Sivers effect: from SIDIS to pp

- sign change and sign mismatch

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Opportunities for Drell-Yan Physics at RHIC
Brookhaven National Laboratory
RBRC, Upton, NY, May 11, 2011

Kang, Qiu, Vogelsang, Yuan arXiv: 1103.1591, PRD 83, 2011
Kang, Prokudin, 2011, in preparation

Outline

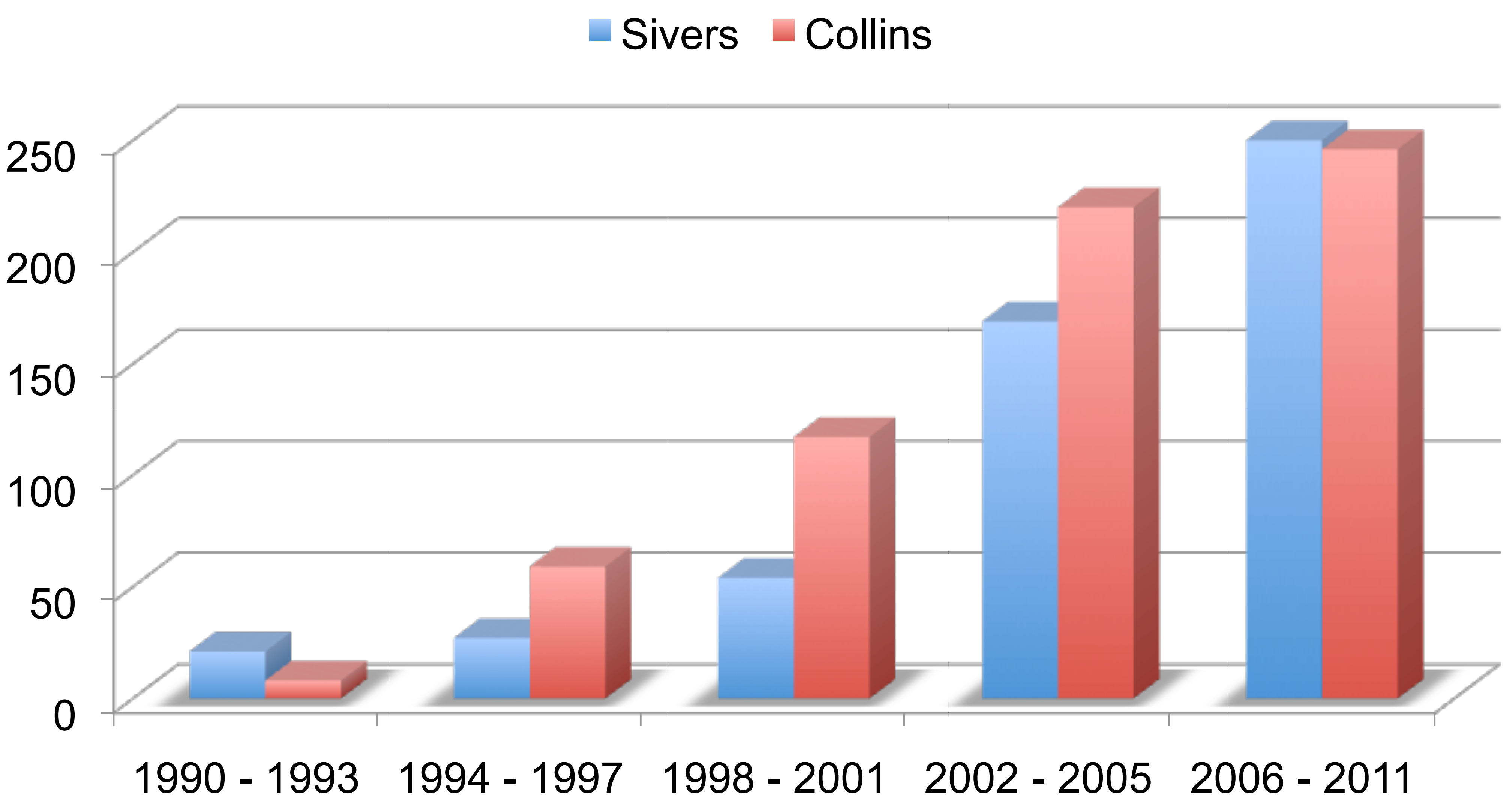
- Single transverse spin asymmetry: Sivers effect
- Sign change: from SIDIS to Drell-Yan
- "Sign mismatch": from SIDIS to pp

Alexei Prokudin (Friday 05/13/2011)

- Solution: detailed phenomenological studies
- Consequences for the Drell-Yan experiments in aiming at checking the sign change

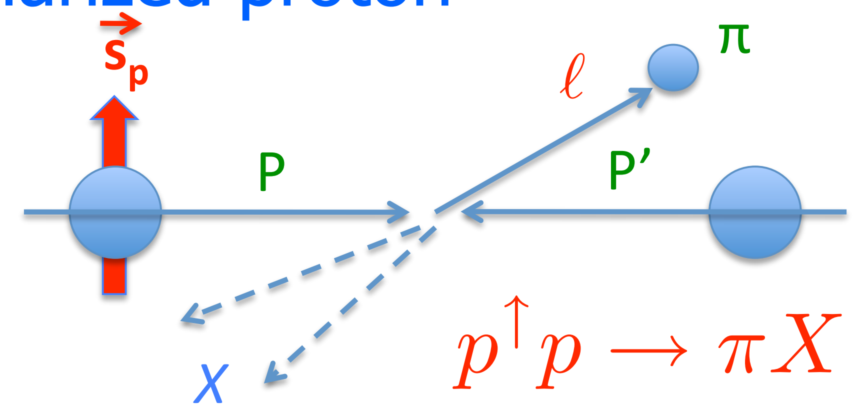
Sivers and Collins functions: birth and growth

- Differential citation for Sivers and Collins functions

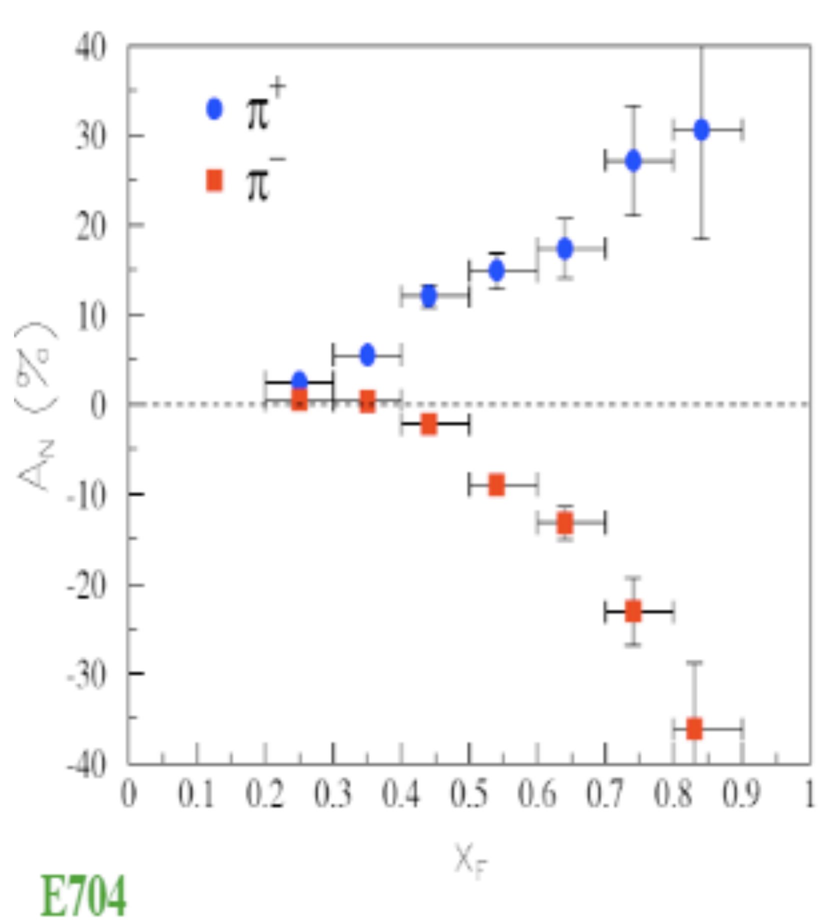


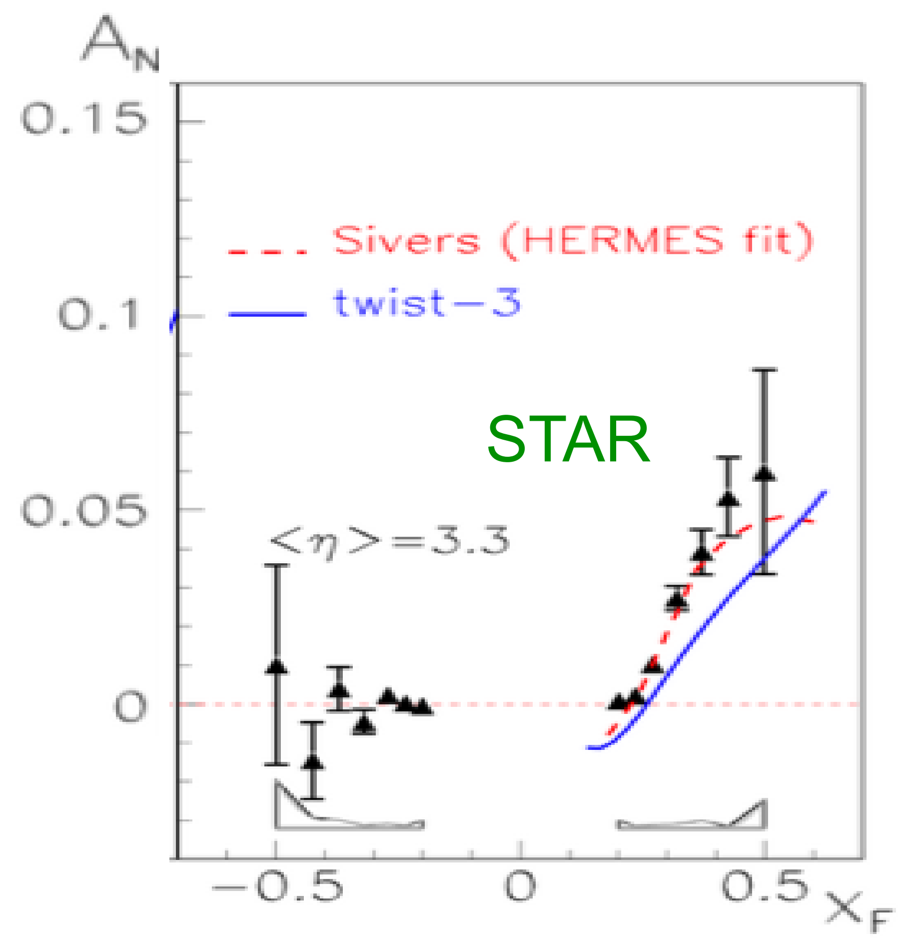
Single transverse spin asymmetry (SSA)

- Consider a transversely polarized proton scatters with another unpolarized proton



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



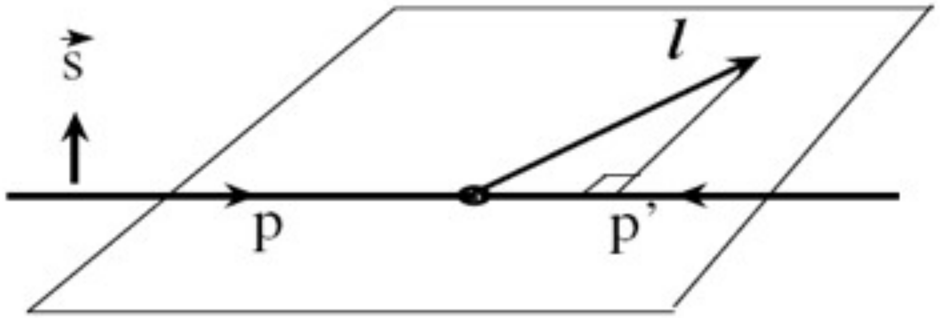


PHENIX
HERMES
COMPASS
JLAB, too

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

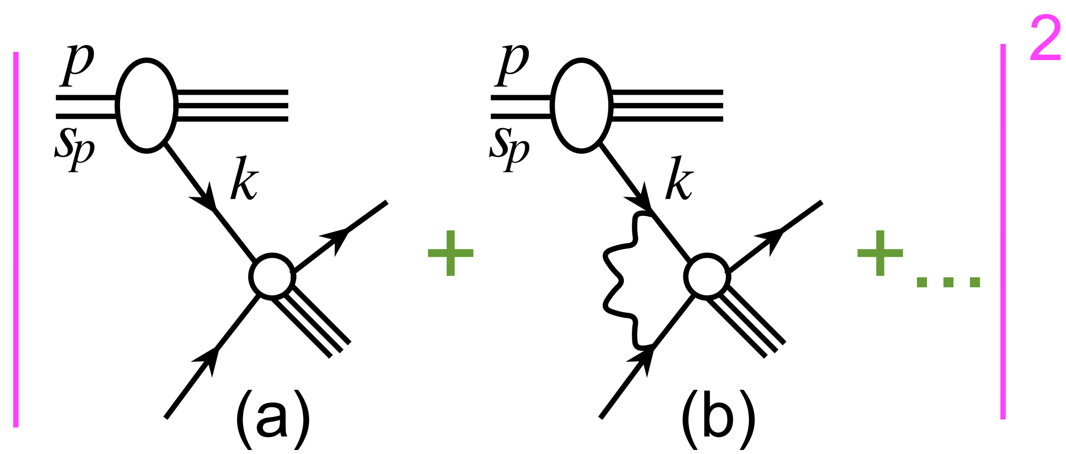
Nonvanishing A_N requires
a phase
a helicity flip
enough vectors to fix a scattering plane

SSA vanishes at leading twist in collinear factorization

- At leading twist formalism: partons are collinear

Kane, Pumplin, Repko, 1978

σ(s_T) ~



➡ Δσ(s_T) ~ Re[(a)]·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

$$A_N \sim \alpha_s \frac{m_q}{P_T} \to 0$$

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

Two mechanisms to generate SSA in QCD

- TMD approach: Transverse Momentum Dependent distributions probe 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

- Collinear twist-3 factorization approach: net K_T information

$$\sigma(p_h, s_\perp) \propto \frac{1}{Q} f_{a/A}^{s_\perp}(x) \otimes D_{h/c}(z) \otimes \hat{\sigma}_{\rm parton}$$

  - Twist-3 three-parton correlation functions: Qiu-Sterman matrix element, ...

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

  - Twist-3 three-parton fragmentation functions:

    Koike, 02, Kang-Yuan-Zhou 2010, ...

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 $Q_T << Q$

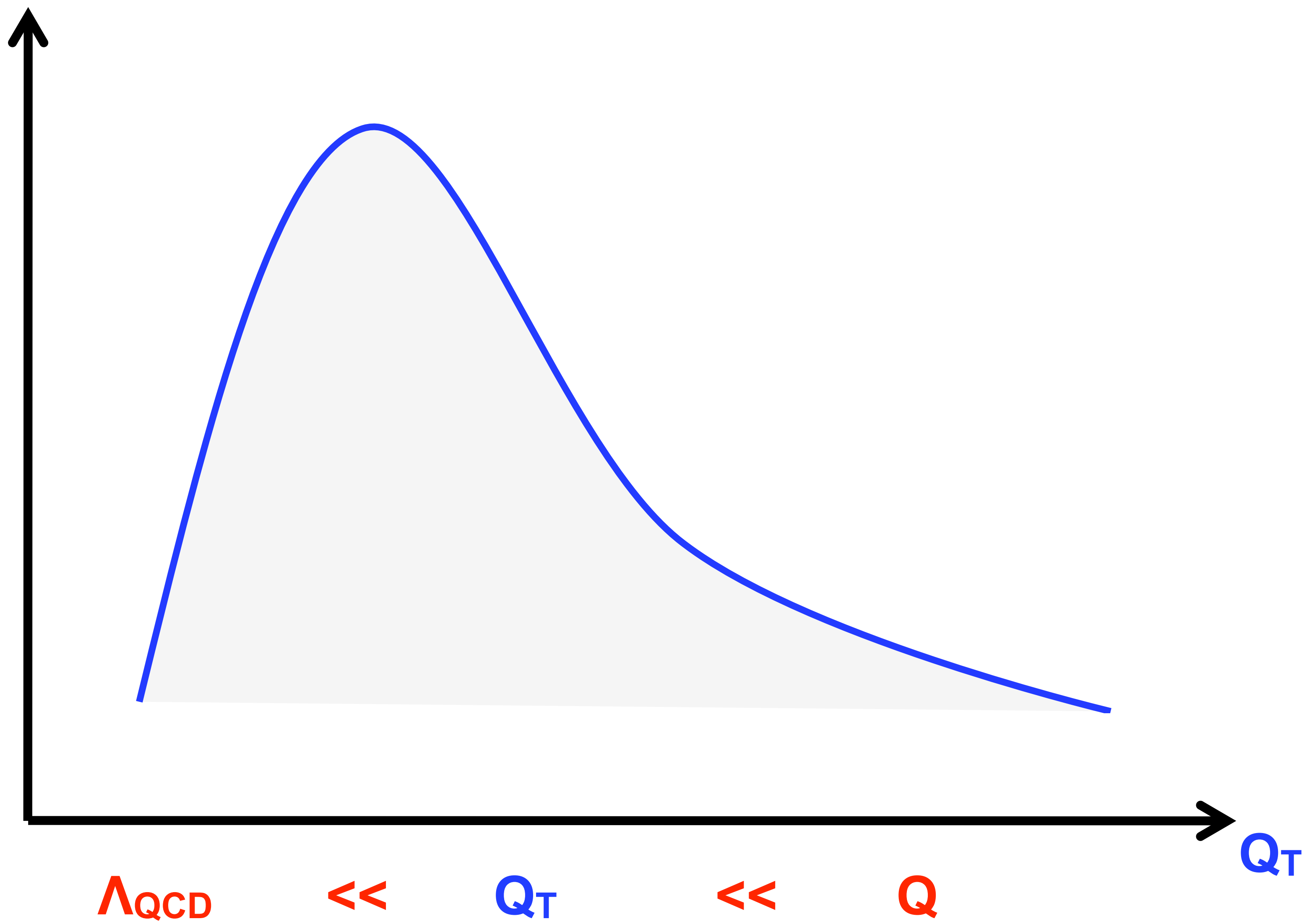
$$Q_1 \gg Q_2 \begin{cases} Q_1 & \text{necessary for pQCD factorization to have a chance} \\ Q_2 & \text{sensitive to parton's transverse momentum} \end{cases}$$

  - 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 $\longleftrightarrow$ Sivers function

    Ji-Qiu-Vogelsang-Yuan, 2006, …
  - Twist-3 three-parton correlation in fragmentation $\longleftrightarrow$ Collins function

    Koike 2002, Zhou-Yuan, 2009, Kang-Yuan-Zhou, 2010, …

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



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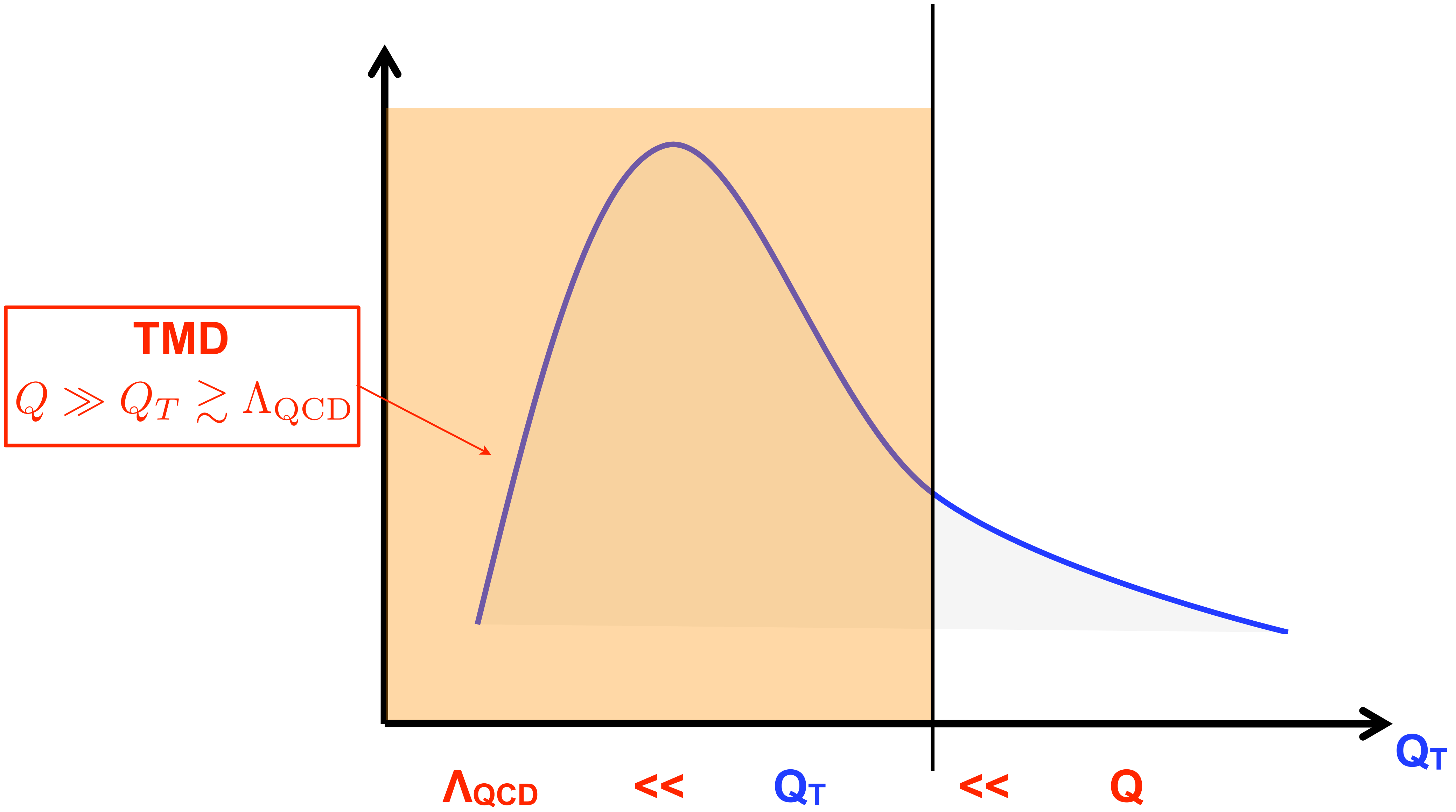

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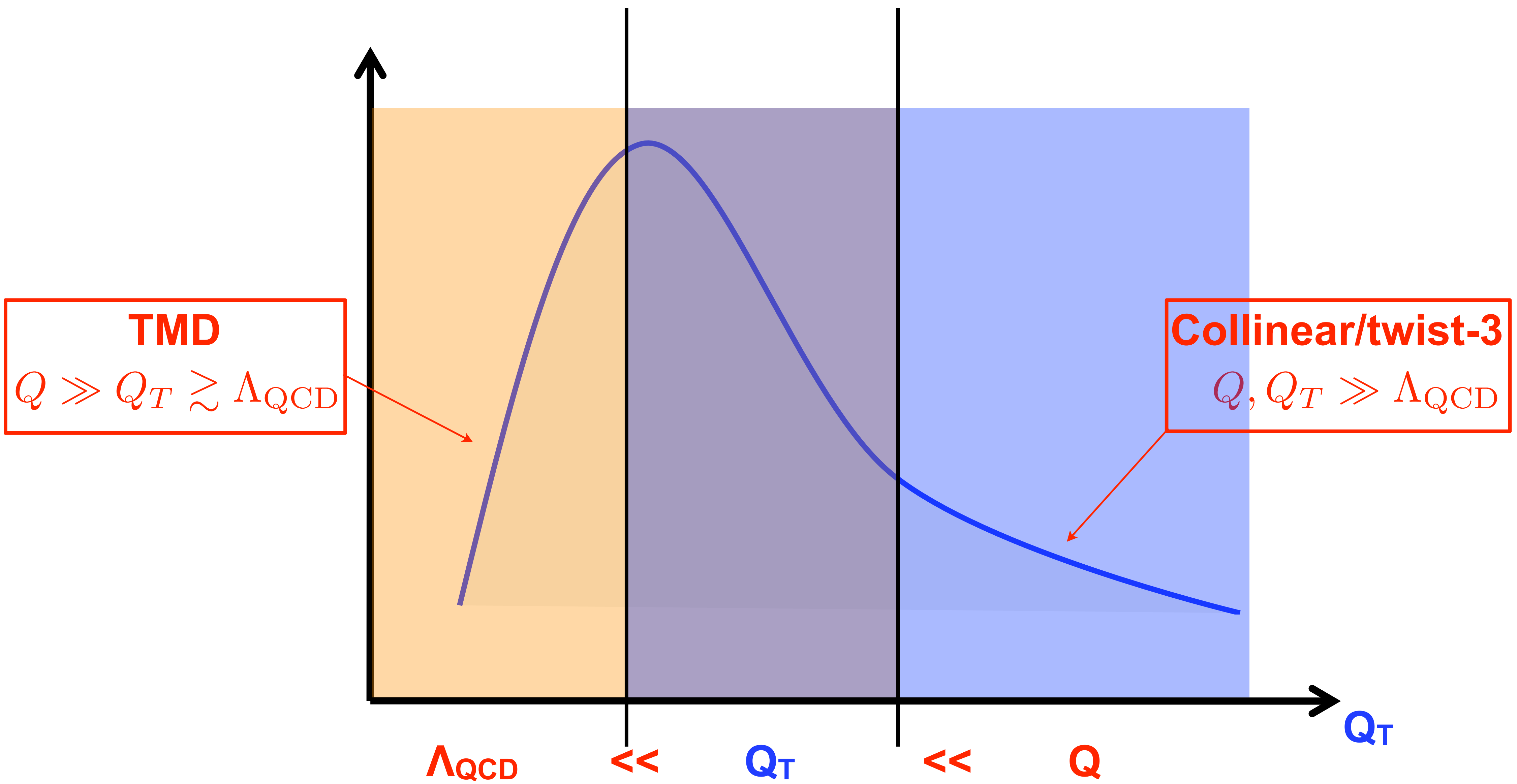

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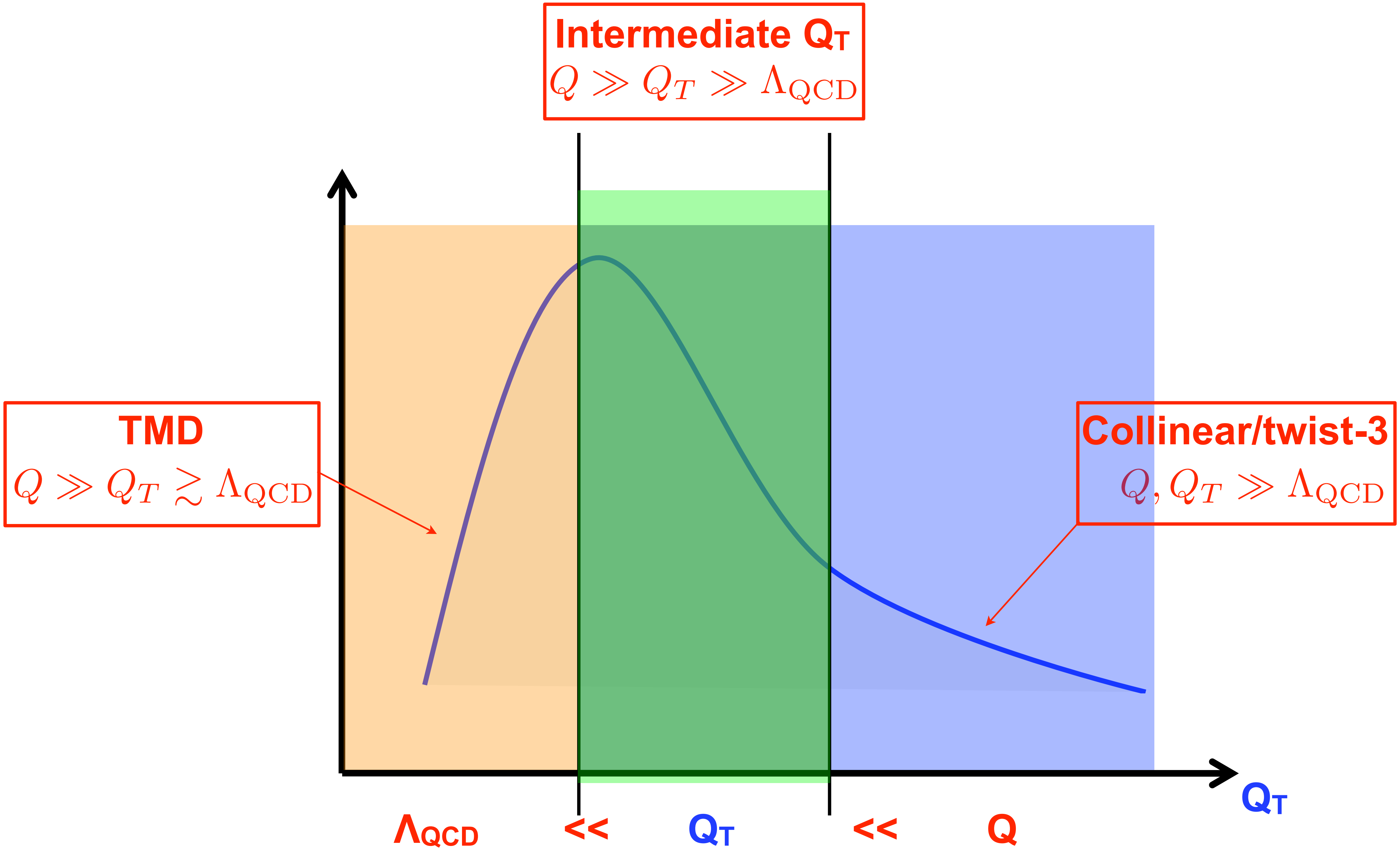


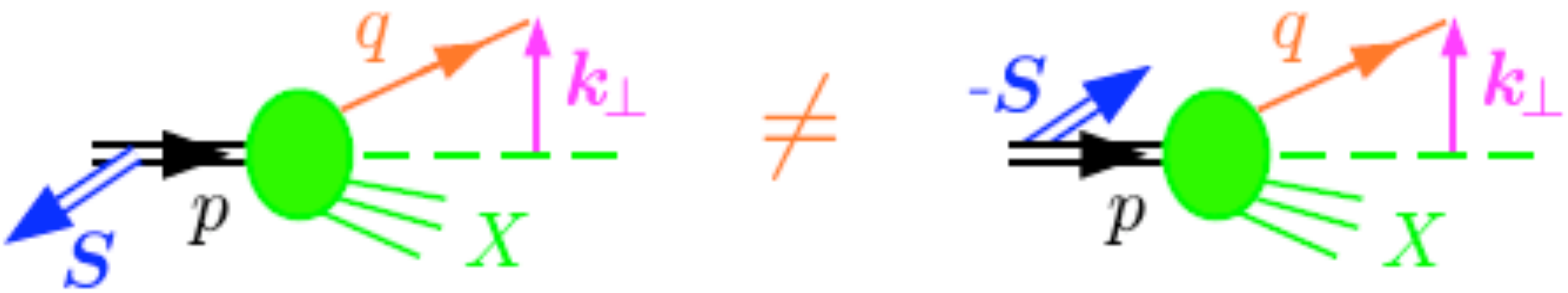
Transverse momentum dependent distribution (TMD)

- Sivers function: an asymmetric parton distribution in a polarized hadron (kt correlated with the spin of the hadron)

Spin-dependent

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

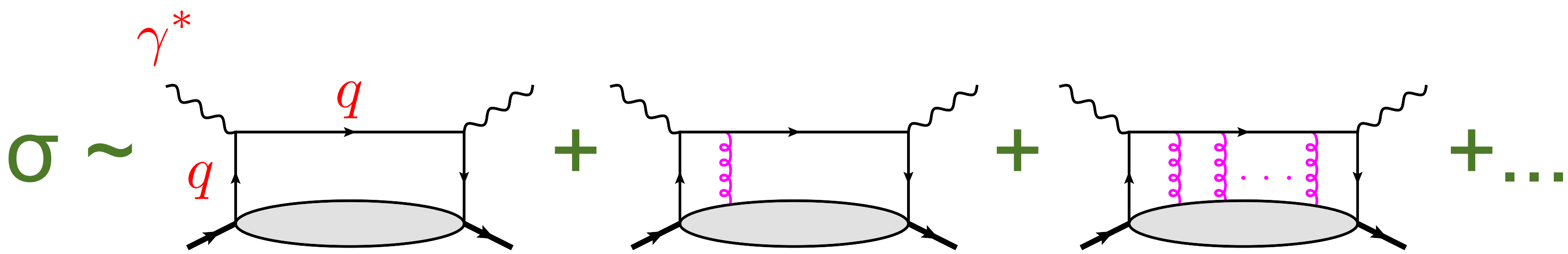
Spin-independent

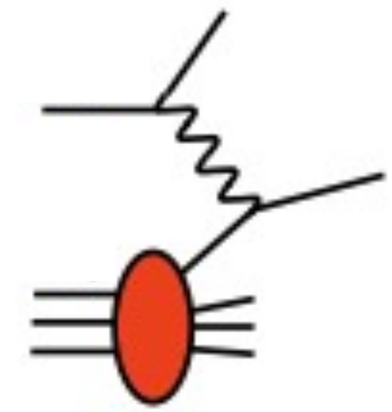


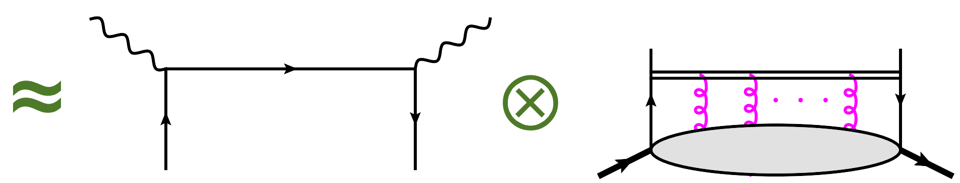
- Where does the phase come from?

Sivers function are process-dependent

- Existence of the Sivers function relies on the interaction between the active parton and the remnant of the hadron (process-dependent)
  - SIDIS: final-state interaction



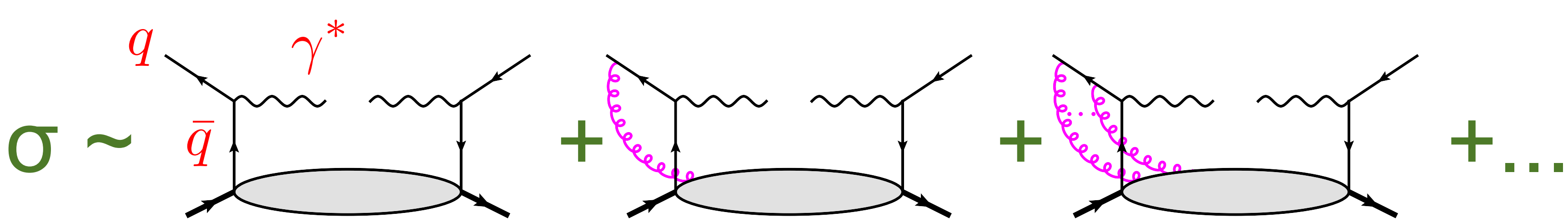


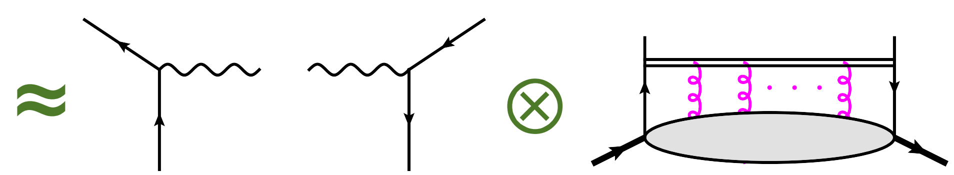


PDFs with SIDIS gauge link

$$\mathcal{P}\, e^{ig\int_y^{\infty} d\lambda\cdot A(\lambda)}$$

  - Drell-Yan: initial-state interaction





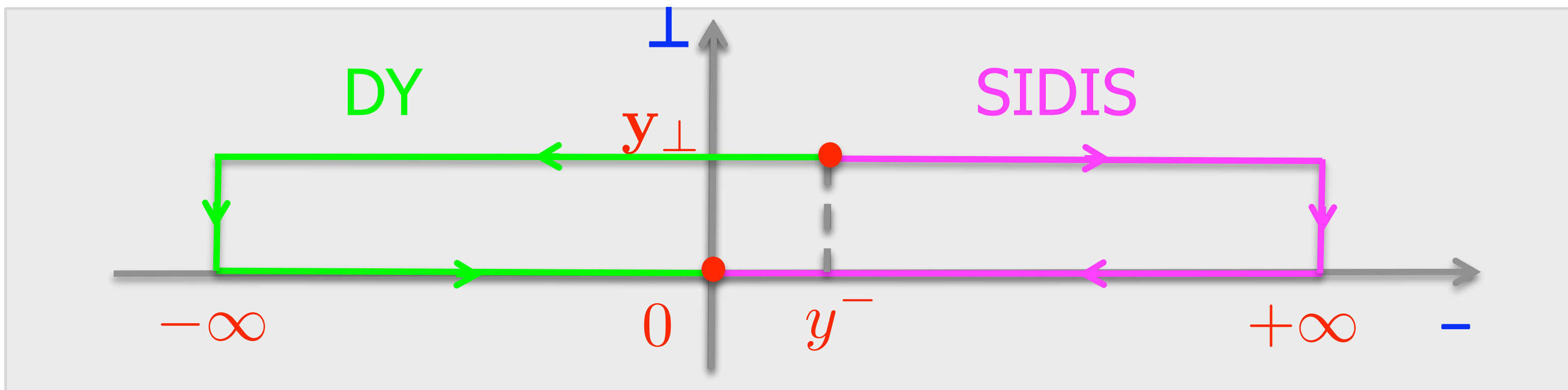
PDFs with DY gauge link

$$\mathcal{P}\, e^{ig\int_y^{-\infty} d\lambda\cdot A(\lambda)}$$

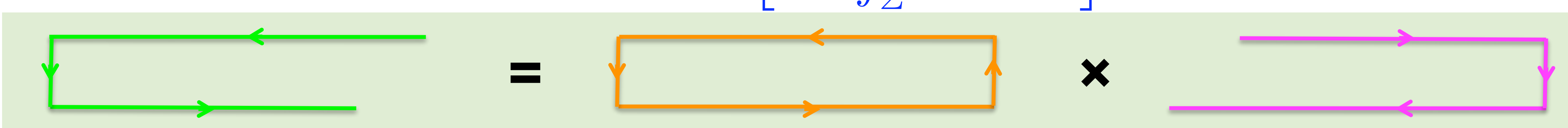
Time-reversal modified universality of the Sivers function

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

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



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



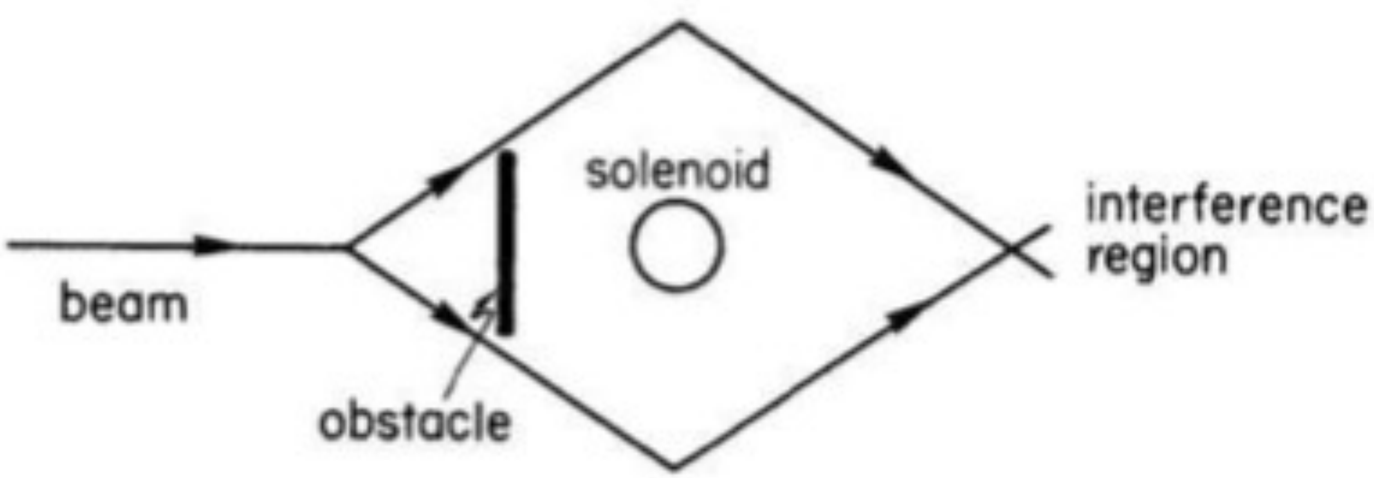
- Parity and time-reversal invariance:

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

Most critical test for TMD approach to SSA

QED: Aharonov-Bohm effect → non-abelian version

- In classical electrodynamics, gauge potential $A^\mu = (V, \vec{A})$ is no more than an auxiliary mathematical quantity for defining E and B field, thus has no independent physical significance
- However, this is decidedly not the case in quantum theory, as the analysis of Aharonov and Bohm has first made clear
- In the following experiment, there is magnetic-B-field confined inside the solenoid. Outside it is magnetic-field-free region, but gauge potential A exists, which eventually leads to a phase for different paths and interference pattern when beams recombine



C. Quigg, Gauge theory of The Strong, Weak and Electromagnetic Interactions

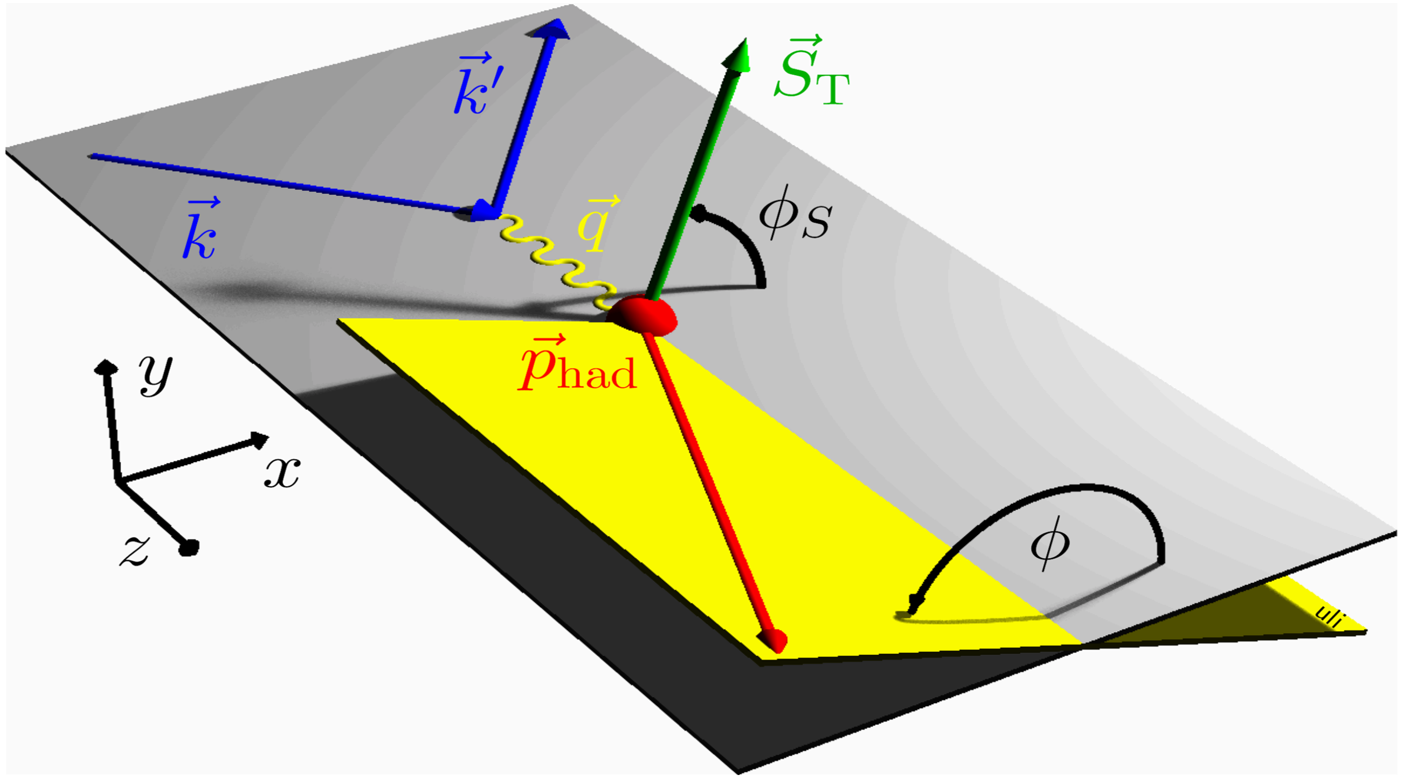
$$\Psi = \Psi_1^0\, e^{iS_1/\hbar} + \Psi_2^0\, e^{iS_2/\hbar}$$

$$S_i = e \int_{\text{path i}} d\vec{x} \cdot \vec{A}$$

Current Sivers function from SIDIS

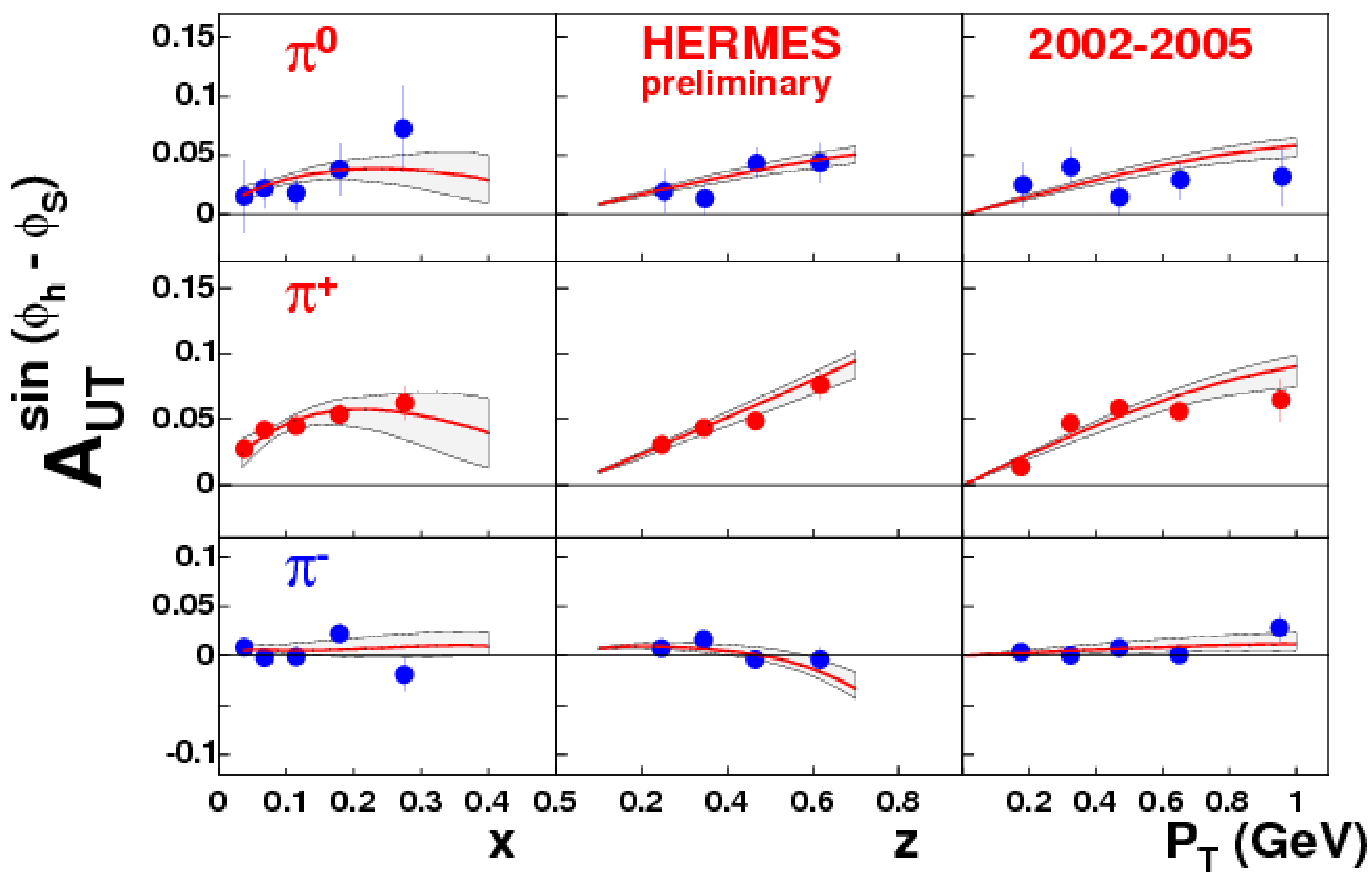
- Sivers and Collins can be separately extracted from SIDIS

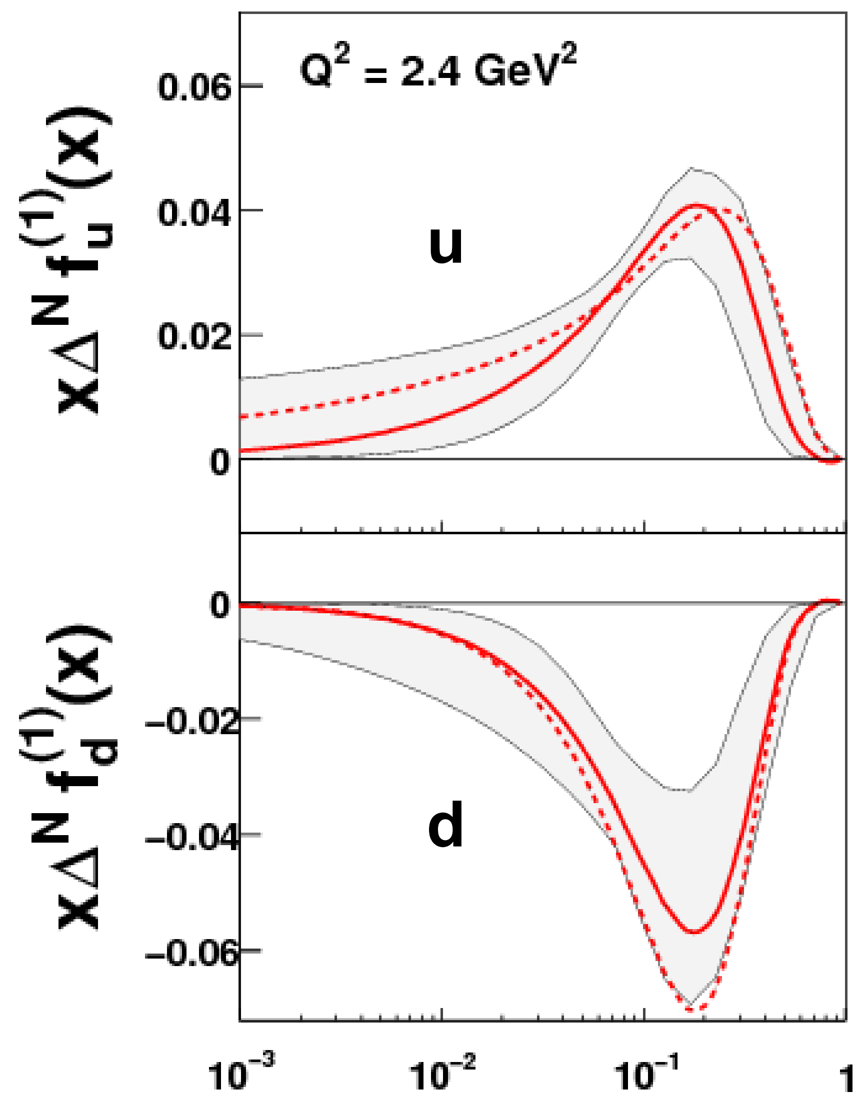
$$\Delta\sigma \propto A_{UT}^{Collins}\sin(\phi+\phi_S) + A_{UT}^{Sivers}\sin(\phi-\phi_S)$$



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

- Extract Sivers function from SIDIS (HERMES&COMPASS)





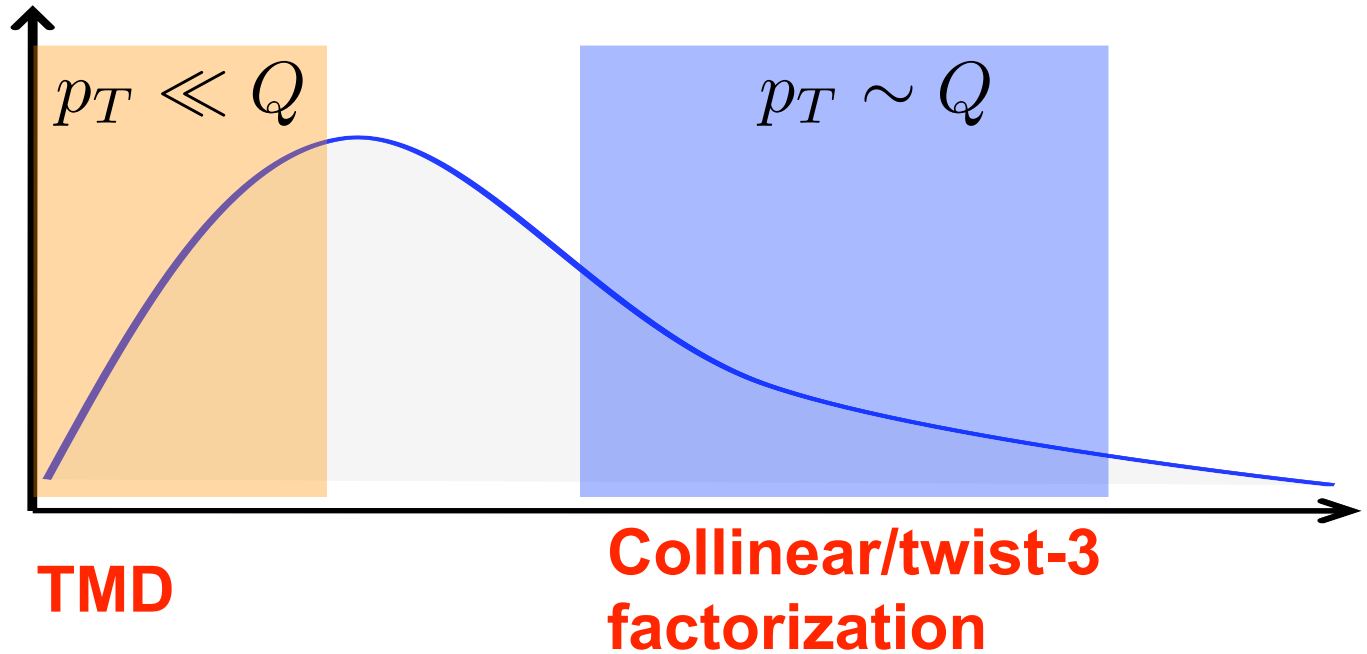
  - u and d almost equal size, different sign
  - d-Sivers is slightly larger

Anselmino, et.al., 2009

- Still needs DY results to verify the sign change, thus fully understand the mechanism of the SSAs

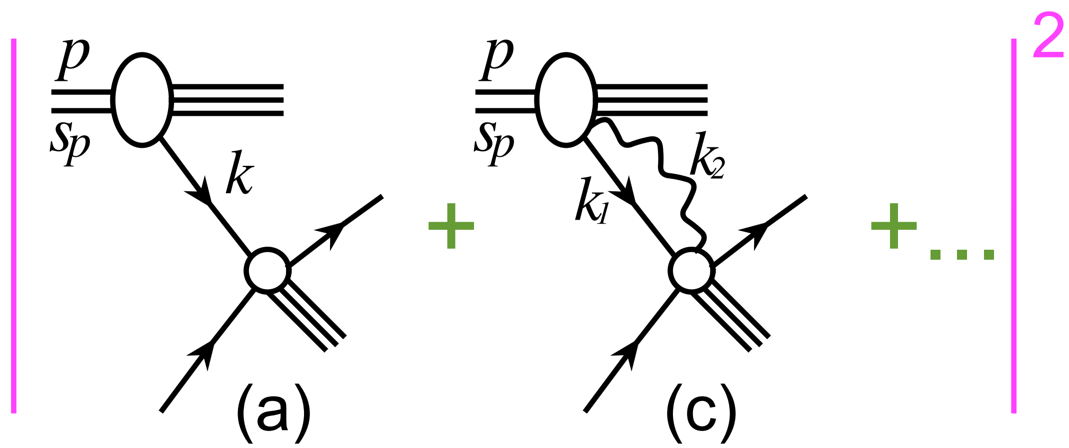
TMD factorization to collinear factorization

- Transition from low p_T to high p_T



- Collinear twist-3 factorization approach: Efremov-Teryaev 82, 84, Qiu-Sterman 91, 98

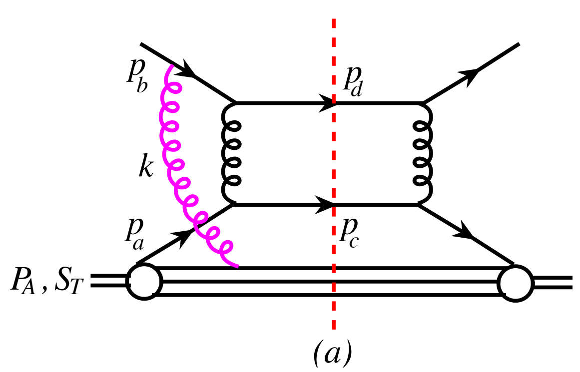
$\sigma(s_T) \sim$



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

Both initial- and final-state interactions

- 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

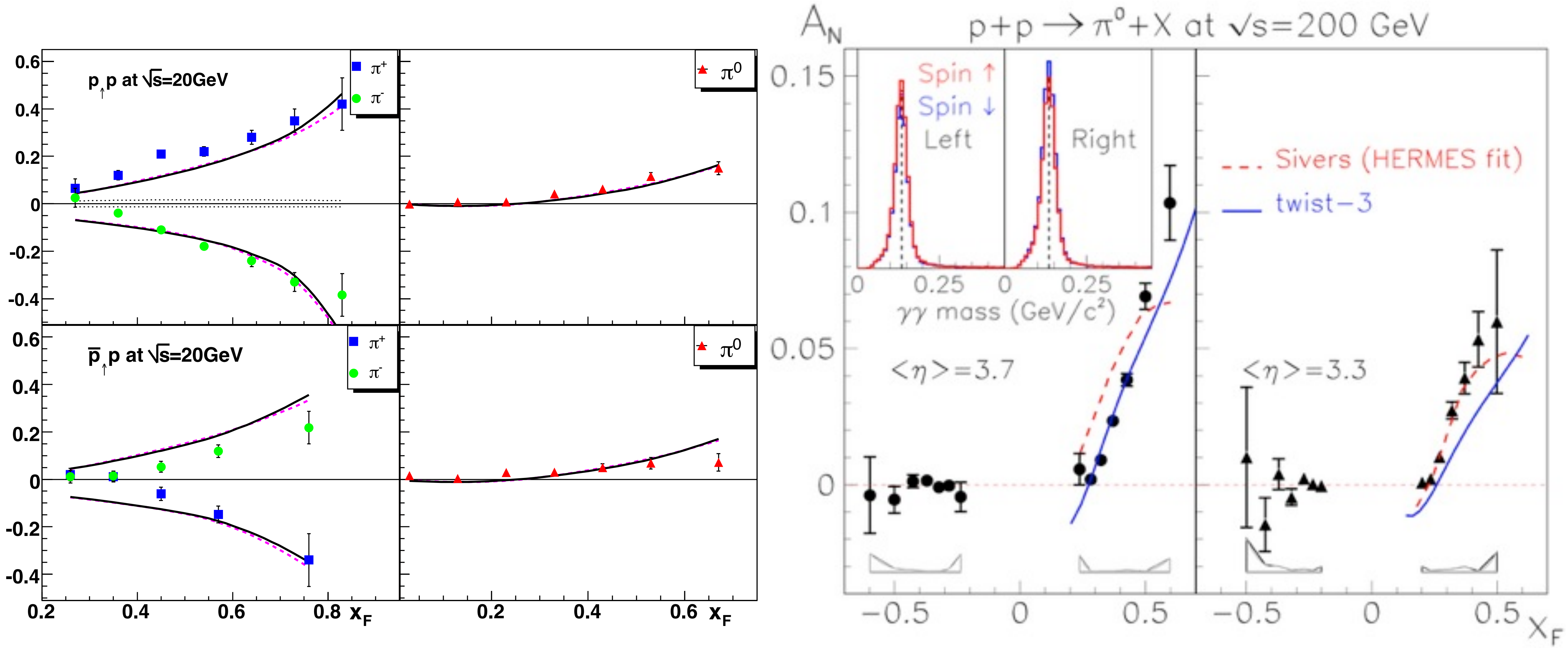
  - The effects of initial- and final-state interaction are absorbed to $H^{\rm Siv}_{ab\to c}$
  - ETQS function $T_{q,F}(x,x)$ is universal

- 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

- Describe both fixed-target and RHIC well: a fit

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

Kouvaris-Qiu-Vogelsang-Yuan, 2006



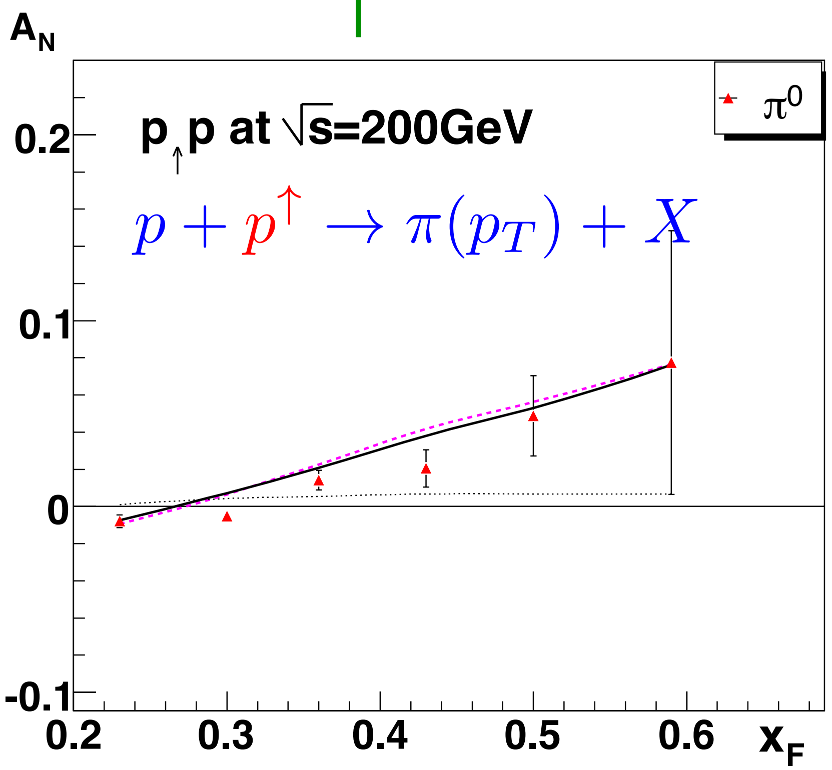
$$p^\uparrow p \to \pi + X$$

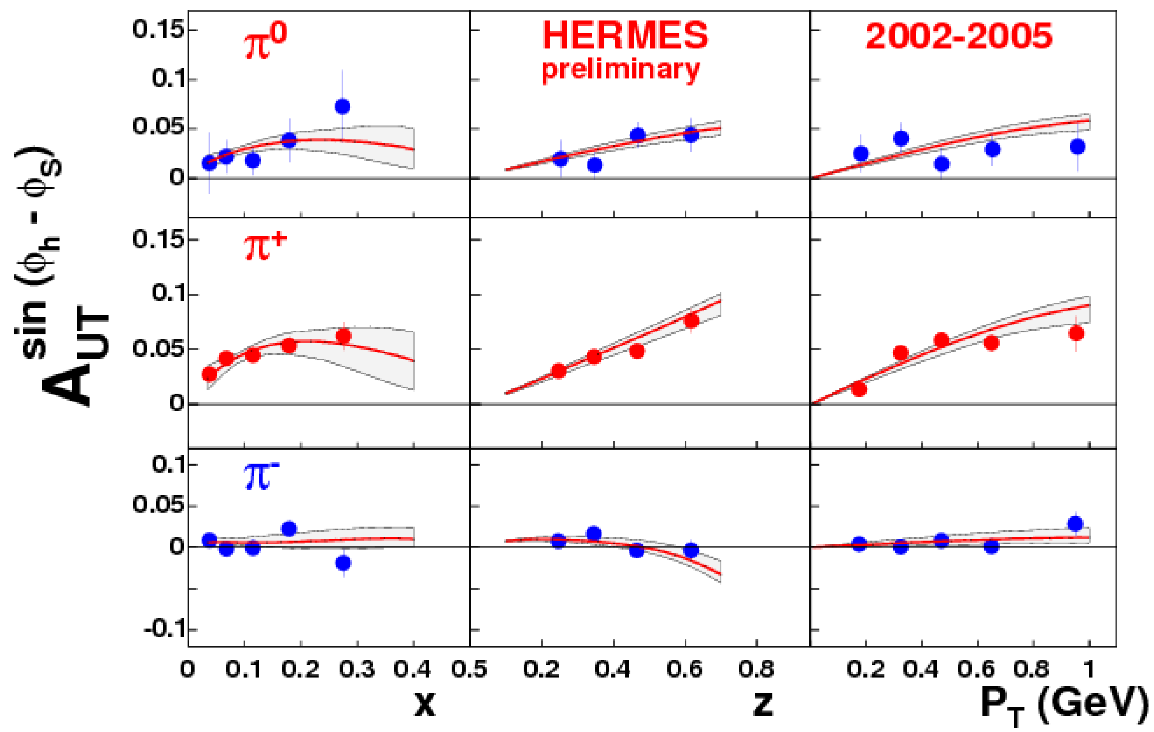
What about the connections?

- 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

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





kt-dependence is a Gaussian in current parameterization

- 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: $$h(k_\perp) = \frac{2k_\perp M_0}{k_\perp^2 + M_0^2}$$ 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

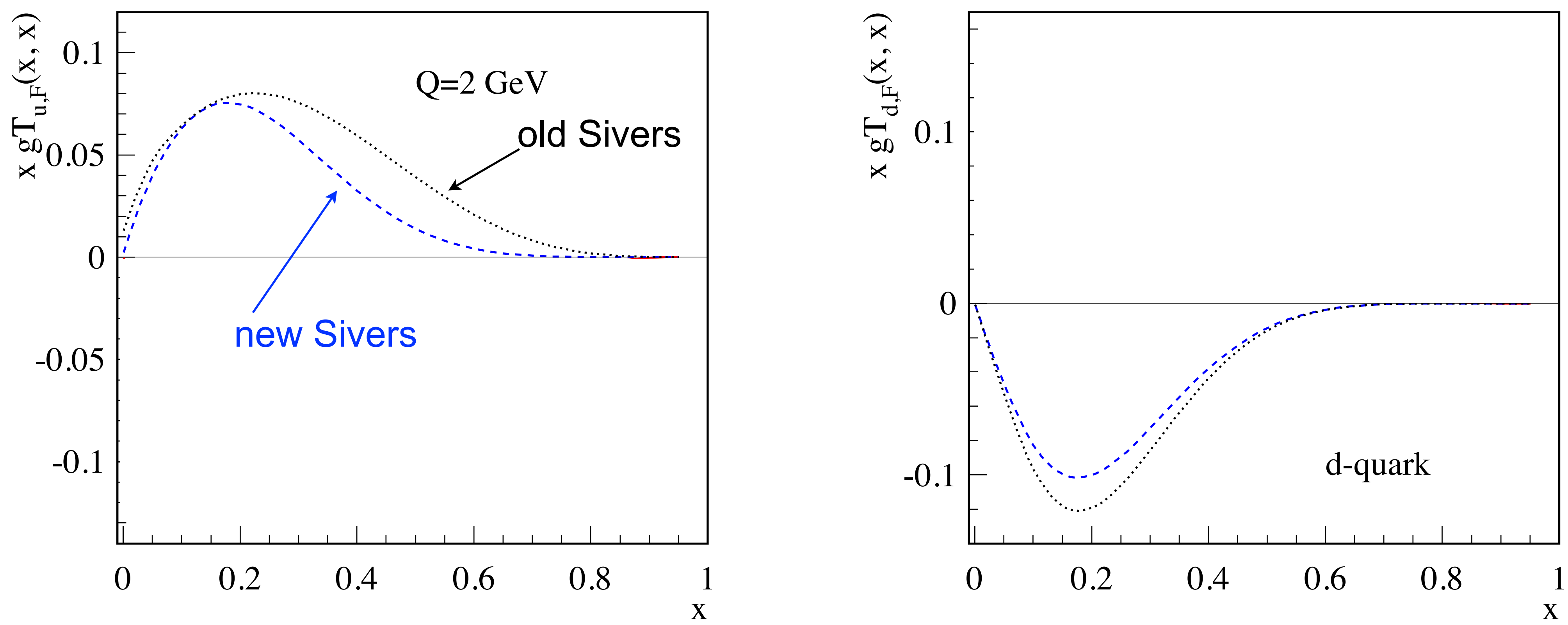
- Using $\Delta^N f_{q/A^\uparrow}(x, k_\perp) = -\frac{2k_\perp}{M} f_{1T}^{\perp q}(x, k_\perp^2)$, one can obtain

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

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

Indirectly obtained ETQS function

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

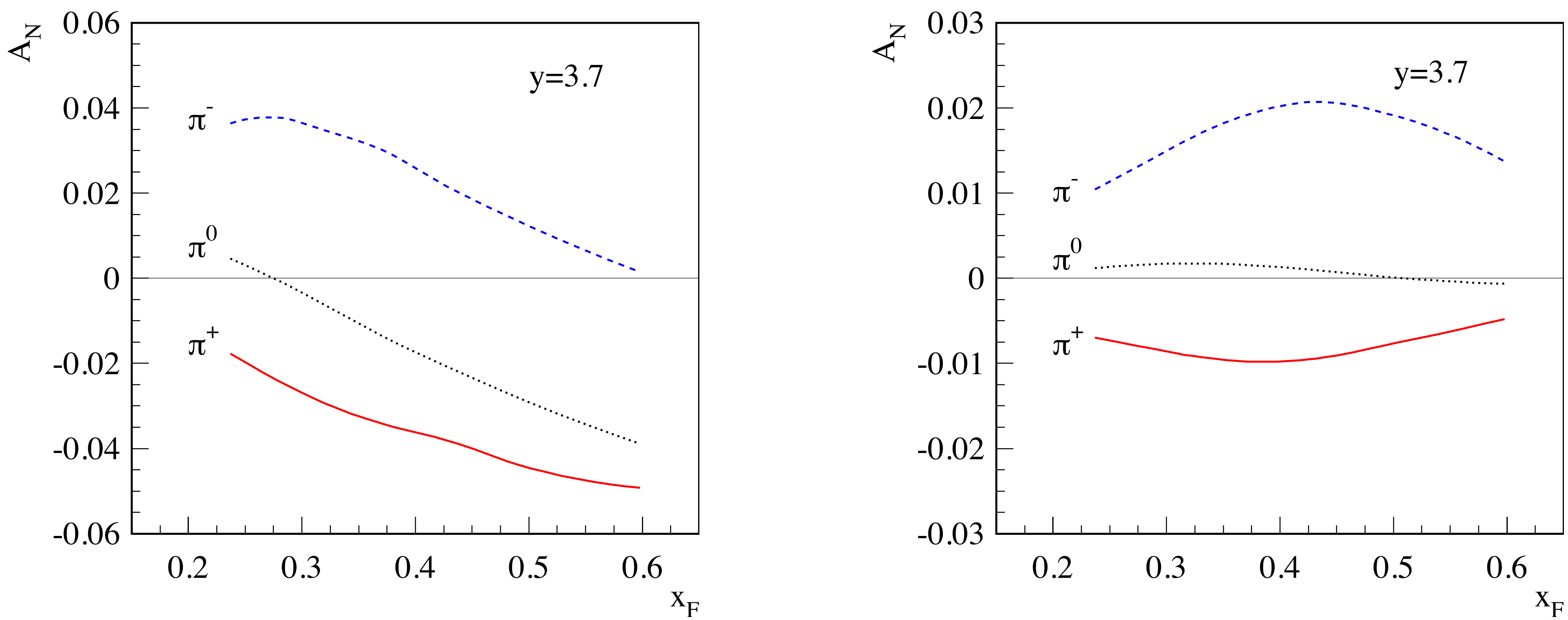


- ETQS function is positive for u-quark
- ETQS function is negative for d-quark

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

Apparent sign mismatch

- 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.

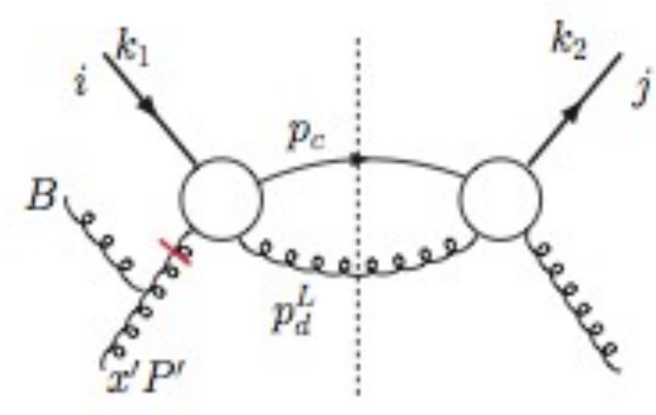


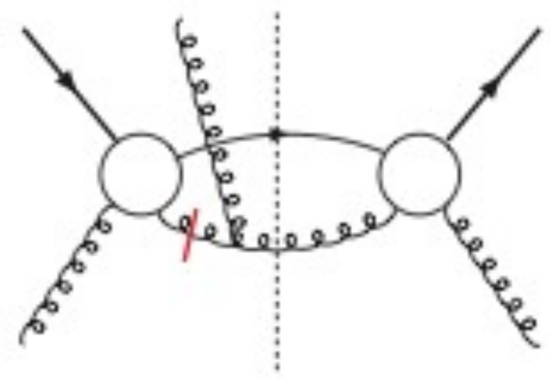
old Sivers new Sivers

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

Initial- and final-state interaction in pp collisions

- The dominant channel is qg → qg





$$H^U_{qg\to qg} = \frac{N_c^2-1}{2N_c^2}\left[-\frac{\hat{s}}{\hat{u}}-\frac{\hat{u}}{\hat{s}}\right]\left[1-\frac{2N_c^2}{N_c^2-1}\frac{\hat{s}\hat{u}}{\hat{t}^2}\right] \xrightarrow{|\hat{t}|\ll\hat{s}\sim|\hat{u}|} \left[\frac{2\hat{s}^2}{\hat{t}^2}\right]$$

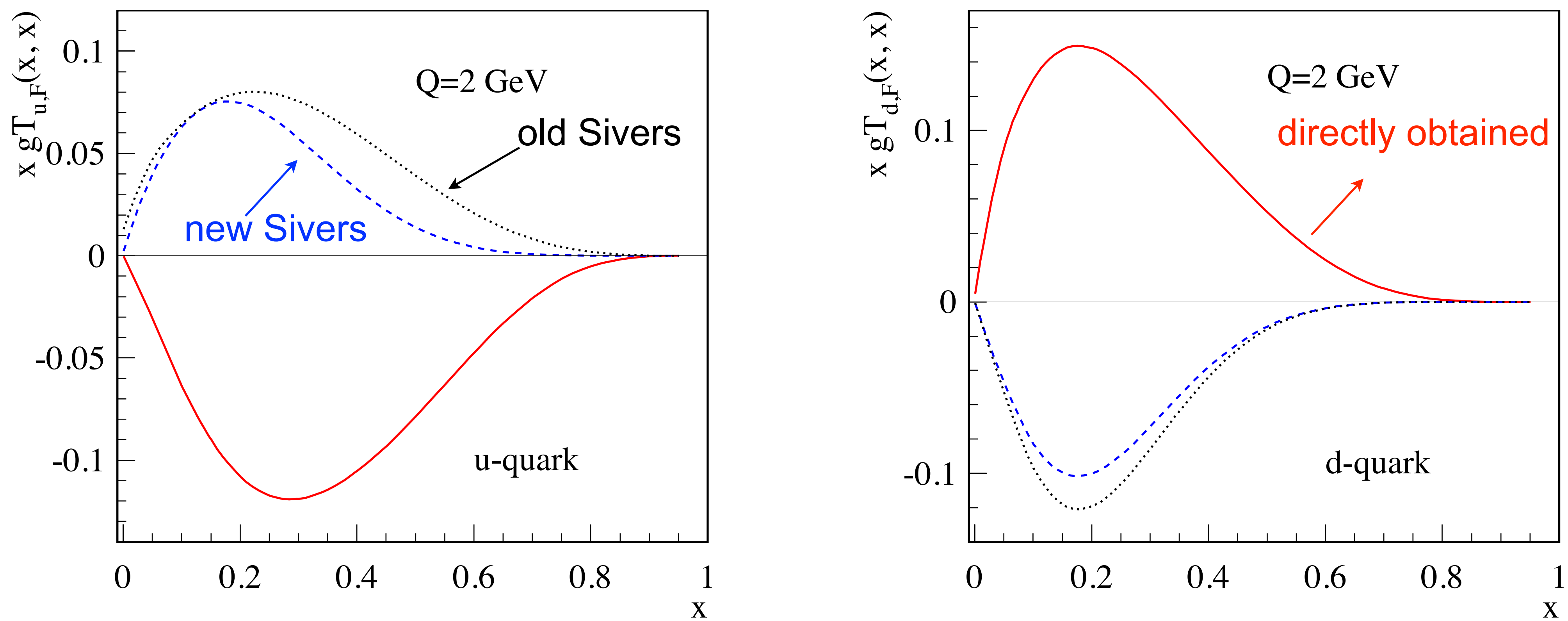
$$H^I_{qg\to qg} = \frac{1}{2(N_c^2-1)}\left[-\frac{\hat{s}}{\hat{u}}-\frac{\hat{u}}{\hat{s}}\right]\left[1-N_c^2\frac{\hat{u}^2}{\hat{t}^2}\right] \xrightarrow{|\hat{t}|\ll\hat{s}\sim|\hat{u}|} \left[-\frac{N_c^2}{2(N_c^2-1)}\right]\left[\frac{2\hat{s}^2}{\hat{t}^2}\right]$$

$$H^F_{qg\to qg} = \frac{1}{2N_c^2(N_c^2-1)}\left[-\frac{\hat{s}}{\hat{u}}-\frac{\hat{u}}{\hat{s}}\right]\left[1+2N_c^2\frac{\hat{s}\hat{u}}{\hat{t}^2}\right] \xrightarrow{|\hat{t}|\ll\hat{s}\sim|\hat{u}|} \left[-\frac{1}{N_c^2-1}\right]\left[\frac{2\hat{s}^2}{\hat{t}^2}\right]$$

- Sivers effect in single hadron production is more similar to DY

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?

Question

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.

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

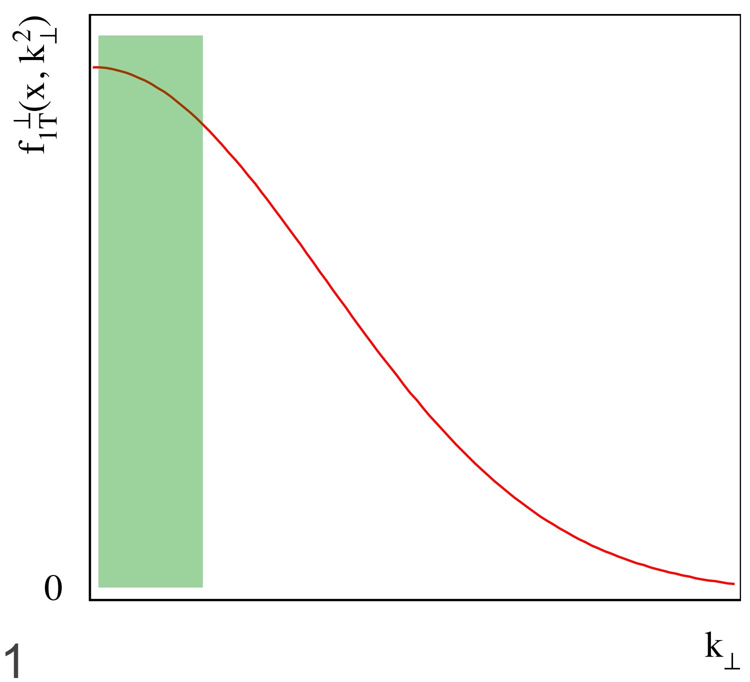
What could go wrong - Scenario I

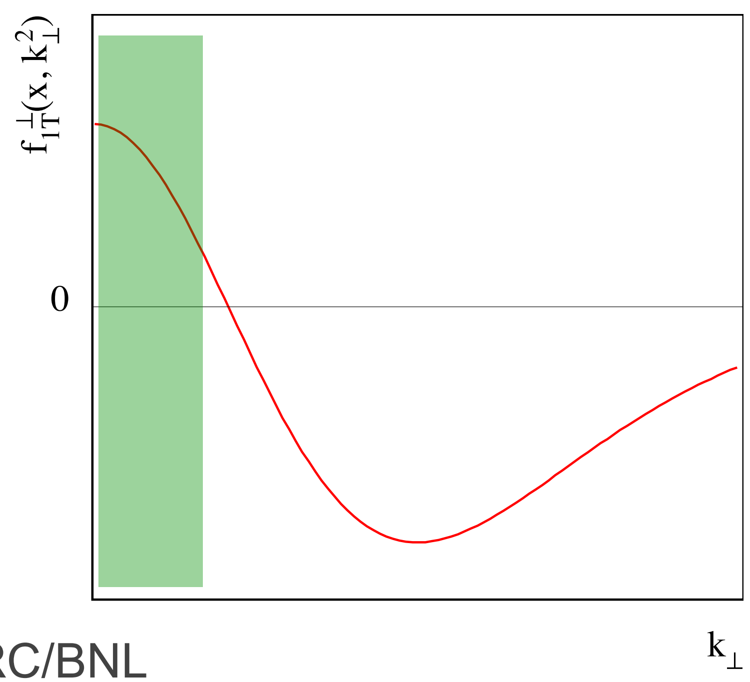
- To obtain ETQS function, one needs the full kt-dependence of the quark Sivers function

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

- 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}.

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





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

- A new global fitting including both SIDIS and pp data is underway:
  - Explore the possibility of a node in kt space or x space

Kang, Prokudin, in preparation
see talk by Produkin on Friday

Scenario II

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

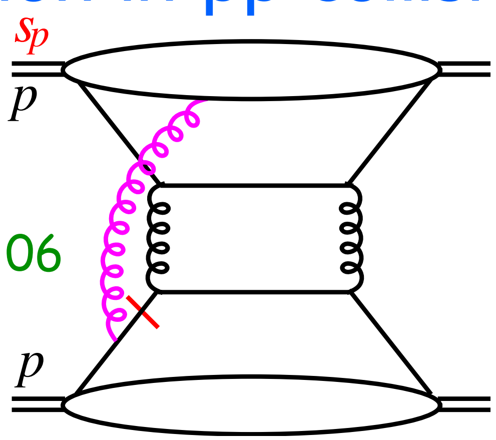
- In such case, to make everything consistent, we need to explain why we obtain a sign-mismatched ETQS function by analyzing the inclusive hadron data

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

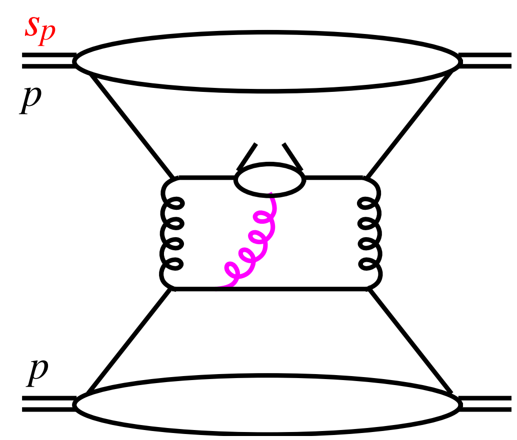
Single inclusive hadron production is complicated

- There are two major contributions to the SSAs of the single inclusive hadron production in pp collisions

Efremov-Teryaev 82, 84,
Qiu-Sterman 91, 98,
Kouvaris-Qiu-Vogelsang-Yuan, 06
Kanazawa-Koike, 11



in PDFs



in FFs

Kang-Yuan-Zhou 2010

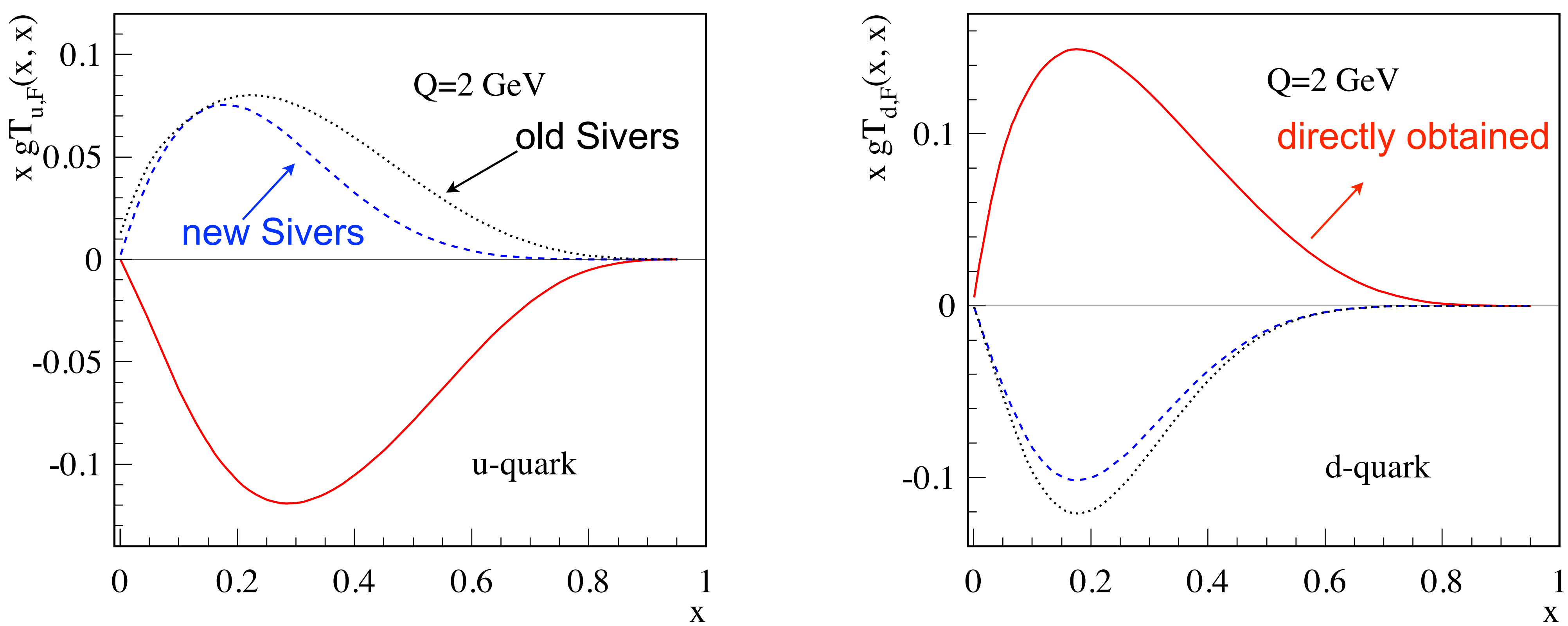
- So far the calculations related to three-parton correlation functions are more complete, while those related to the twist-3 fragmentation functions are available only very recently (not complete)
  - The current available global fittings are based on the assumptions that the SSAs mainly come from the 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

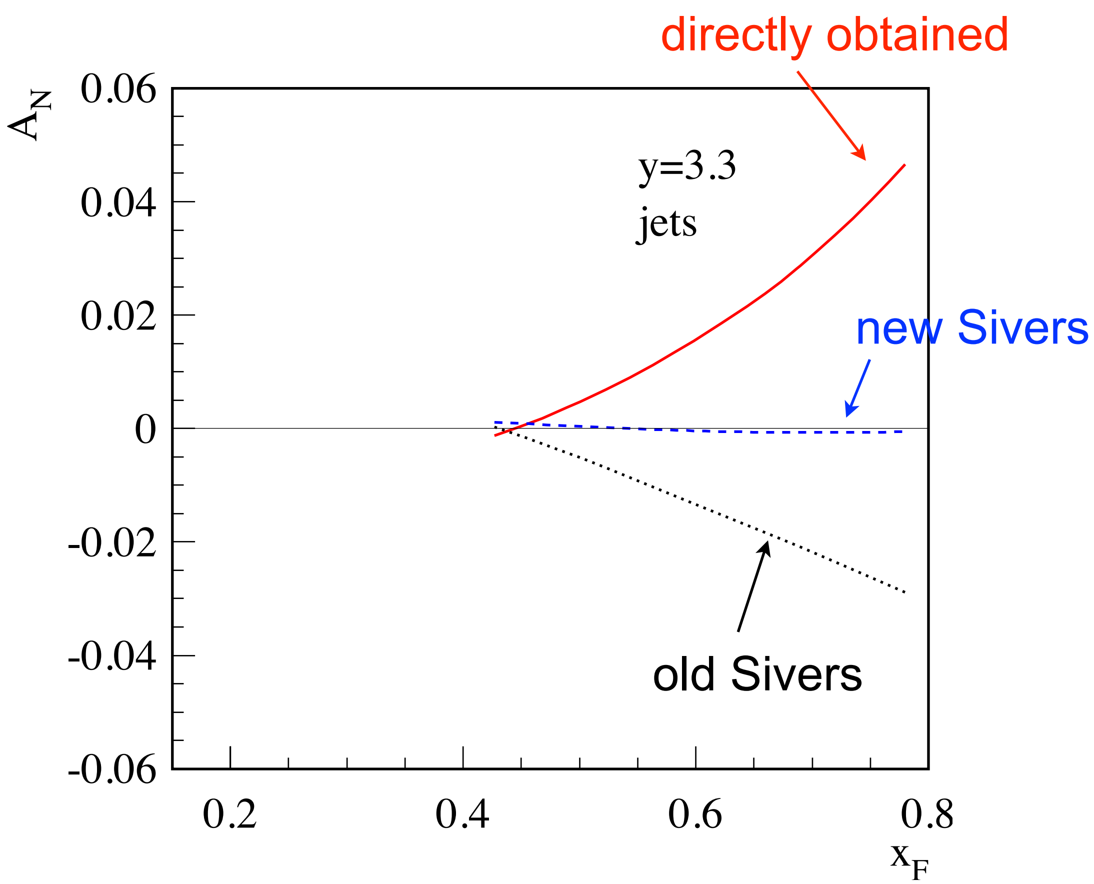
- Scenario I and II are completely different from each other

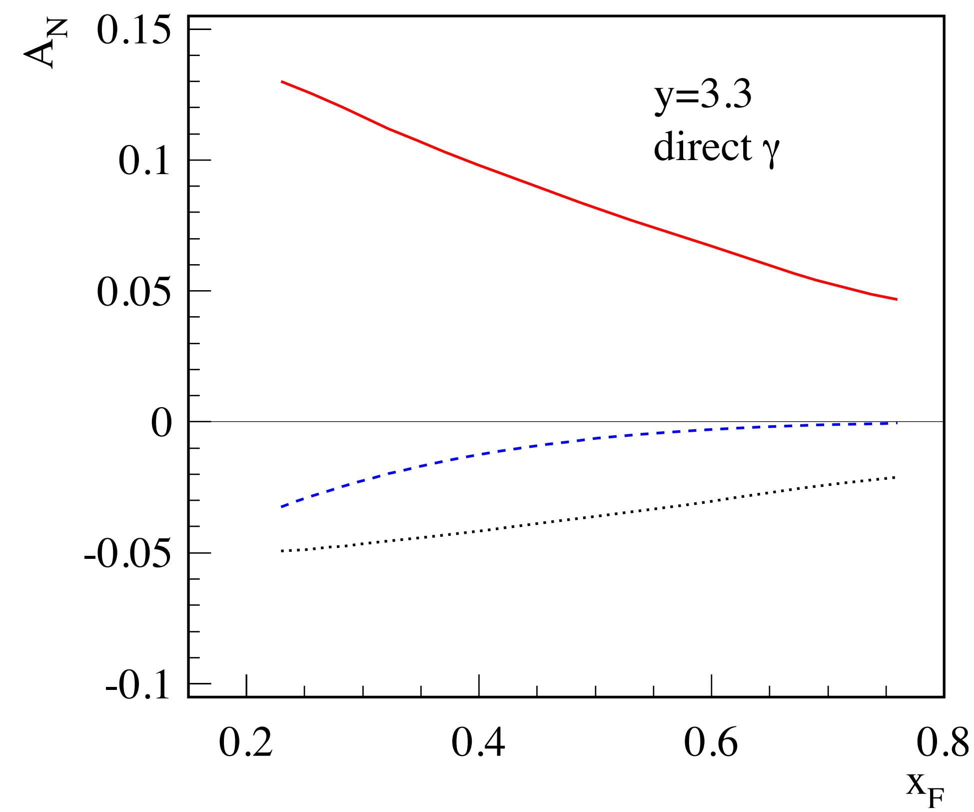


- To distinguish one from the other, in hadronic machine (like RHIC), one needs to find observables which are sensitive to twist-3 correlation function (not fragmentation function), such as single inclusive jet production, direct photon production

Predictions for jet and direct photon

- at RHIC 200 GeV:





Summary

- The existence of Sivers function relies on the initial and final-state interactions
- Sivers effect is process dependent
  - Test process-dependence is very important to understand the SSAs: sign change between SIDIS and DY
  - 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

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Thank you

Backup

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

$$\sigma \sim H^U \otimes f(x, k_\perp)$$

$$\Delta\sigma \sim \Delta H \otimes f_{1T}^{\perp}(x, k_\perp) \qquad \Delta H = H^U$$

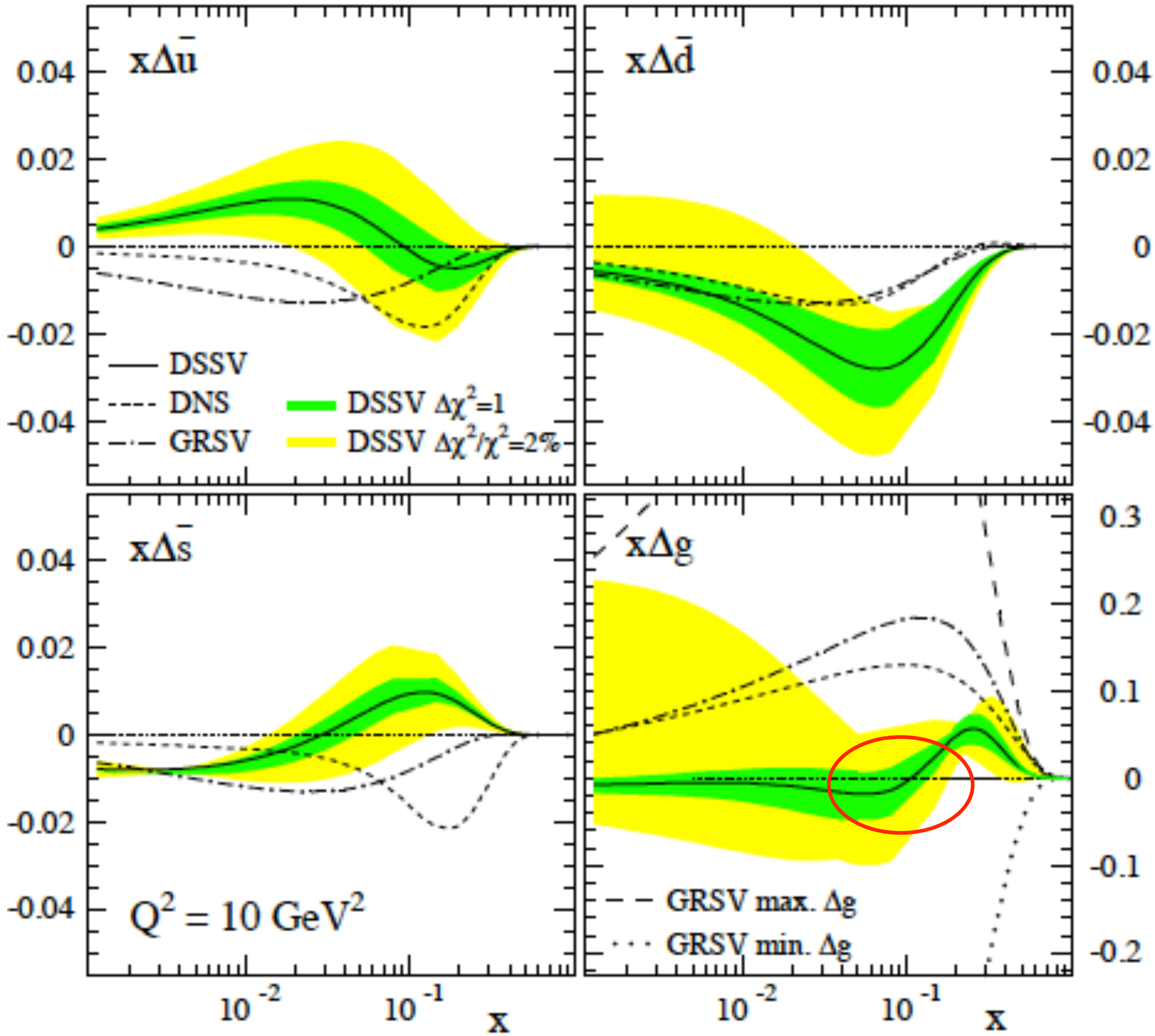
- Collinear twist-3 approach: the process-dependence of the SSAs is completely absorbed into the hard-part functions, thus the relevant collinear twist-3 correlation functions are universal
  - twist-3 correlation function is universal

$$\sigma \sim H^U \otimes f(x)$$

$$\Delta\sigma \sim \Delta H \otimes T_F(x, x) \qquad \Delta H = H^I + H^F$$

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



Definition of A_N in experiments