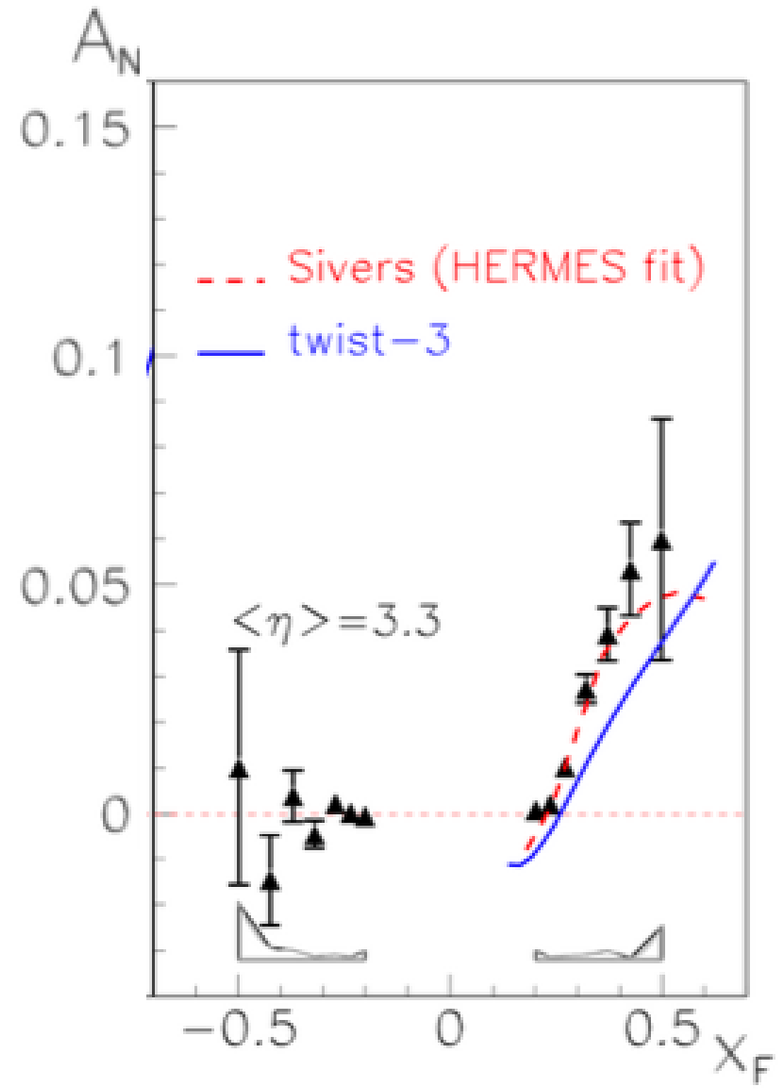
- Single transverse spin asymmetries (SSAs) have been observed in various experiments at different CM energies
  - PHENIX, BRAHMS, COMPASS, JLAB, too

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



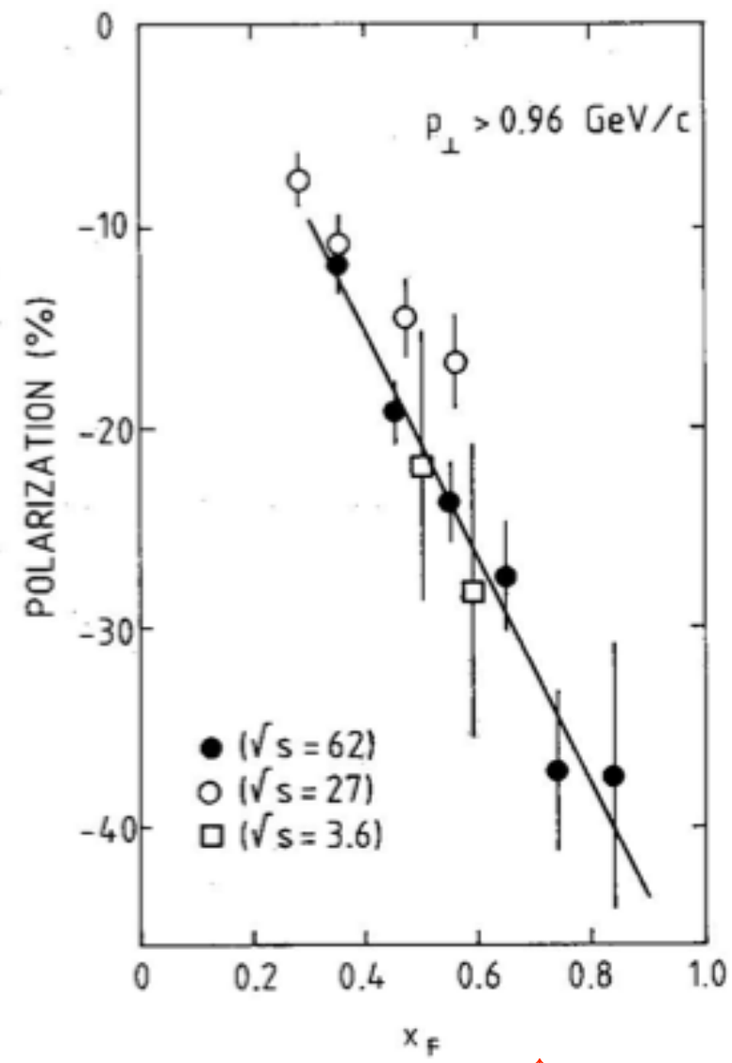
$\ell + p^{\uparrow} \to \ell' + \pi + X$

HERMES



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

STAR



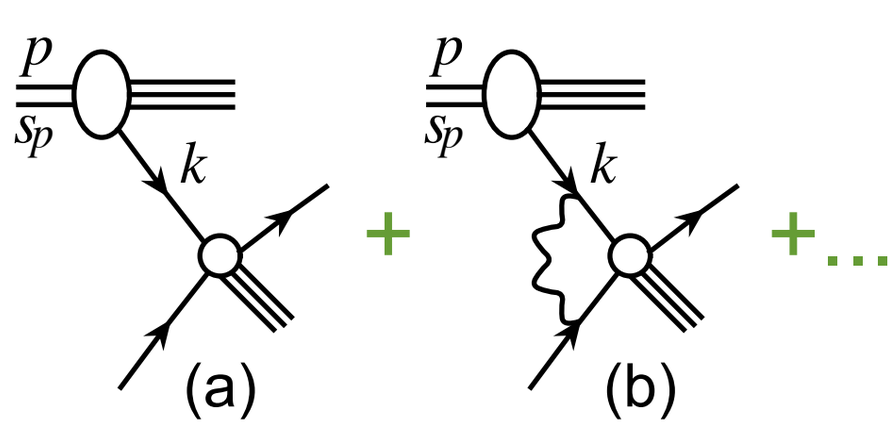
$p + p \to \Lambda^{\uparrow} + X$

E704

SSA vanishes at leading twist in collinear factorization

- At leading twist formalism: partons are collinear

Kane, Pumplin, Repko, 1978

$\sigma(s_T) \sim$ 

$+ \ldots \Big|^2$ ➡ $\Delta\sigma(s_T) \sim \mathrm{Re}[(a)]\cdot\mathrm{Im}[(b)]$

  - 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

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

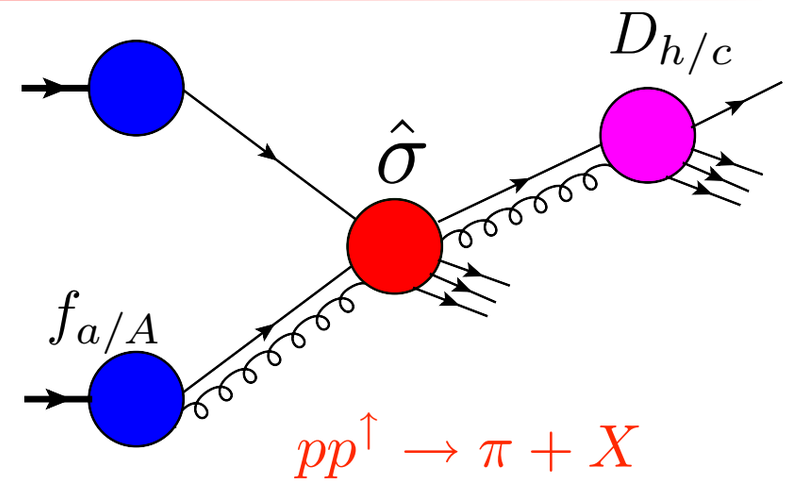
- $A_N \neq 0$: result of parton's transverse motion or correlations!

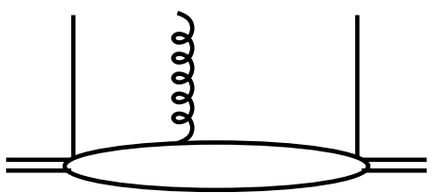
Two mechanisms to generate SSA in QCD

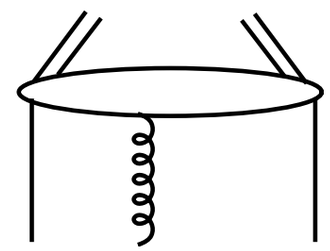
- Collinear twist-3 factorization approach

$$\sigma(p_h, s_\perp) \propto f^{s_\perp}_{a/A}(x) \otimes D_{h/c}(z) \otimes \hat{\sigma}_{\rm parton}$$

  - Twist-3 three-parton corrlation functions (PDFs)
  - Twist-3 three-parton fragmentation functions







Efremov-Teryaev 82, 84, Qiu-Sterman 91, 98, ...

Koike, 02, Kang, Yuan, Zhou 2010

- TMD approach: Transverse Momentum Dependent distributions probe the parton's intrinsic transverse momentum

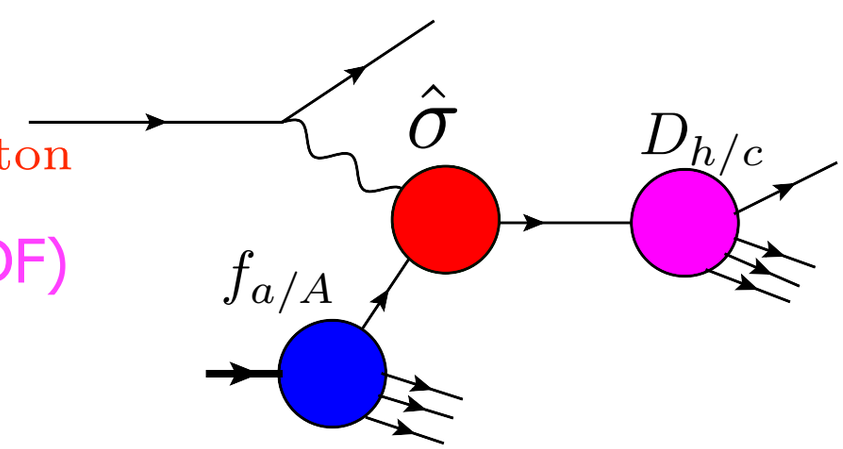
$$\sigma(p_h, s_\perp) \propto f_{a/A}(x, k_\perp) \otimes D_{h/c}(z, p_\perp) \otimes \hat{\sigma}_{\rm parton}$$

  - Sivers function: in Parton Distribution Function (PDF)

    Sivers 90

  - Collins function: in Fragmentation Function (FF)

    Collins 93



$\ell p^\uparrow \to \ell' \pi + X$

Relation between twist-3 and TMD approaches

- They apply in different kinematic domain:
  - TMD approach: need TMD factorization, applies for the process with two observed momentum scales: DY at small $Q_T << Q$

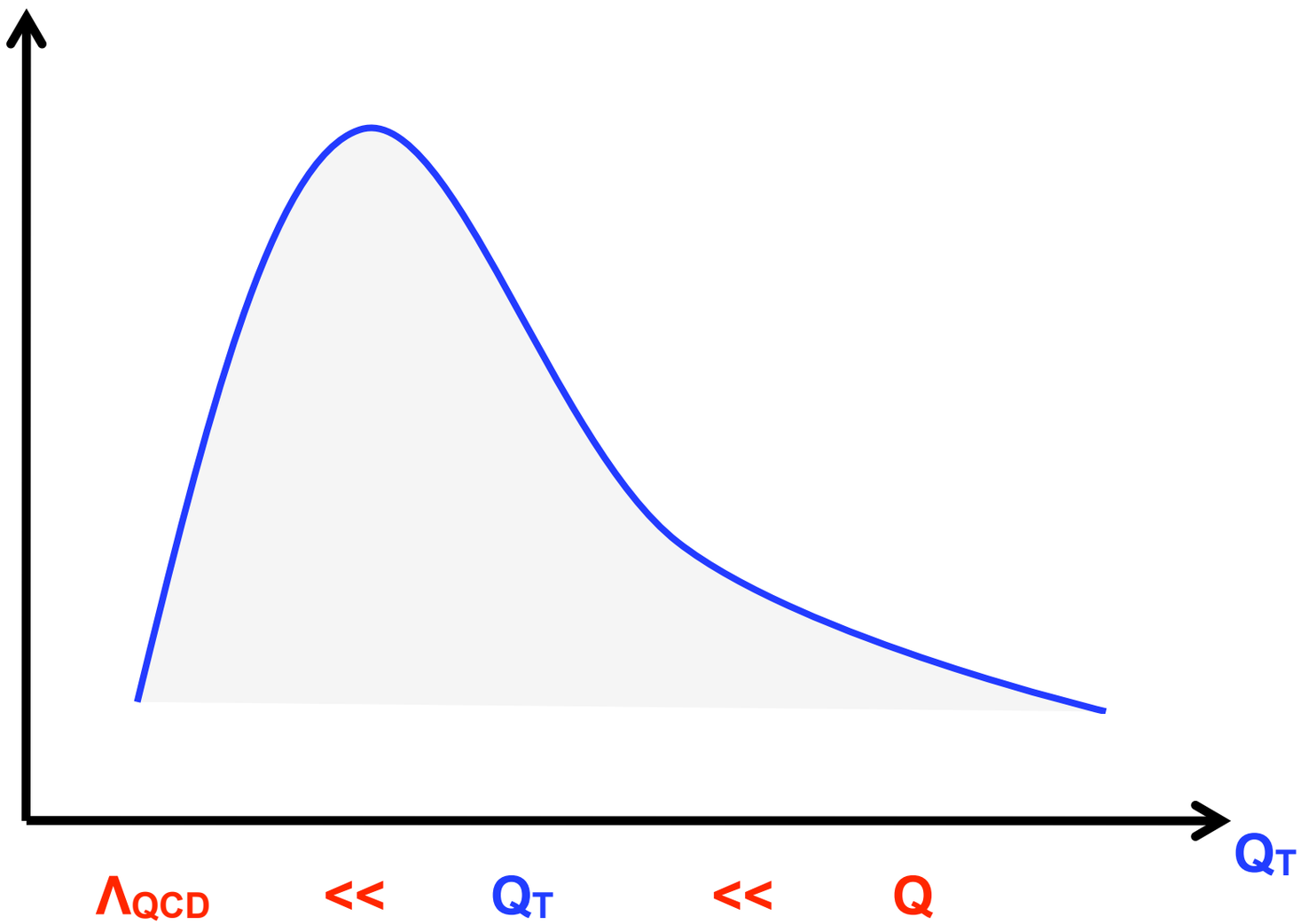
$$Q_1 \gg Q_2 \begin{cases} Q_1 & \text{necessary for pQCD factorization to have a chance} \\ Q_2 & \text{sensitive to parton's transverse momentum} \end{cases}$$

  - Collinear factorization approach: more relevant for single scale hard process inclusive pion production at high p_T in pp collision
- They generate same results in the overlap region when they both apply:
  - Twist-3 three-parton correlation in distribution ⟷ Sivers function

    Ji, Qiu, Vogelsang, Yuan, 2006, ...
  - Twist-3 three-parton correlation in fragmentation ⟷ Collins function

    Zhou, Yuan, 2009, Kang, Yuan, Zhou, 2010

A unified picture for Drell-Yan (leading Q_T/Q)



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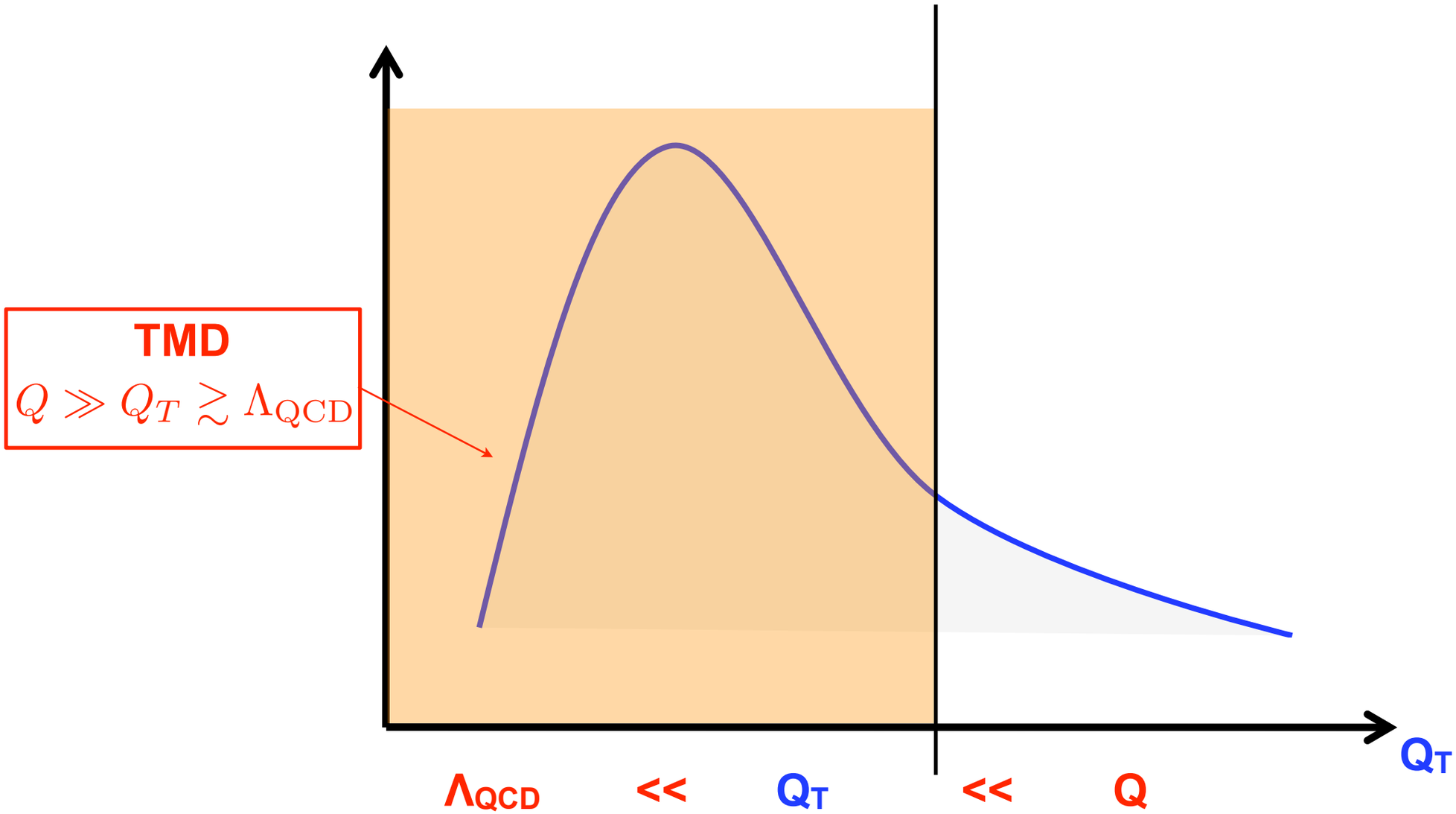

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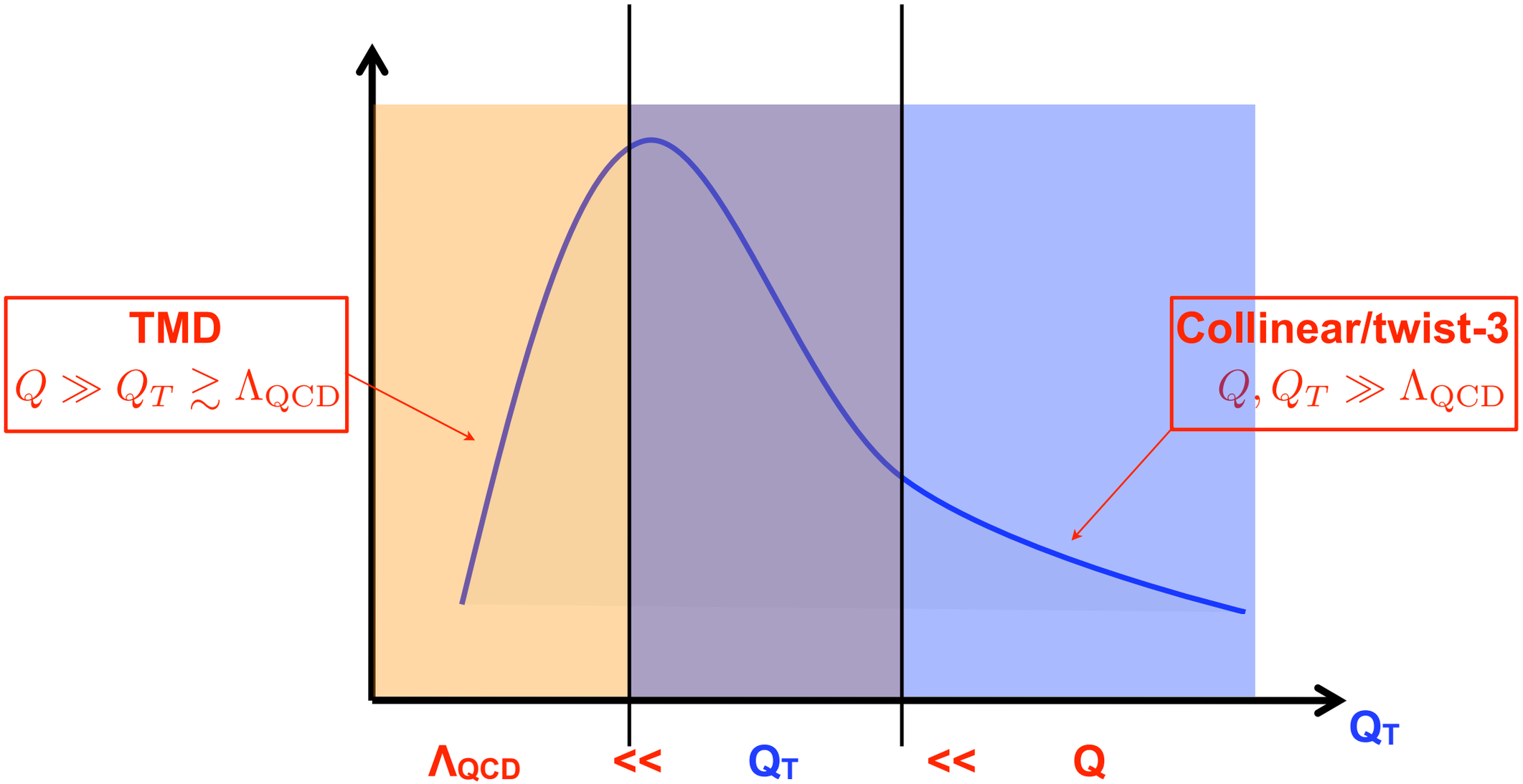

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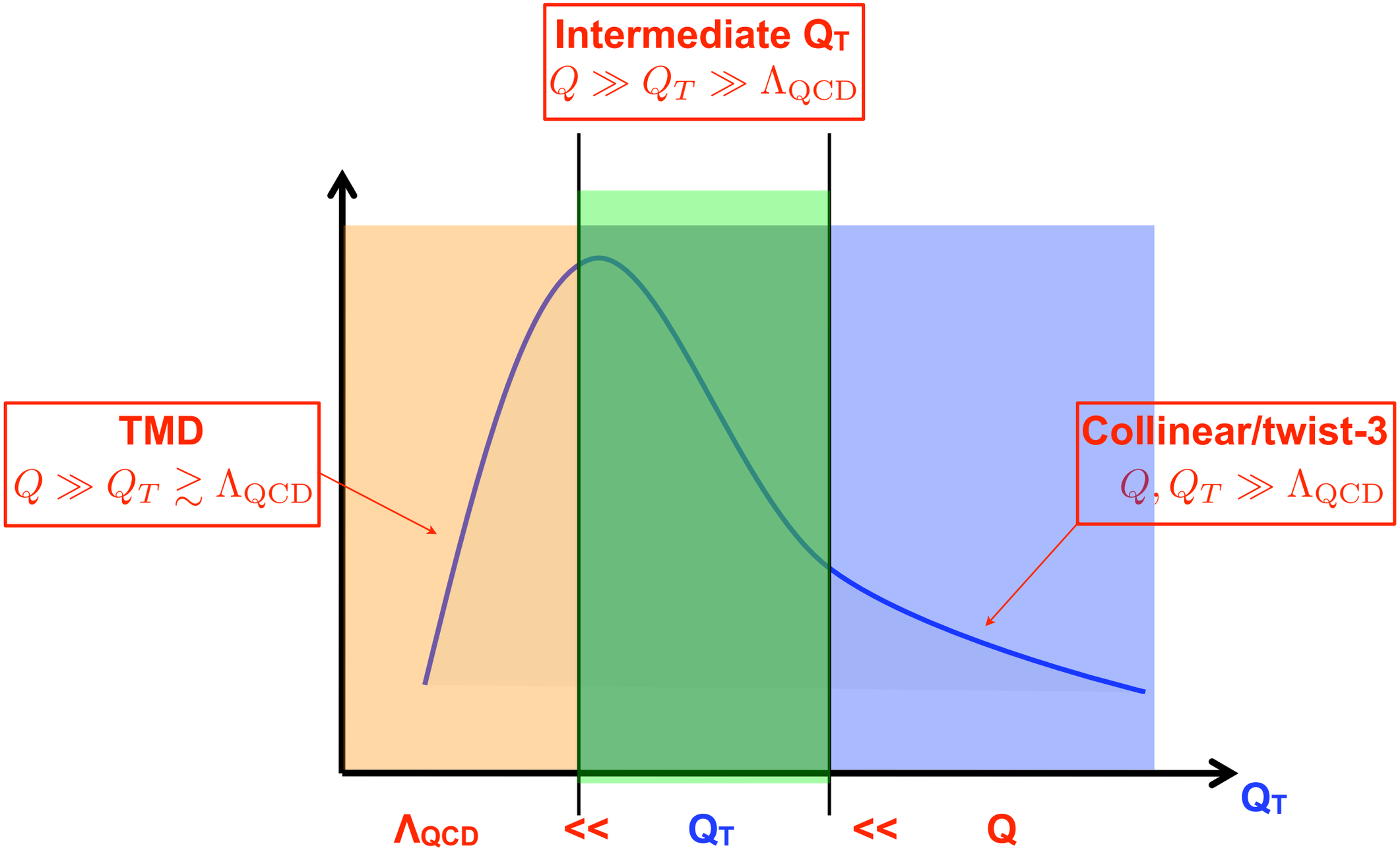


TMD approach: Sivers function

- An asymmetric parton distribution in a polarized hadron (kt correlated with the spin of the hadron)

Spin-dependent

$$f_{q/h^\uparrow}(x, \mathbf{k}_\perp, \vec{S}) \equiv f_{q/h}(x, k_\perp) + \frac{1}{2}\Delta^N f_{q/h^\uparrow}(x, k_\perp)\, \vec{S} \cdot \hat{p} \times \hat{\mathbf{k}}_\perp$$

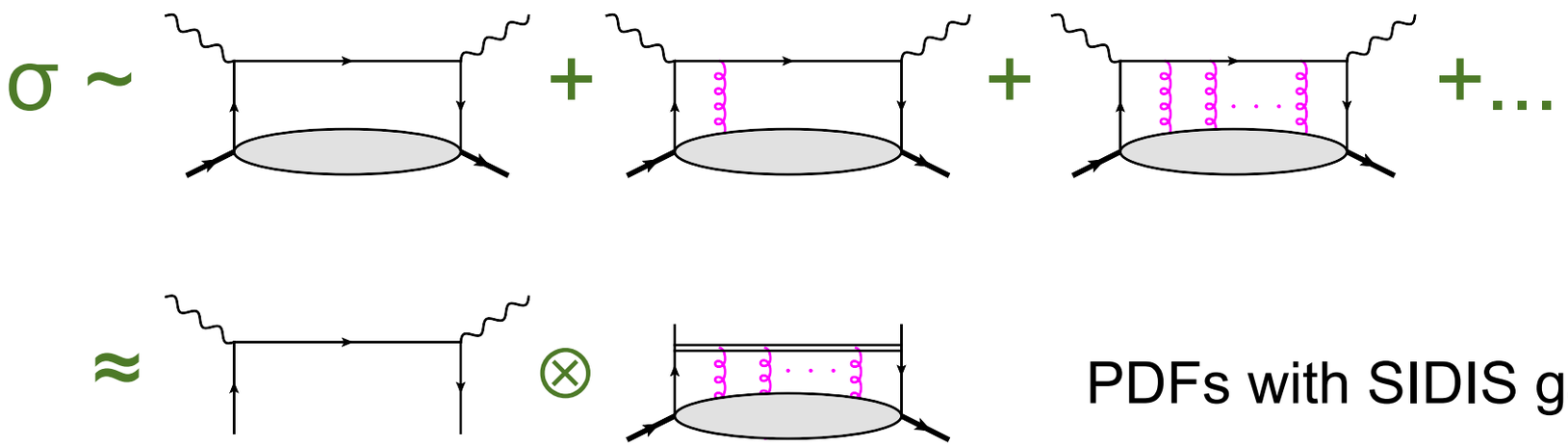
Spin-independent

The existence of Sivers function

- 1990: Sivers function
  - introduce kt dependence of PDFs, generate the SSA through a correlation between the hadron spin and the parton kt
- 1993: Collins
  - show Sivers function vanishes due to time-reversal invariance
- 2002: Brodsky, Hwang, Schmidt
  - explicit model calculation show the existence of the Sivers function
  - the existence of Sivers function relies on the initial- and final-state interactions between the active parton and the remnant of the polarized hadron
- 2002: Ji, Yuan, Belitsky
  - the initial- and final-state interaction presented by Brodsky, et.al. is equivalent to the color gauge links in the definition of the TMD distribution functions
  - since the details of the initial- and final-state interaction depend on the specific scattering process, the gauge link thus the Sivers function could be process-dependent

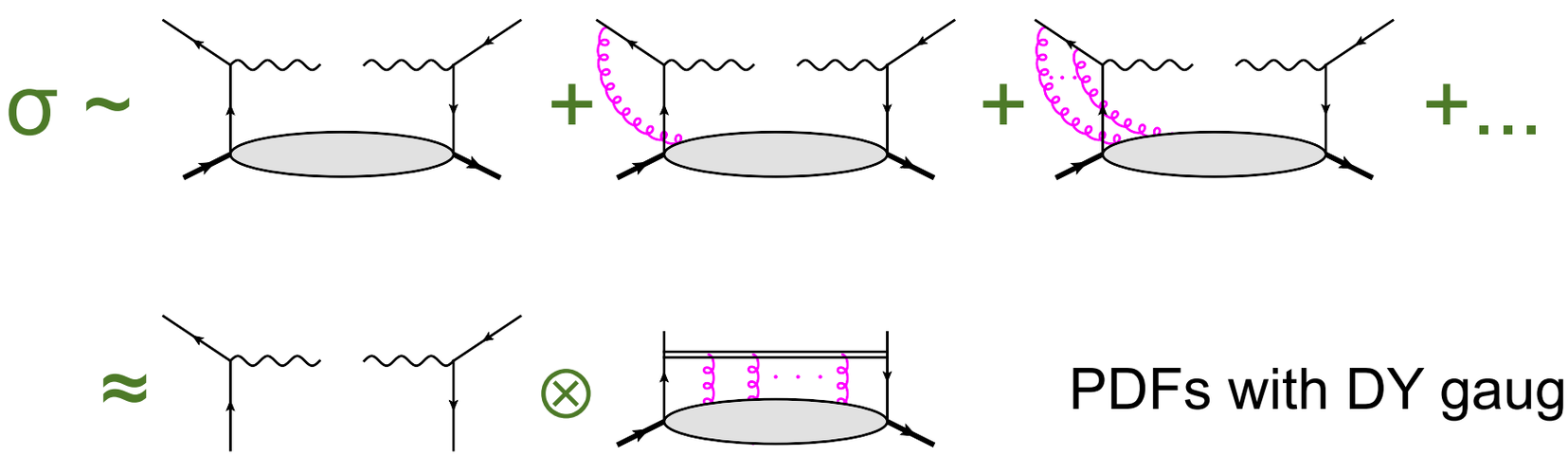
Sivers functions are process-dependent

- The existence of Sivers function relies on the initial- and final-state interaction, which could be process-dependent
  - SIDIS: final-state interaction



PDFs with SIDIS gauge link

  - DY: initial-state interaction



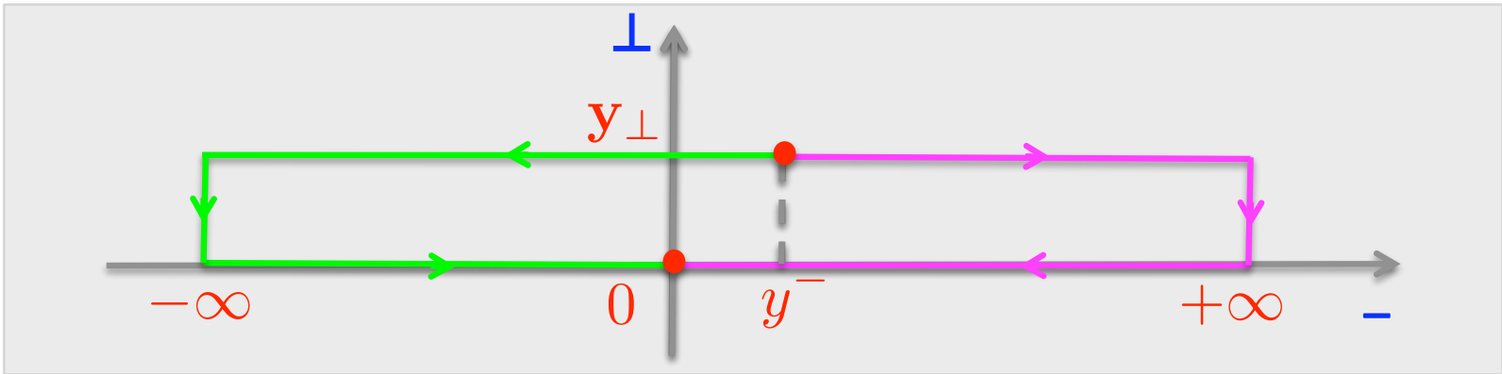
PDFs with DY gauge link

Non-universality of the Sivers function

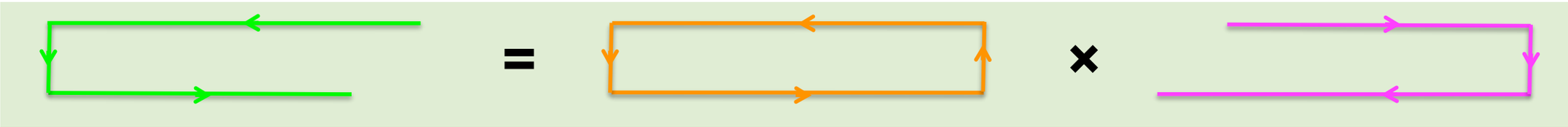
- Different gauge link for gauge-invariant TMD distribution in SIDIS and DY

$$f_{q/h^\uparrow}(x,\mathbf{k}_\perp,\vec{S}) = \int \frac{dy^- d^2y_\perp}{(2\pi)^3} e^{ixp^+y^- - i\,\mathbf{k}_\perp\cdot\mathbf{y}_\perp} \langle p,\vec{S}|\overline{\psi}(0^-,\mathbf{0}_\perp)\,\boxed{\text{Gauge link}}\,\frac{\gamma^+}{2}\psi(y^-,\mathbf{y}_\perp)|p,\vec{S}\rangle$$

- SIDIS: $\Phi_n^\dagger(\{+\infty,0\},\mathbf{0}_\perp)\Phi_{\mathbf{n}_\perp}^\dagger(+\infty,\{\mathbf{y}_\perp,\mathbf{0}_\perp\})\Phi_n(\{+\infty,y^-\},\mathbf{y}_\perp)$
- DY: $\Phi_n^\dagger(\{-\infty,0\},\mathbf{0}_\perp)\Phi_{\mathbf{n}_\perp}^\dagger(-\infty,\{\mathbf{y}_\perp,\mathbf{0}_\perp\})\Phi_n(\{-\infty,y^-\},\mathbf{y}_\perp)$



Wilson Loop ~ $\exp\left[-ig\int_\Sigma d\sigma^{\mu\nu}F_{\mu\nu}\right]$ Area is NOT zero



$$\Delta^N f_{q/h^\uparrow}^{\rm SIDIS}(x,k_\perp) = -\Delta^N f_{q/h^\uparrow}^{\rm DY}(x,k_\perp)$$

Most critical test for TMD approach to SSA

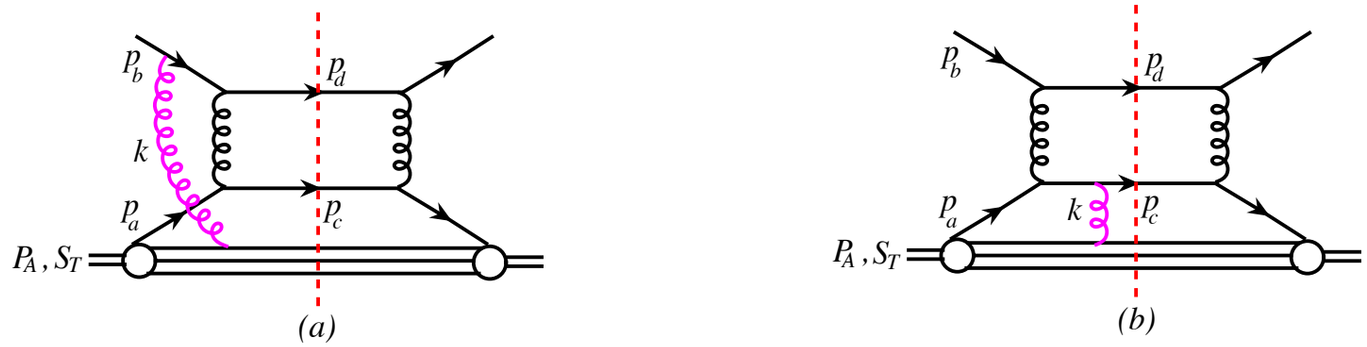
Process-dependence: TMD vs collinear twist-3

- TMD approach: the process-dependence of the SSAs is completely absorbed into the process-dependence of the Sivers function
  - Sivers function is process-dependent

- Collinear twist-3 approach: the process-dependence of the SSAs is completely absorbed into the hard-part functions, thus the relevant collinear twist-3 correlation functions are universal
  - twist-3 correlation function is universal

One example to show process dependence in twist-3

- For the process $pp^{\uparrow} \to \pi + X$, one of the partonic channel: $qq' \to qq'$



$$E_h \frac{d\Delta\sigma}{d^3 P_h} \propto \epsilon^{P_{hT} S_A n \bar{n}} \sum_{a,b,c} D_{h/c}(z_c) \otimes f_{b/B}(x_b) \otimes T_{a,F}(x,x) \otimes H^{\rm Siv}_{ab\to c}$$

Efremov-Teryaev-Qiu-Sterman (ETQS) function

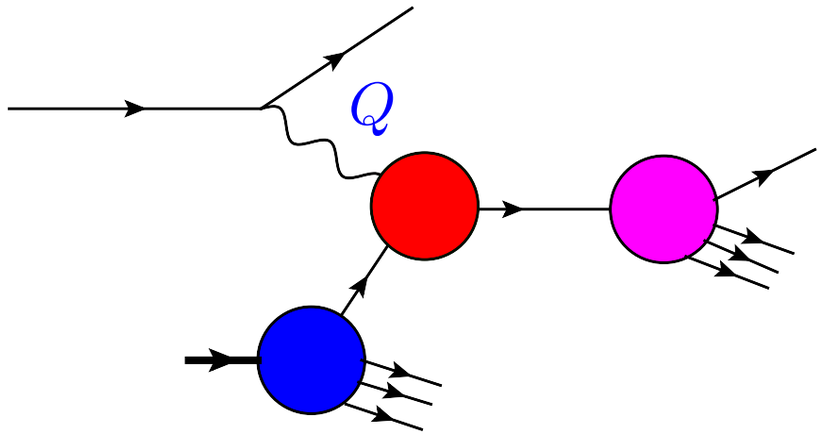
  - The effects of initial- and final-state interaction are absorbed to $H^{\rm Siv}_{ab\to c}$
  - ETQS function $T_{q,F}(x,x)$ is universal

- Since TMD and collinear twist-3 approaches provide a unified picture for the SSAs, ETQS function and Sivers function are closely related to each other

Success of TMD and collinear twist-3 approaches

- Both TMD and collinear twist-3 approaches are successful phenomenologically in their own kinematic domain
  - TMD approach: semi-inclusive hadron production at low p_T in deep inelastic scattering (SIDIS) - two scales p_T and Q

$$\ell + p^{\uparrow} \to \ell' + \pi(p_T) + X : \quad p_T \ll Q$$



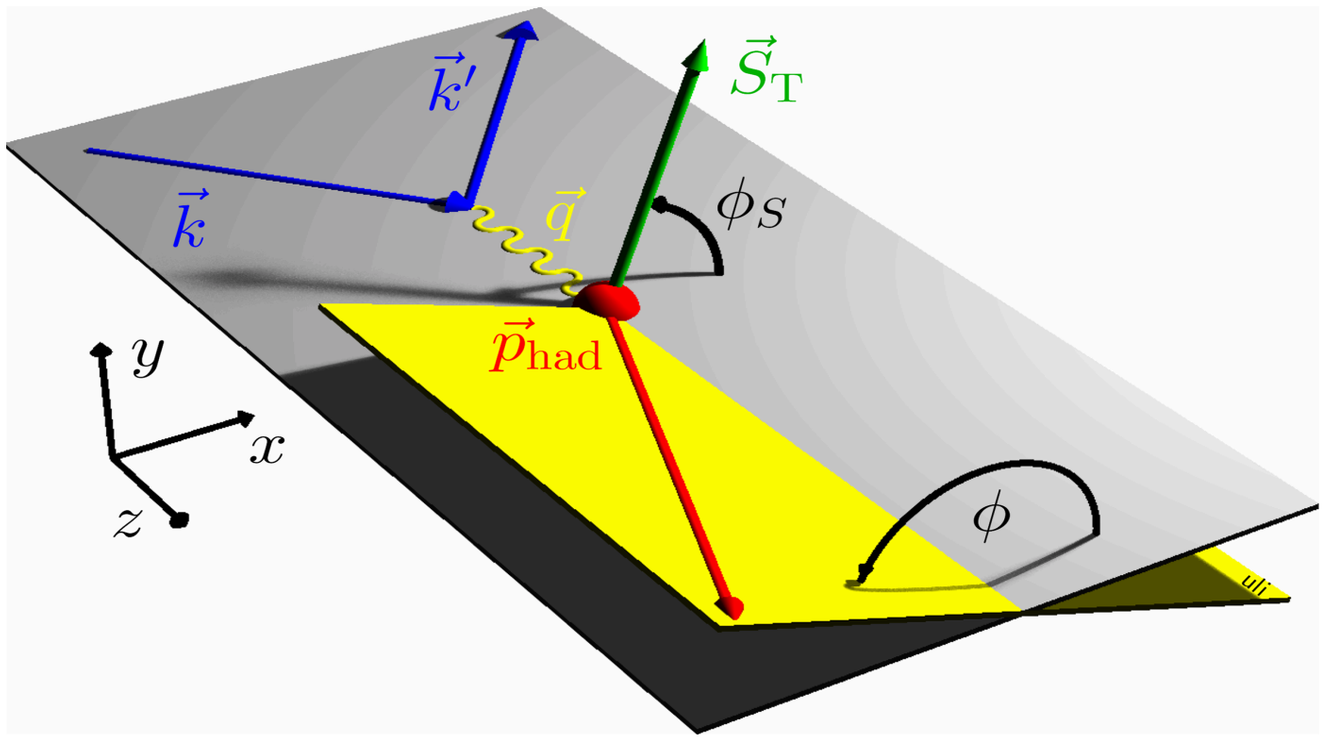
  - Collinear twist-3 approach: single inclusive hadron production at high p_T in pp collisions - p_T is the only large scale

$$p + p^{\uparrow} \to \pi(p_T) + X : p_T \gg \Lambda_{\rm QCD}$$

Current Sivers function from SIDIS

- Sivers and Collins can be separately extracted from SIDIS

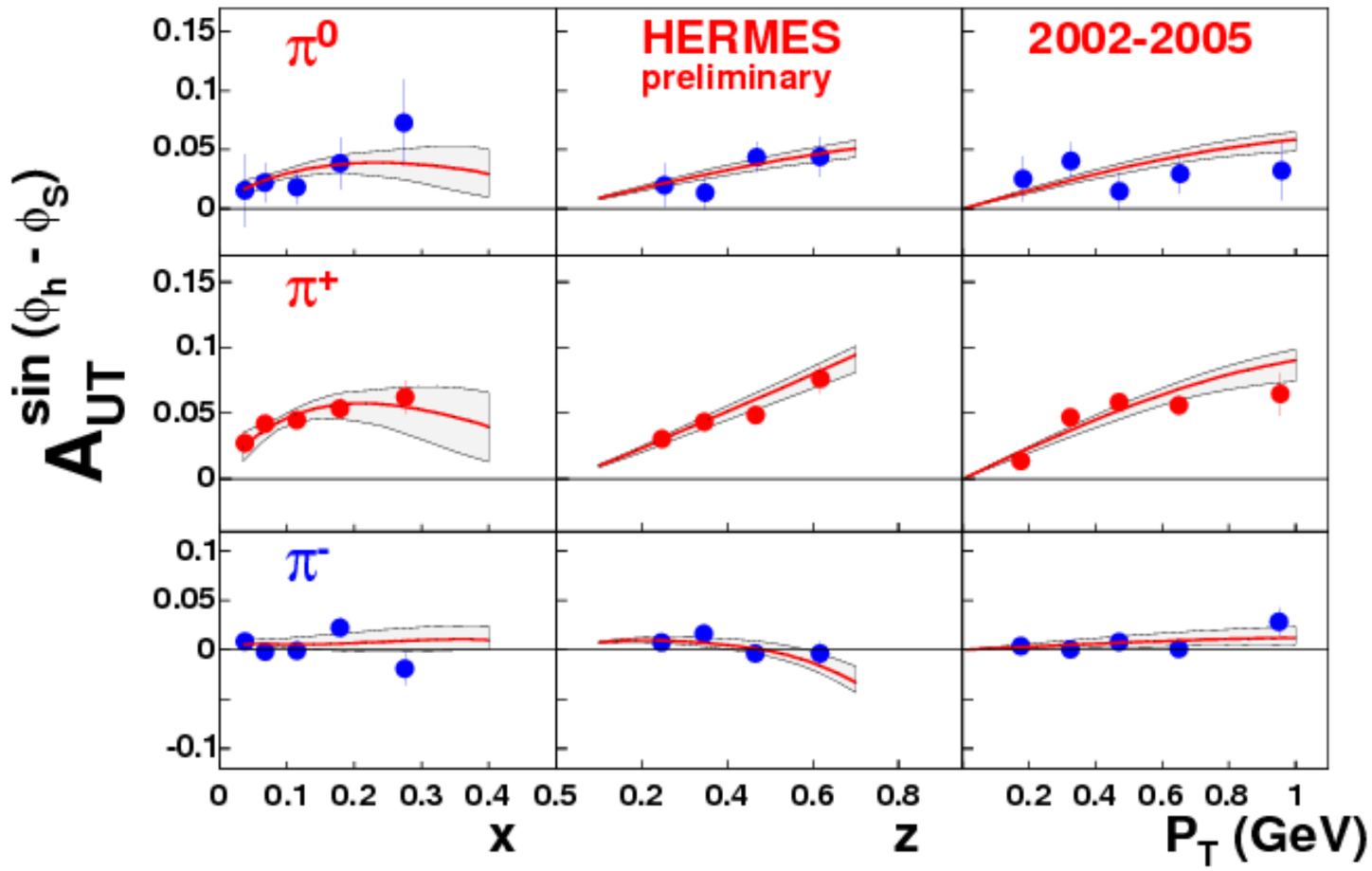
$$\Delta\sigma \propto A_{UT}^{Collins}\sin(\phi+\phi_S) + A_{UT}^{Sivers}\sin(\phi-\phi_S)$$

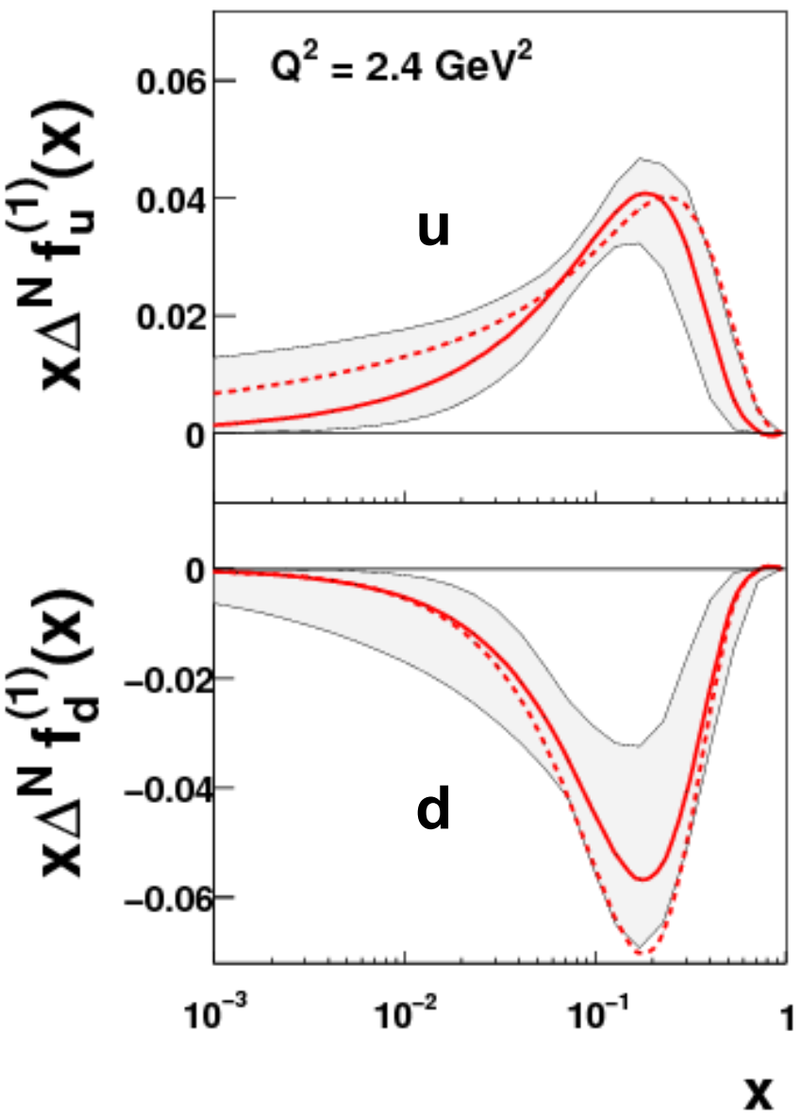


Sivers function from SIDIS: Current Global Analysis

- Includes HERMES Proton data and COMPASS Deuteron data

Anselmino, et.al., 2009





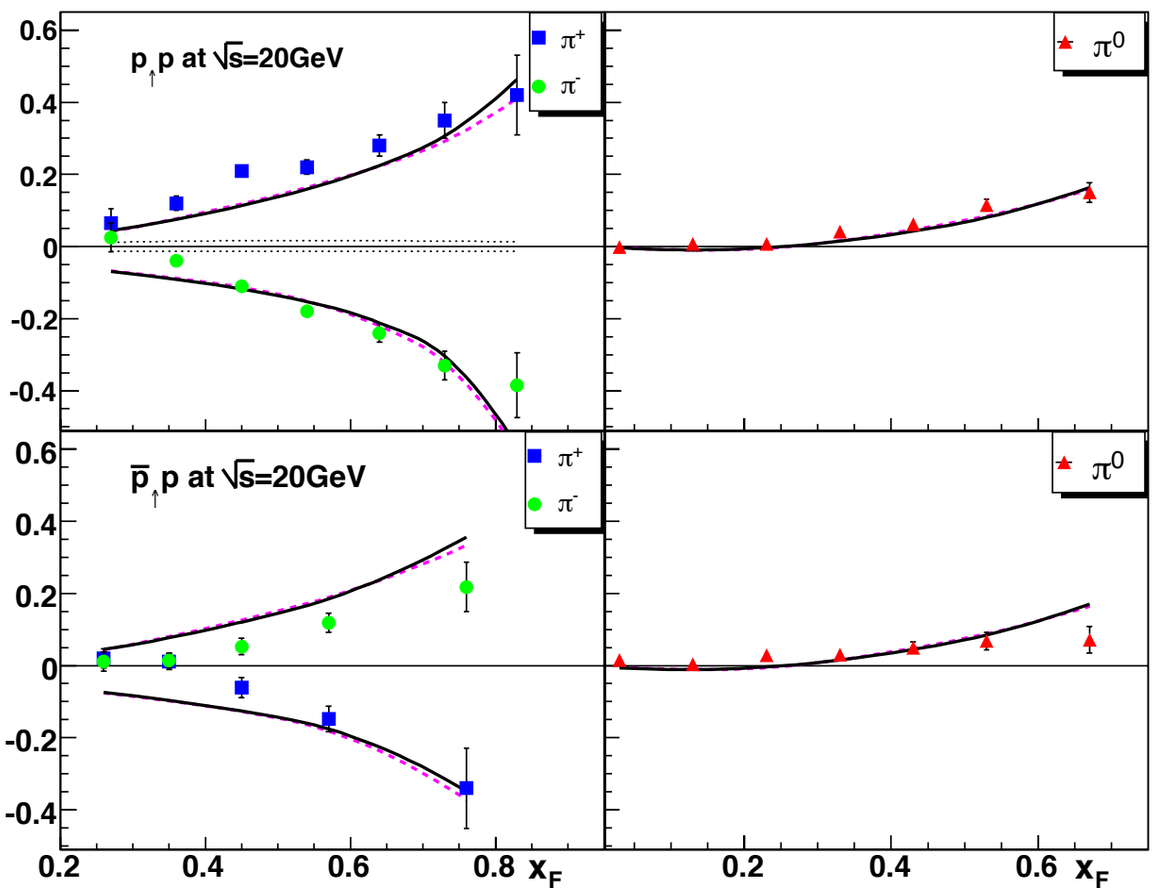
- Also seem to work fine for Collins effect

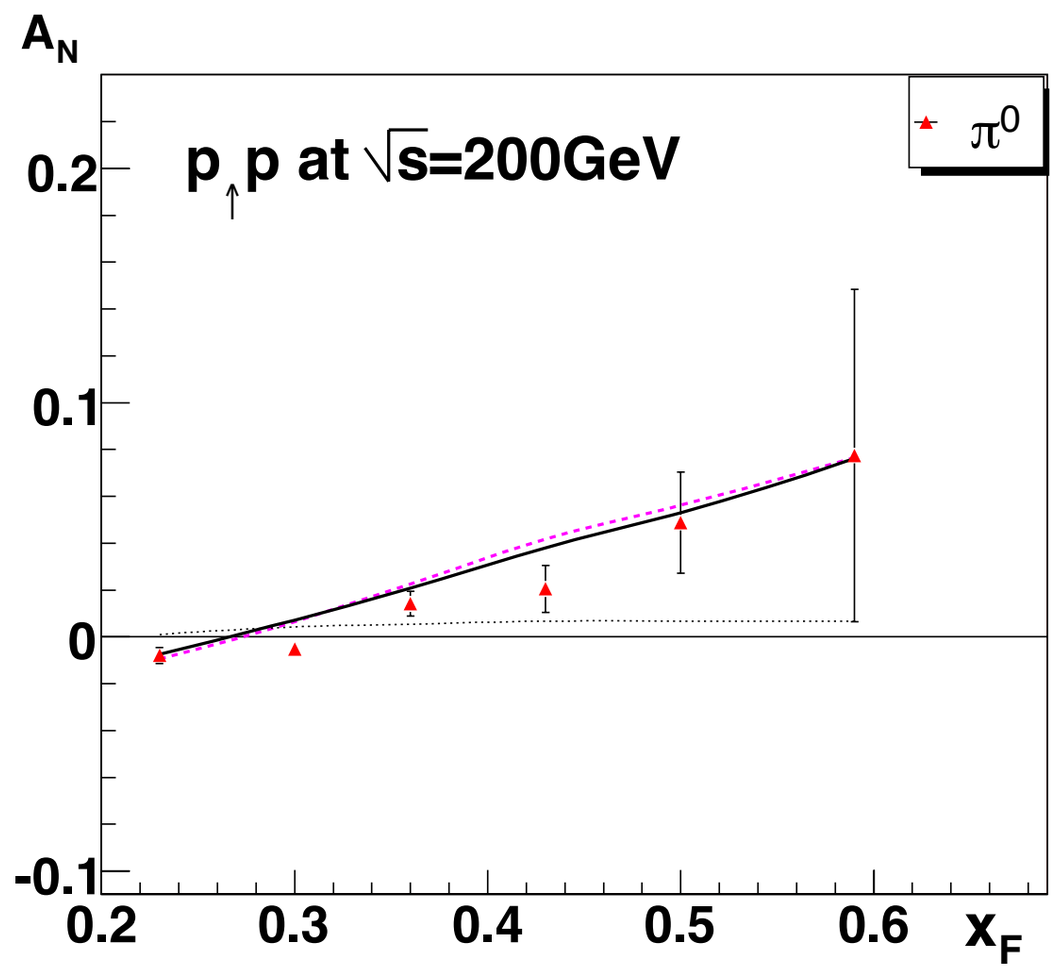
Twist-3 approach: initial success

- Describe both E704 and RHIC data simultaneously with a universal set of $T_{q,F}(x,x)$

Kouvaris, Qiu, Vogelsang, Yuan, 2006

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





- Evolution has been derived for both twist-3 correlation function and fragmentation functions

Kang, Qiu, 2009, Vogelsang, Yuan, 2009, Zhou, Yuan, Liang, 2009, Braun, Manashov, Pirnay, 2009, Kang, 2010

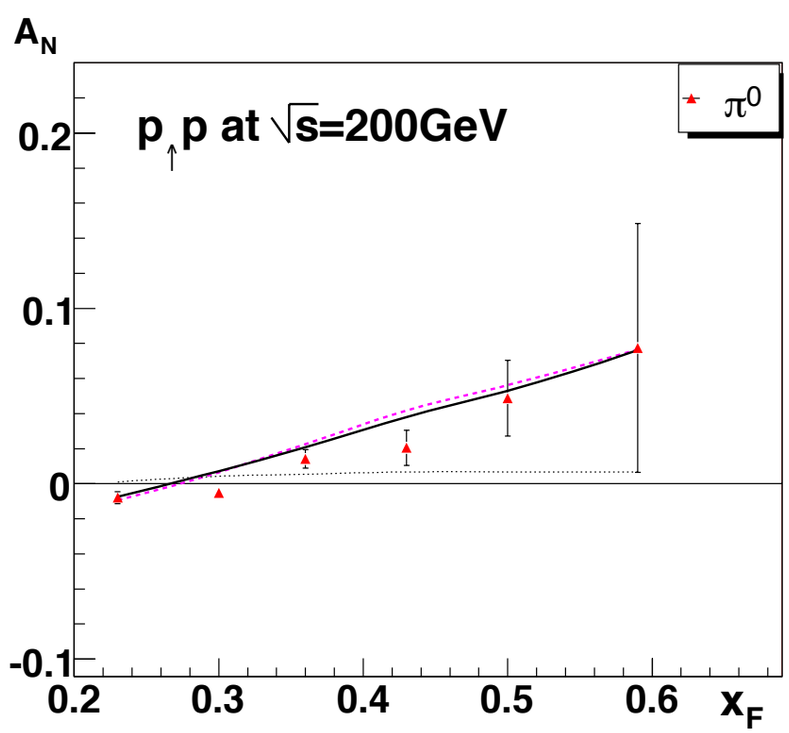
What about the connections?

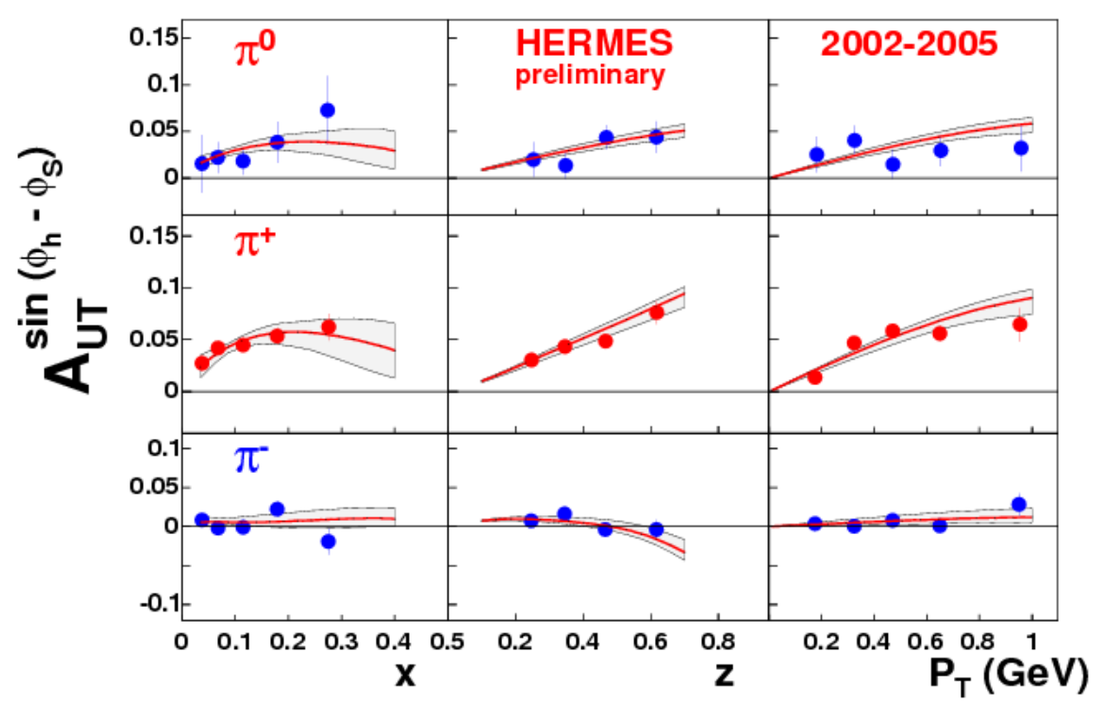
- Both seem to describe the data well (in their own kinematic region), but what about their connections?
  - At the operator level, ETQS function is related to the first kt-moment of the Sivers function

Boer, Mulders, Pijlman, 2003
Ji, Qiu, Vogelsang, Yuan, 2006

$$gT_{q,F}(x,x) = -\int d^2k_\perp \frac{|k_\perp|^2}{M} f_{1T}^{\perp q}(x,k_\perp^2)|_{\rm SIDIS}$$

  - Left hand side: from $p + p^\uparrow \to \pi(p_T) + X$
  - Right hand side: from $\ell + p^\uparrow \to \ell' + \pi(p_T) + X$
  - There is a "sign mismatch"





Parametrization of Sivers function

- To extract the Sivers function, the following parametrization is used
  - unpolarized PDFs: $f_1^q(x, k_\perp^2) = f_1^q(x) g(k_\perp)$
  - Sivers function: $\Delta^N f_{q/h^\uparrow}(x, k_\perp) = 2\mathcal{N}_q(x) f_1^q(x) h(k_\perp) g(k_\perp)$

    $\mathcal{N}_q(x)$ is a fitted function

$$g(k_\perp) = \frac{1}{\pi \langle k_\perp^2 \rangle} e^{-k_\perp^2/\langle k_\perp^2 \rangle}$$

old Sivers: $$h(k_\perp) = \frac{2 k_\perp M_0}{k_\perp^2 + M_0^2}$$ Anselmino, et.al, 2005

new Sivers: $$h(k_\perp) = \sqrt{2e}\, \frac{k_\perp}{M_1} e^{-k_\perp^2/M_1^2}$$ Anselmino, et.al, 2009

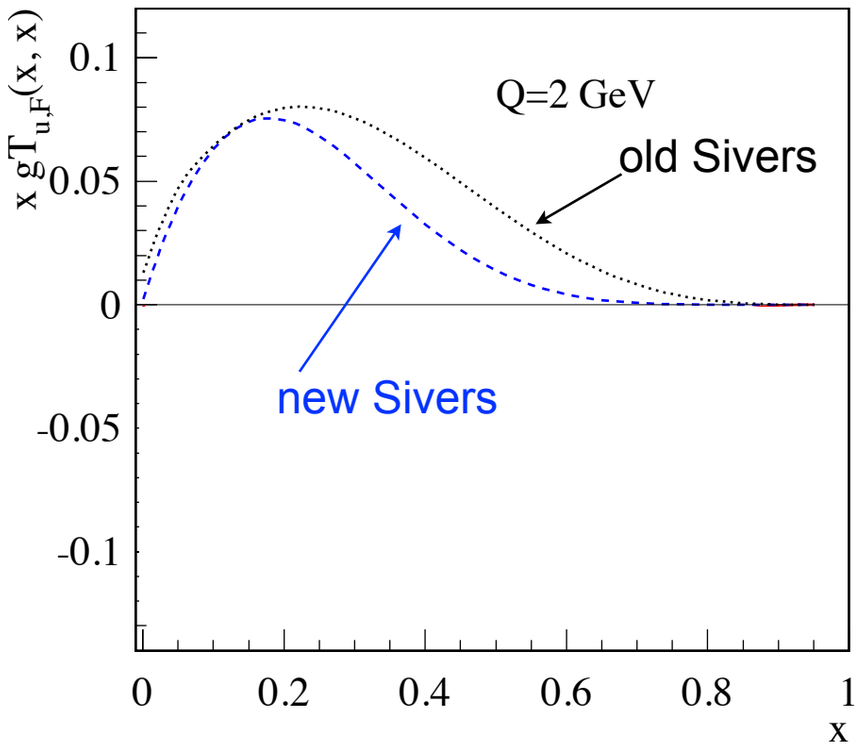
- Using $\Delta^N f_{q/A^\uparrow}(x, k_\perp) = -\frac{2k_\perp}{M} f_{1T}^{\perp q}(x, k_\perp^2)$, one can obtain

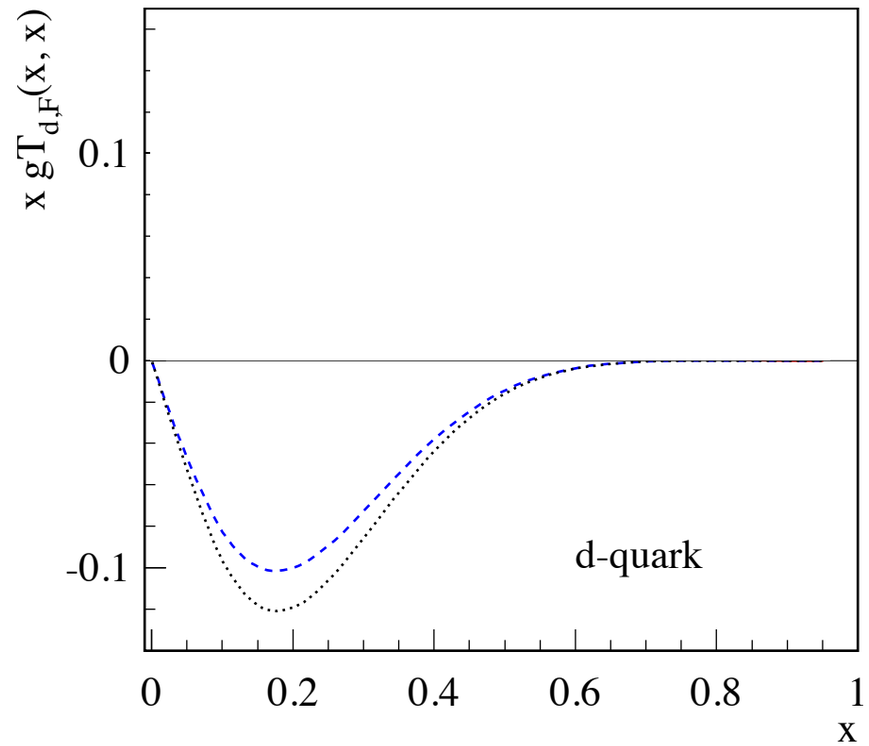
$$gT_{q,F}(x,x)|_{\text{old Sivers}} = 0.40 f_1^q(x) \mathcal{N}_q(x)|_{\text{old}}$$

$$gT_{q,F}(x,x)|_{\text{new Sivers}} = 0.33 f_1^q(x) \mathcal{N}_q(x)|_{\text{new}}$$

Indirectly obtained ETQS function

- The plot of indirectly obtained ETQS function $T_{q,F}(x, x)$

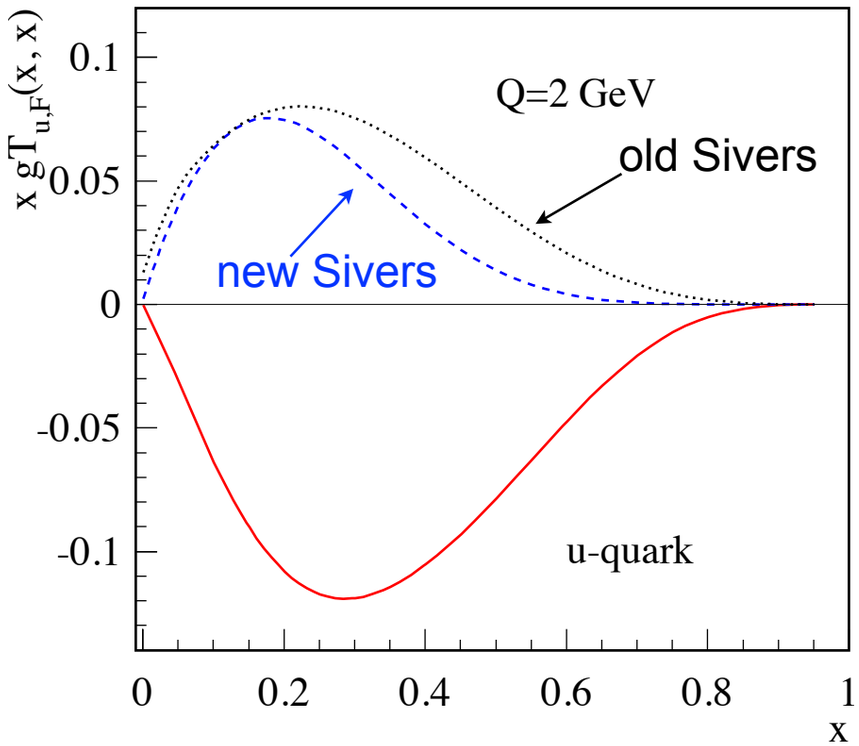


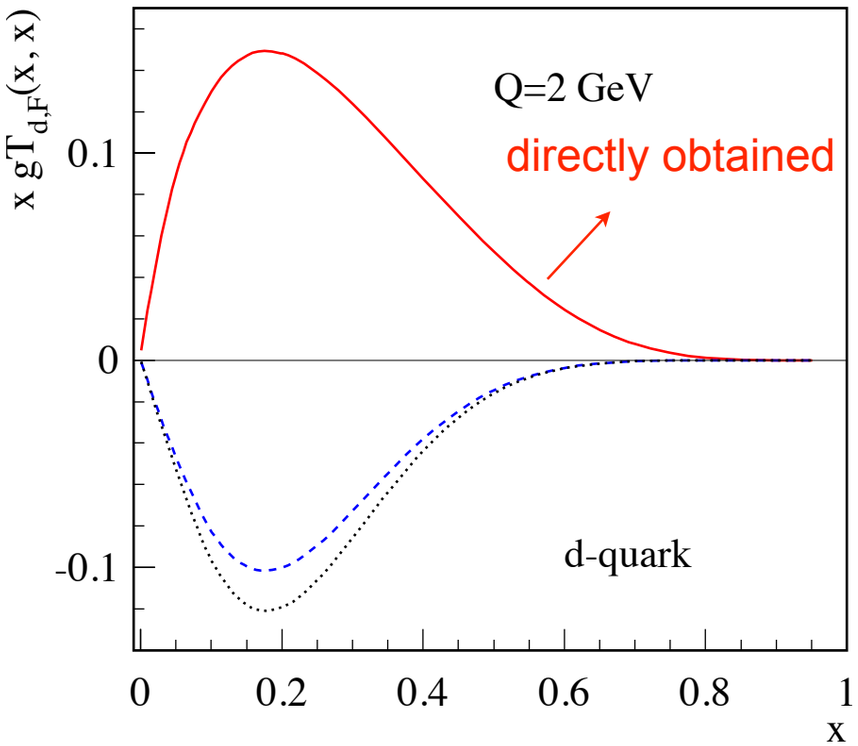


- ETQS function is positive for u-quark
- ETQS function is negative for d-quark

Directly obtained ETQS function

- ETQS function could be directly obtained from the global fitting of inclusive hadron production in hadronic collisions





- directly obtained ETQS functions for both u and d quarks are opposite in sign to those indirectly obtained from the kt-moment of the quark Sivers function - "a sign mismatach"

Question

Does this apparent sign “mismatch” indicate an inconsistency in our current QCD formalism for describing the SSAs?

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Does this apparent sign “mismatch” indicate an inconsistency in our current QCD formalism for describing the SSAs?

The answer is possibly yes, but not necessarily.

Scenario I

- Let us assume the directly obtained ETQS function from inclusive hadron production reflects the true sign of these functions.

- In such case, to make everything consistent, we need to explain how the sign of the kt-moment of the Sivers function is different from the sign of the Sivers function.

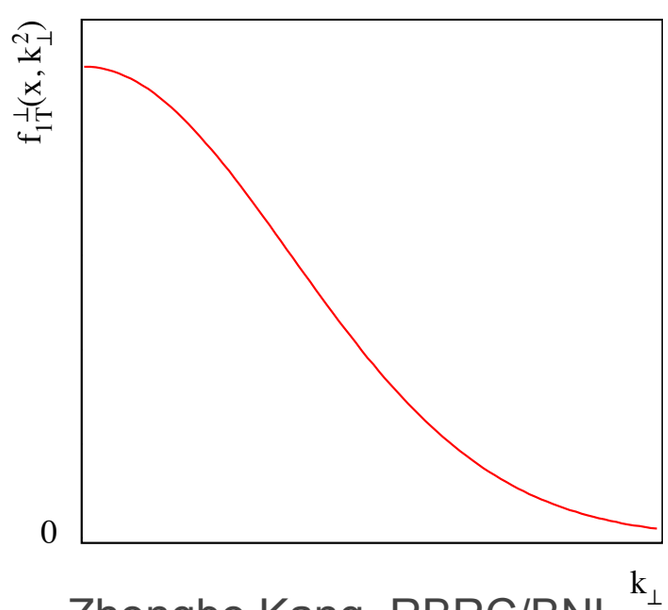
$$gT_{q,F}(x,x) = -\int d^2k_\perp \frac{|k_\perp|^2}{M} f_{1T}^{\perp q}(x,k_\perp^2)|_{\rm SIDIS}$$

What could go wrong - Scenario I

- To obtain ETQS function, one needs the full kt-dependence of the quark Sivers function

$$gT_{q,F}(x,x) = -\int d^2k_\perp \frac{|k_\perp|^2}{M} f_{1T}^{\perp q}(x,k_\perp^2)|_{\rm SIDIS}$$

- However, the Sivers functions are extracted mainly from HERMES data at rather low $Q^2 \sim 2.4$ GeV^2, and TMD formalism is only valid for the kinematic region kt << Q.
  - HERMES data only constrain the behavior (or the sign) of the Sivers function at very low kt ~ Λ_{QCD}.
  - The current Torino group has assumed that a Gaussian-type kt-dependence, thus low kt and high kt has the same sign, which needs not to be true.

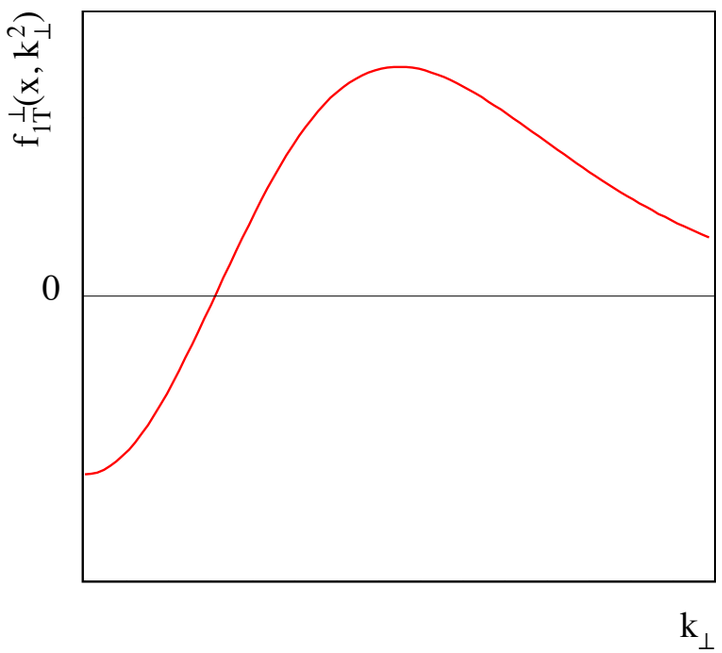


Sivers function needs not to be positive

- Sivers function corresponds to the difference between two PDFs, and thus could be negative, or even have a node

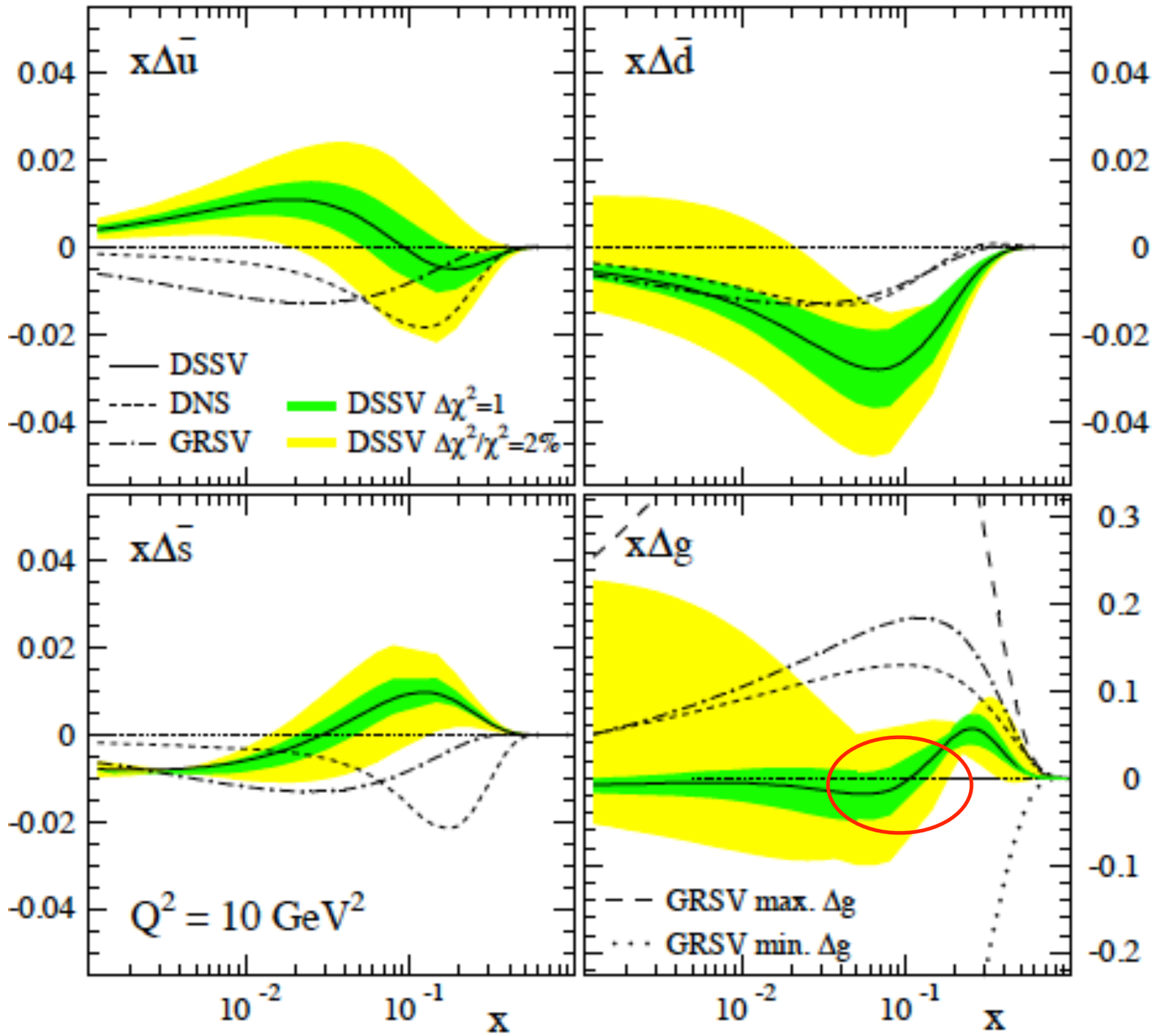
$$\Delta^N f_{q/h^\uparrow}(x, k_\perp)\, \vec{S} \cdot \hat{p} \times \hat{\mathbf{k}}_\perp = f_{q/h^\uparrow}(x, \mathbf{k}_\perp, \vec{S}) - f_{q/h^\uparrow}(x, \mathbf{k}_\perp, -\vec{S})$$

  - node situation: if $f_{q/h^\uparrow}(x, \mathbf{k}_\perp, \vec{S})$ and $f_{q/h^\uparrow}(x, \mathbf{k}_\perp, -\vec{S})$ are both Gaussian, but with different width, one could immediately find out the Sivers function could have the following kt-behavior
  - The kt-moment of the Sivers function now will depends on the competition between low kt and high kt. It is possible that the high kt region wins, thus the sign of the kt-moment is actually opposite to the sign of the Sivers function itself at low kt.



Difference of distributions has a node is not new

- Current best fit for gluon helicity distribution function $\Delta g(x)$ seems to favor a x-distribution with a node



Measure kt-dependence of Sivers function

- To test whether we have a sign change in the kt-distribution (or have a node), we need to expand the reach of kt in the SIDIS
  - With a much broader Q and energy coverage
  - a Electron Ion Collider might be ideal

Scenario II

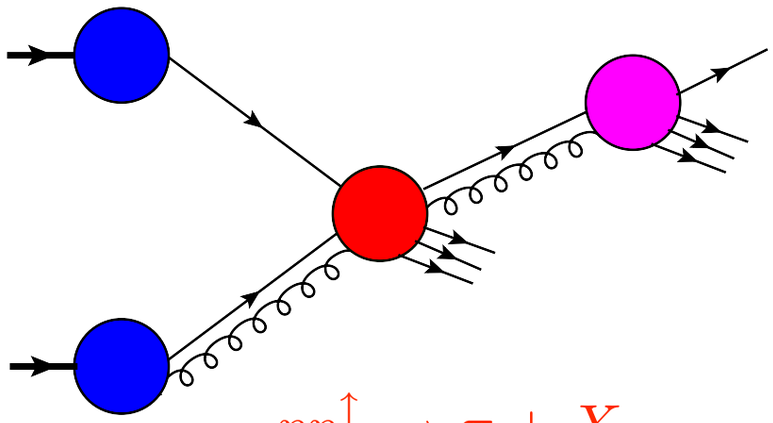
- Let assume the indirectly obtained (from the kt-moment of the Sivers function) ETQS function reflects the true sign of these functions

- In such case, to make everything consistent, we need to explain why we obtain a sign-mismatched ETQS function by analyzing the inclusive hadron data

$$gT_{q,F}(x,x) = -\int d^2k_\perp \frac{|k_\perp|^2}{M} f_{1T}^{\perp q}(x,k_\perp^2)|_{\rm SIDIS}$$

Single inclusive hadron production is complicated

- There are two major contributions to the SSAs of the single inclusive hadron production in pp collisions
  - Twist-3 three-parton corrlation functions (PDFs)
  - Twist-3 three-parton fragmentation functions



$pp^{\uparrow} \to \pi + X$

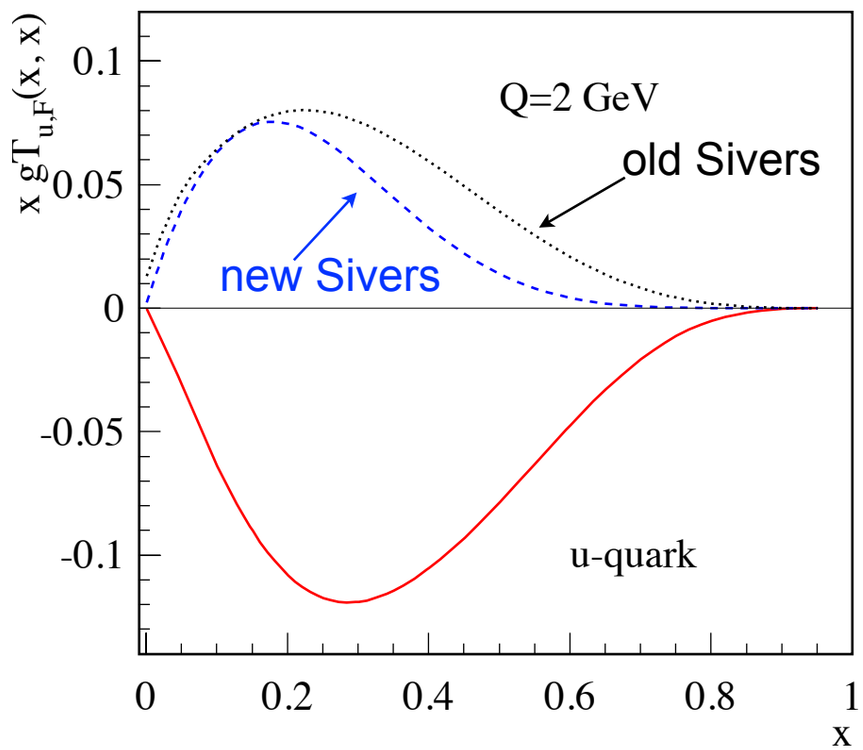
- So far the calculations related to three-parton correlation functions are more complete, while those related to the twist-3 fragmentation functions are available only very recently (not complete) Kang, Yuan, Zhou 2010
  - The current available global fittings are based on the assumptions that the SSAs mainly come from the twist-3 correlation functions, which might not be the case
  - If the contribution from the twist-3 fragmentation functions dominates, one might even reverse the sign of the ETQS function?

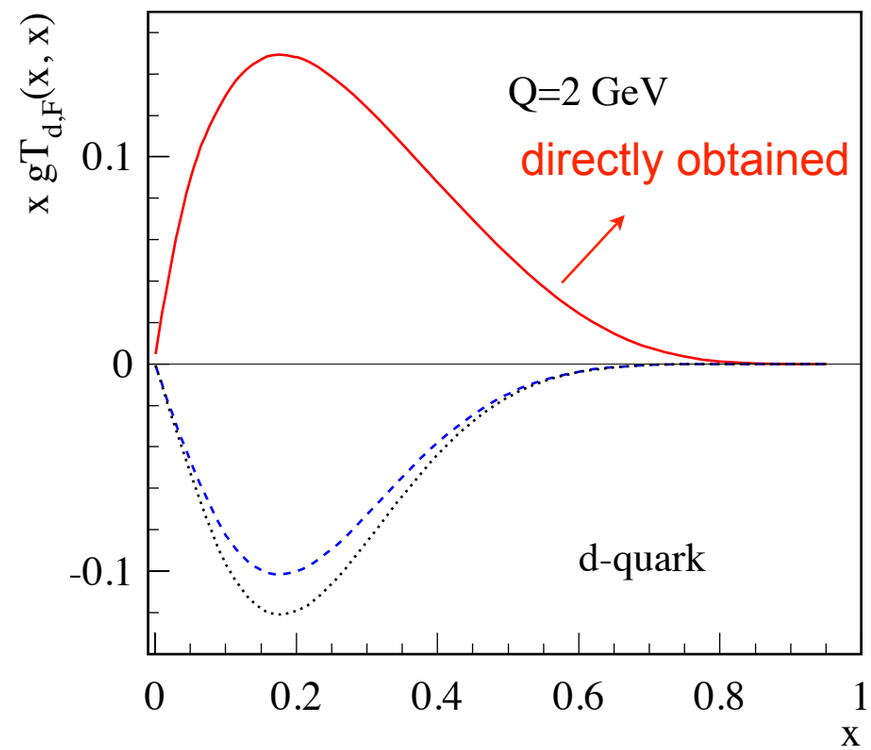
$$A_N = A_N|^{\rm PDFs} + A_N|^{\rm FFs}$$

If $A_N|^{\rm FFs} > A_N$, sign of $A_N|^{\rm PDFs}$ is opposite to A_N

Distinguish scenario I and II

- Scenario I and II are completely different from each other

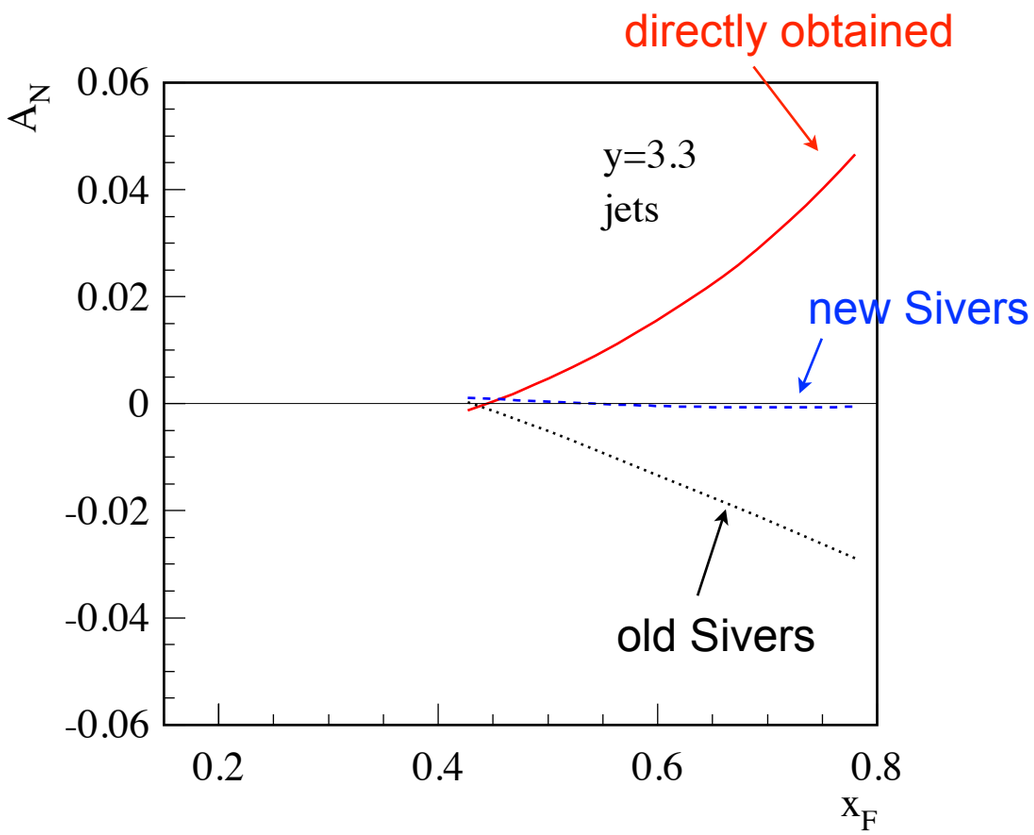


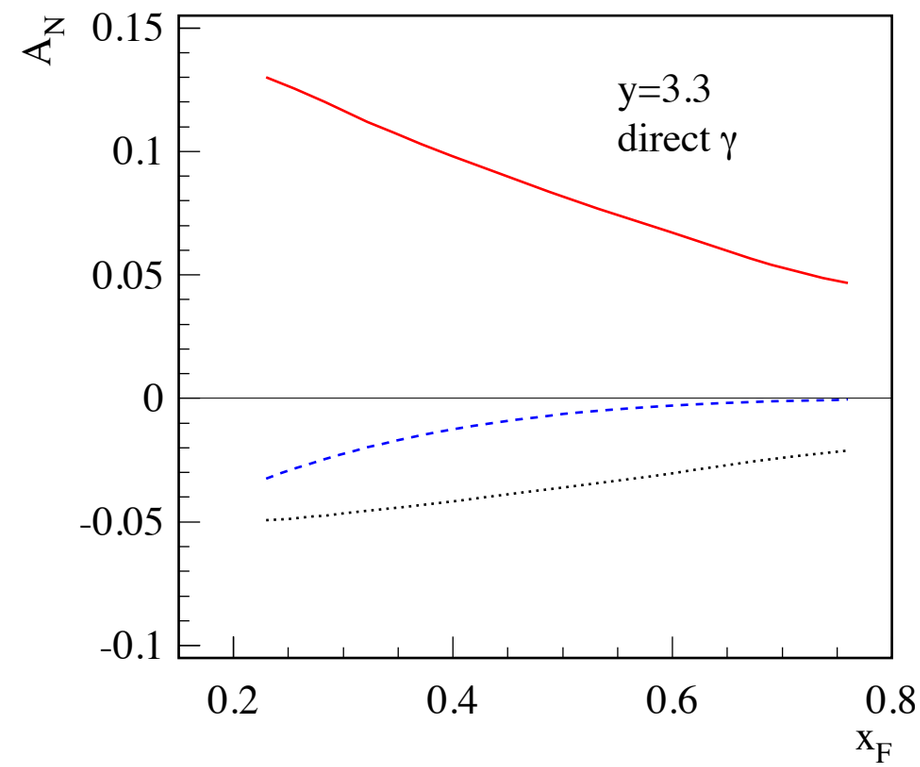


- To distinguish one from the other, in hadronic machine (like RHIC), one needs to find observables which are sensitive to twist-3 correlation function (not fragmentation function), such as single inclusive jet production, direct photon production

Predictions for jet and direct photon

- at RHIC 200 GeV:



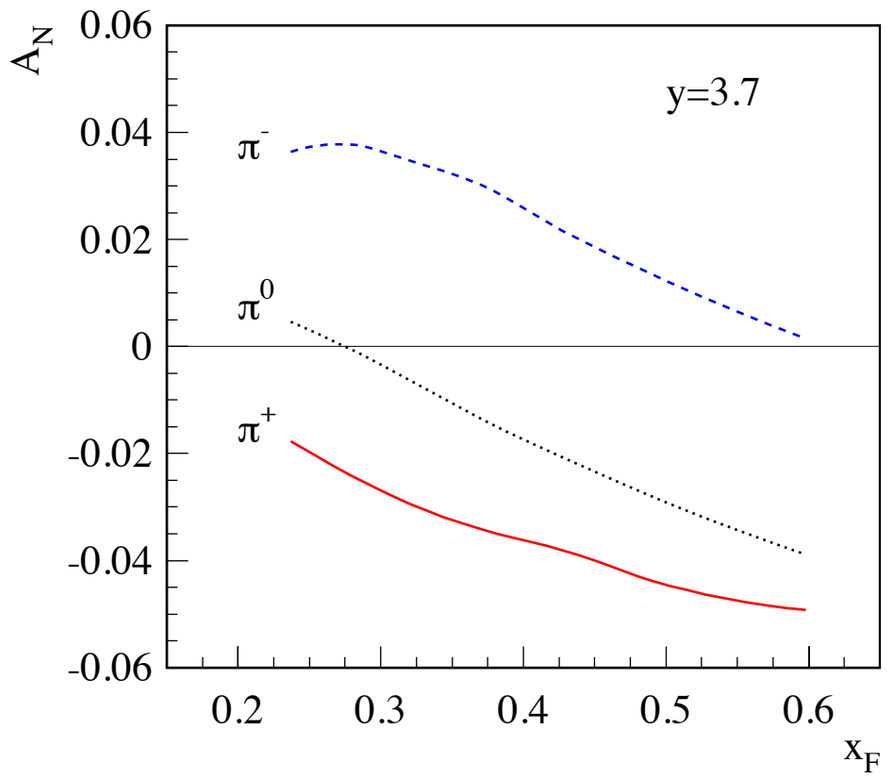


Summary

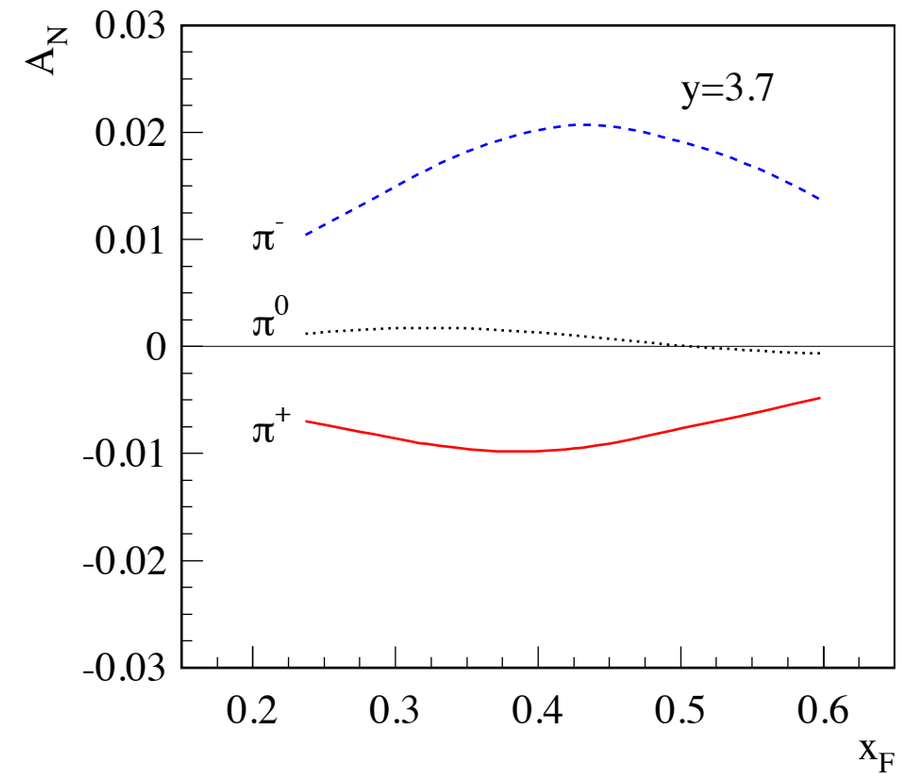
- Much progress has made in understanding single transverse spin asymmtry
  - Both TMD and collinear twist-3 approaches seem to be successful phenomenologically
- Their connection seems to have a puzzle
  - Directly obtained ETQS functions are opposite in sign to those indirectly obtained from the kt-moment of the quark Sivers function
  - This sign mismatch does not necessarily lead to any inconsistency in our current formalism for describing the SSAs
  - Future experiments could help resolve different scenarios, which will help understand the SSAs and hadron structure better

Backup

- Use the ETQS function derived from the old Sivers and new Sivers functions, one could make predictions for the single inclusive hadron production. We find they are opposite to the experimental observations.



old Sivers



new Sivers

Definition of A_N in experiments