Theory for Drell-Yan Single Transverse Spin Asymmetry

Zhong-Bo Kang

RIKEN BNL Research Center
Brookhaven National Laboratory

PHENIX Forward Upgrade (Next Decade)
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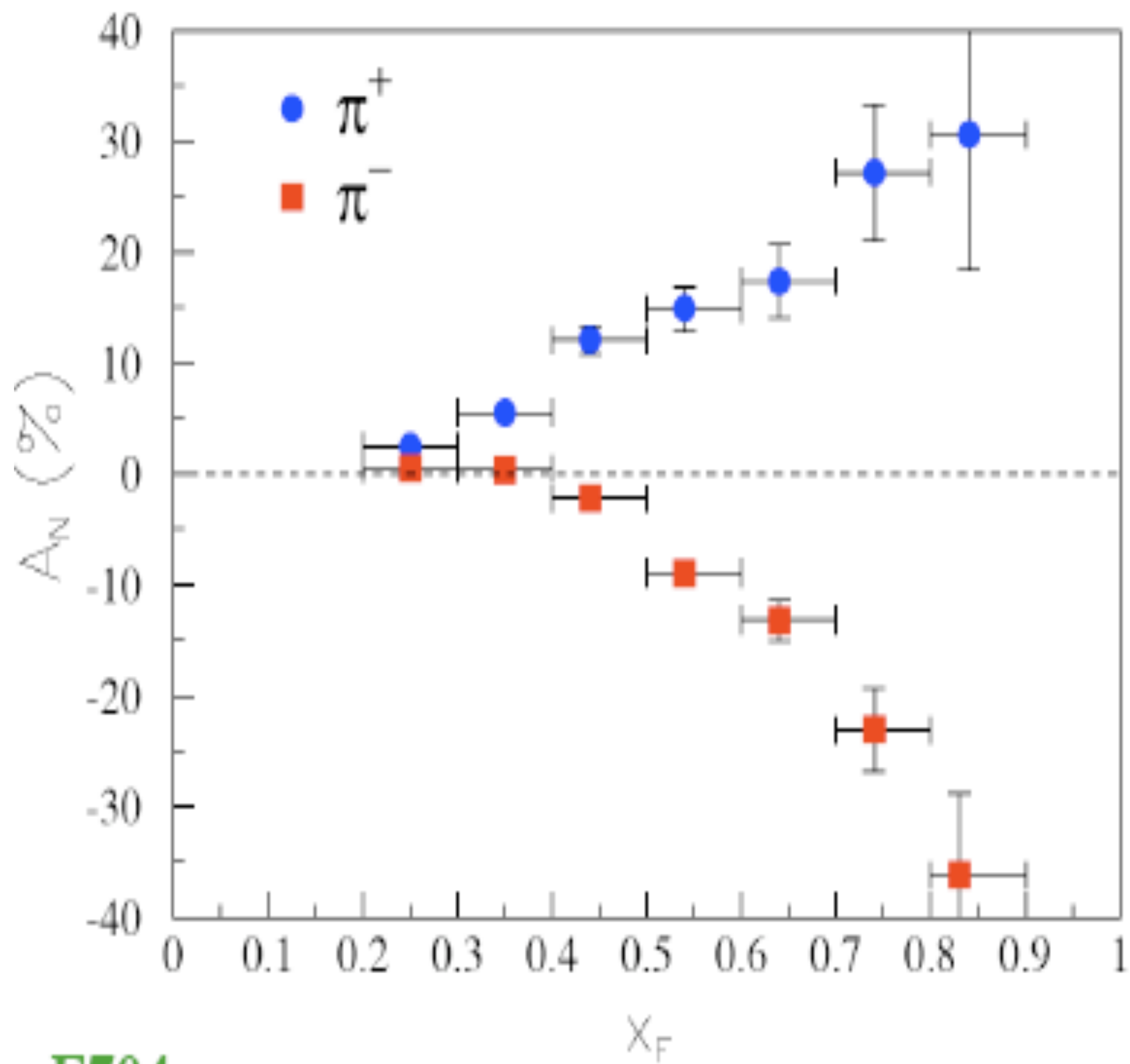
Plan

- Brief introduction
  - SSA theory
  - Sign change
- Sivers function and current predictions
  - Global fitting from SIDIS
  - Predictions for DY
- Consequence of RHIC DY measurements

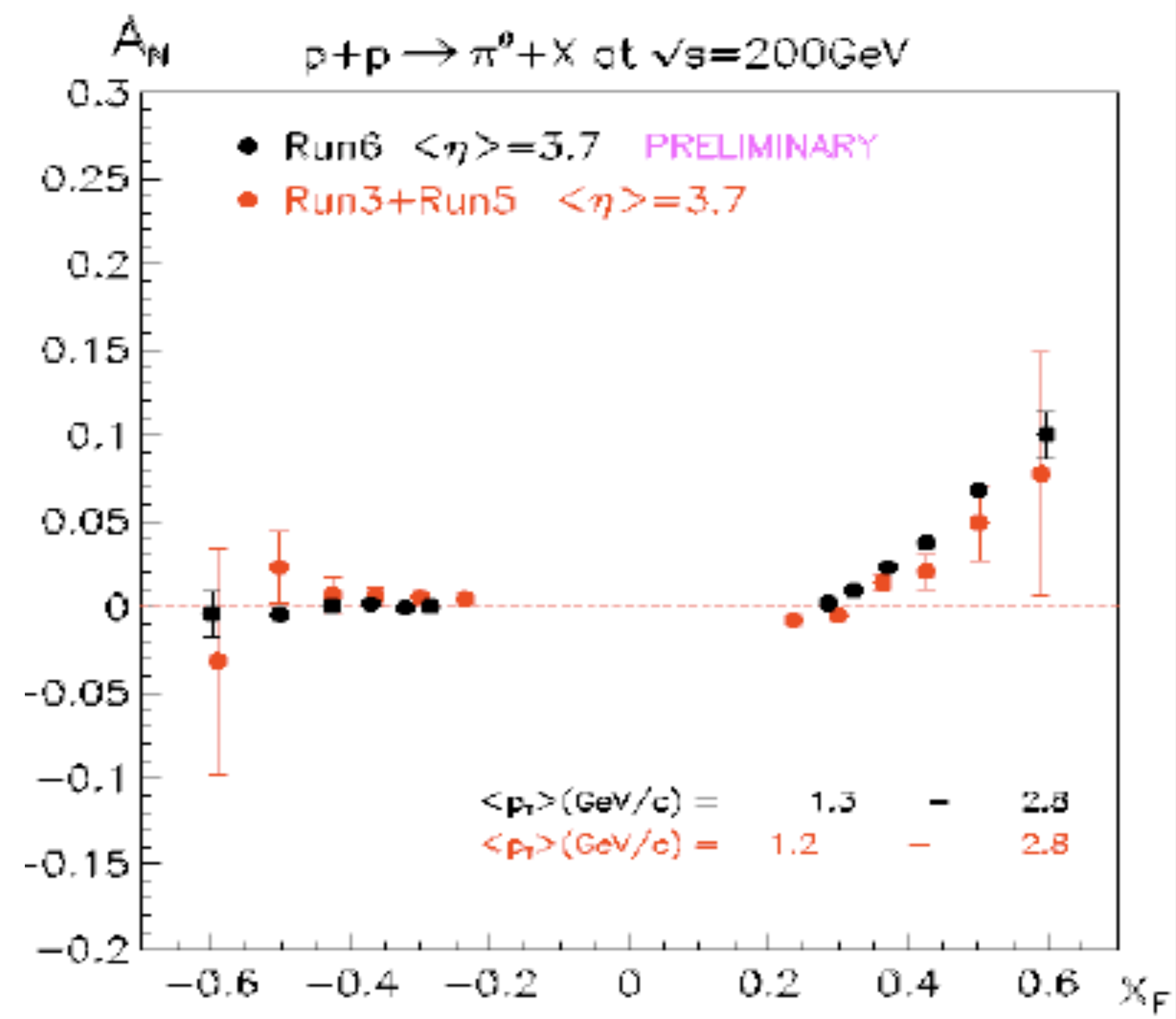
Experiment: Single Spin Asymmetries

- Fermilab E704, STAR, PHENIX, BRAHMS, COMPASS, HERMES, JLAB:

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



E704

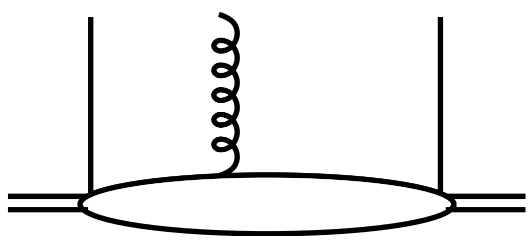


STAR (BRAHMS, too)

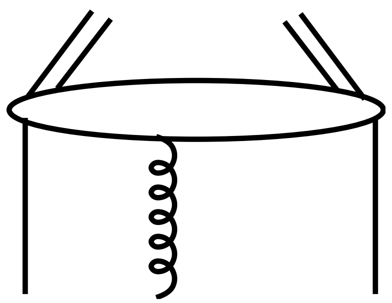
SSAs are observed in various experiments at different √s

Two mechanisms to generate SSA in QCD

- SSA is related to parton's transverse motion
- Collinear factorization approach:
  - Twist-3 three-parton correlation functions: Qiu-Sterman matrix element, ...
  - Twist-3 three-parton fragmentation functions:



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



Koike, 02, Zhou, Yuan, 2009,
Kang, Yuan, Zhou 2010

- TMD approach: Transverse Momentum Dependent distributions probe the parton's intrinsic transverse momentum
  - Sivers function: in Parton Distribution Function (PDF)

    Sivers 90
  - Collins function: in Fragmentation Function (FF)

    Collins 93

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

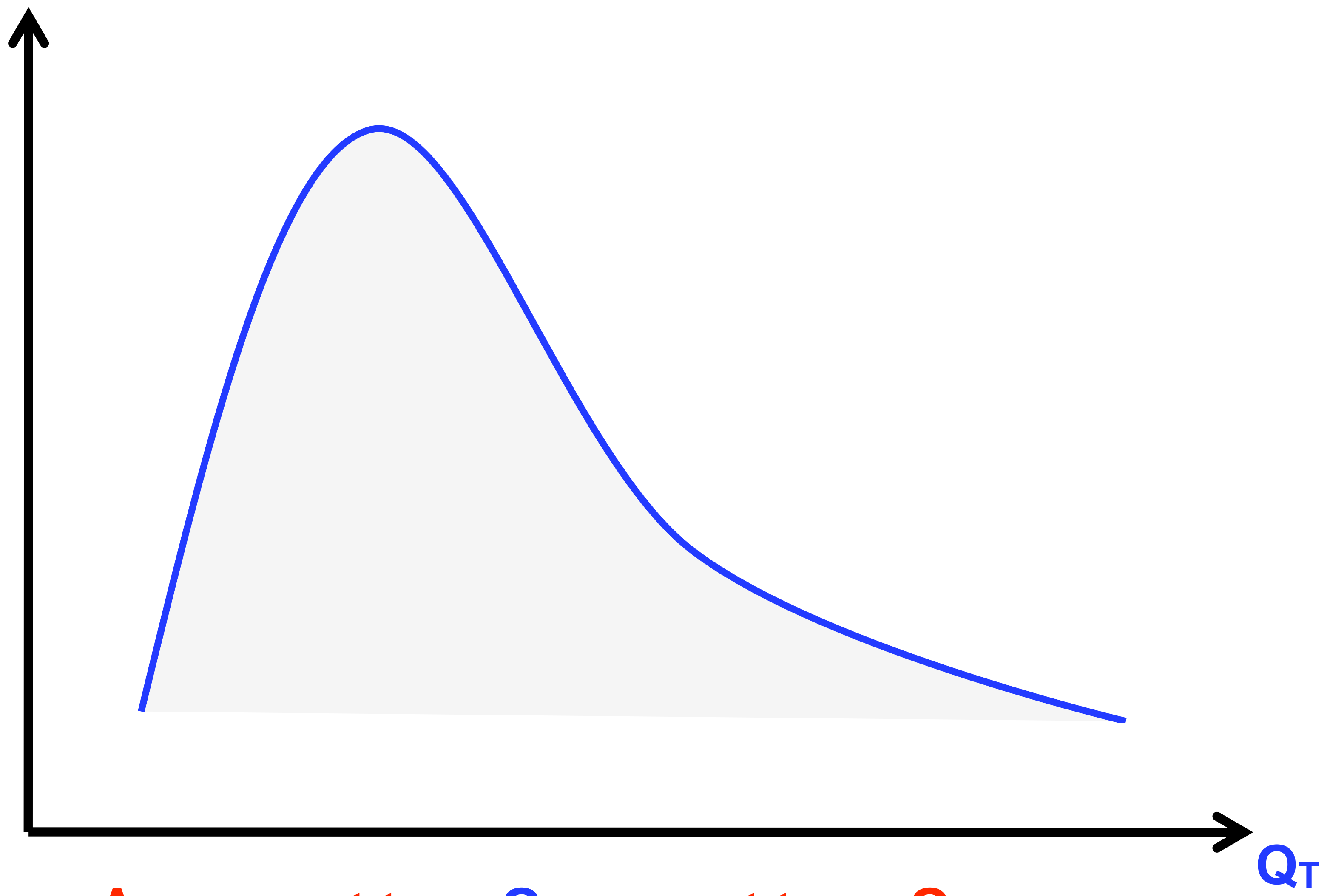
$$Q_1 \gg Q_2 \begin{cases} Q_1 & \text{necessary for pQCD factorization to have a chance} \\ Q_2 & \text{sensitive to parton's transverse momentum} \end{cases}$$

  - Collinear factorization approach: more relevant for single scale hard process: inclusive pion production at 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

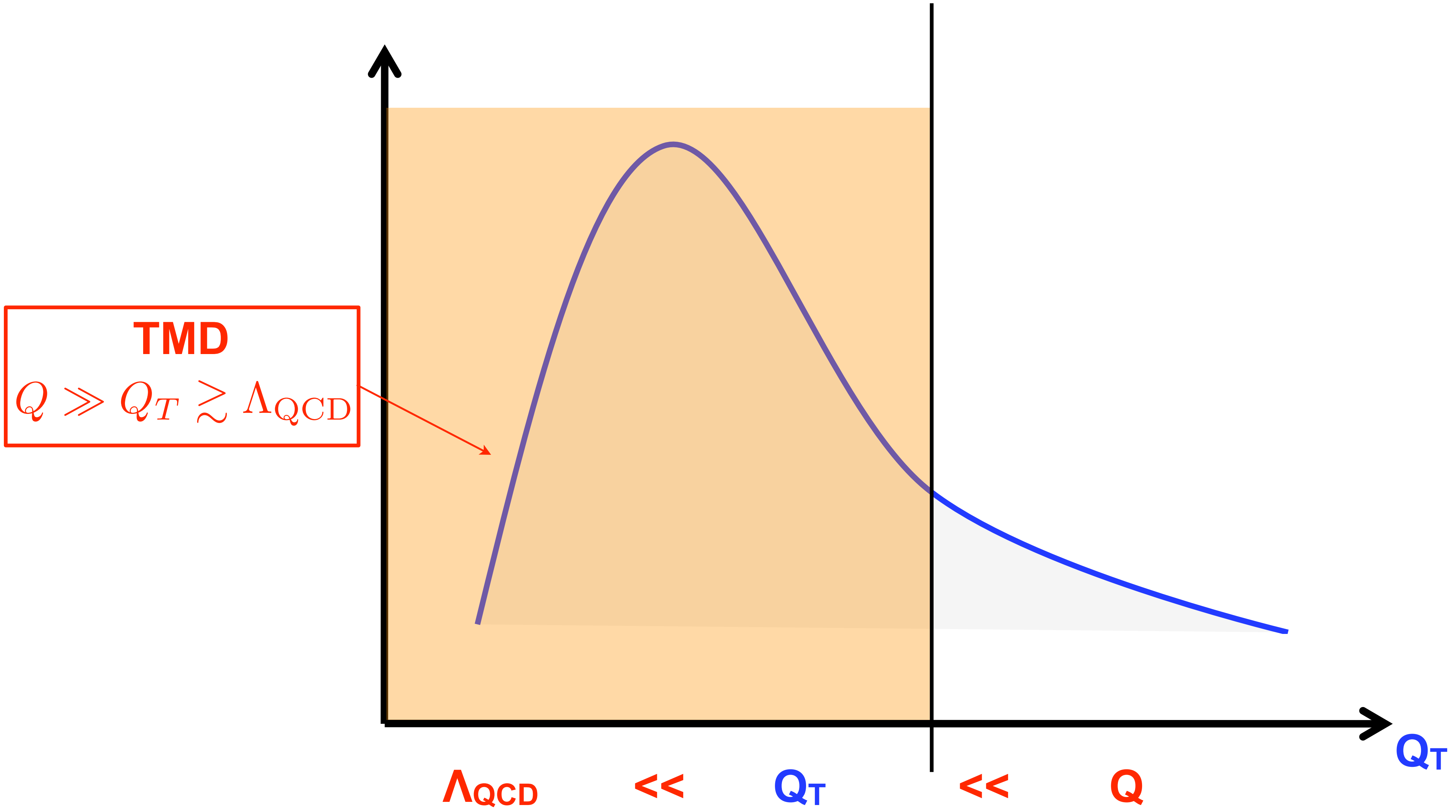
    Zhou, Yuan, 2009, Kang, Yuan, Zhou, 2010

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



Λ_{QCD} << Q_T << Q

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



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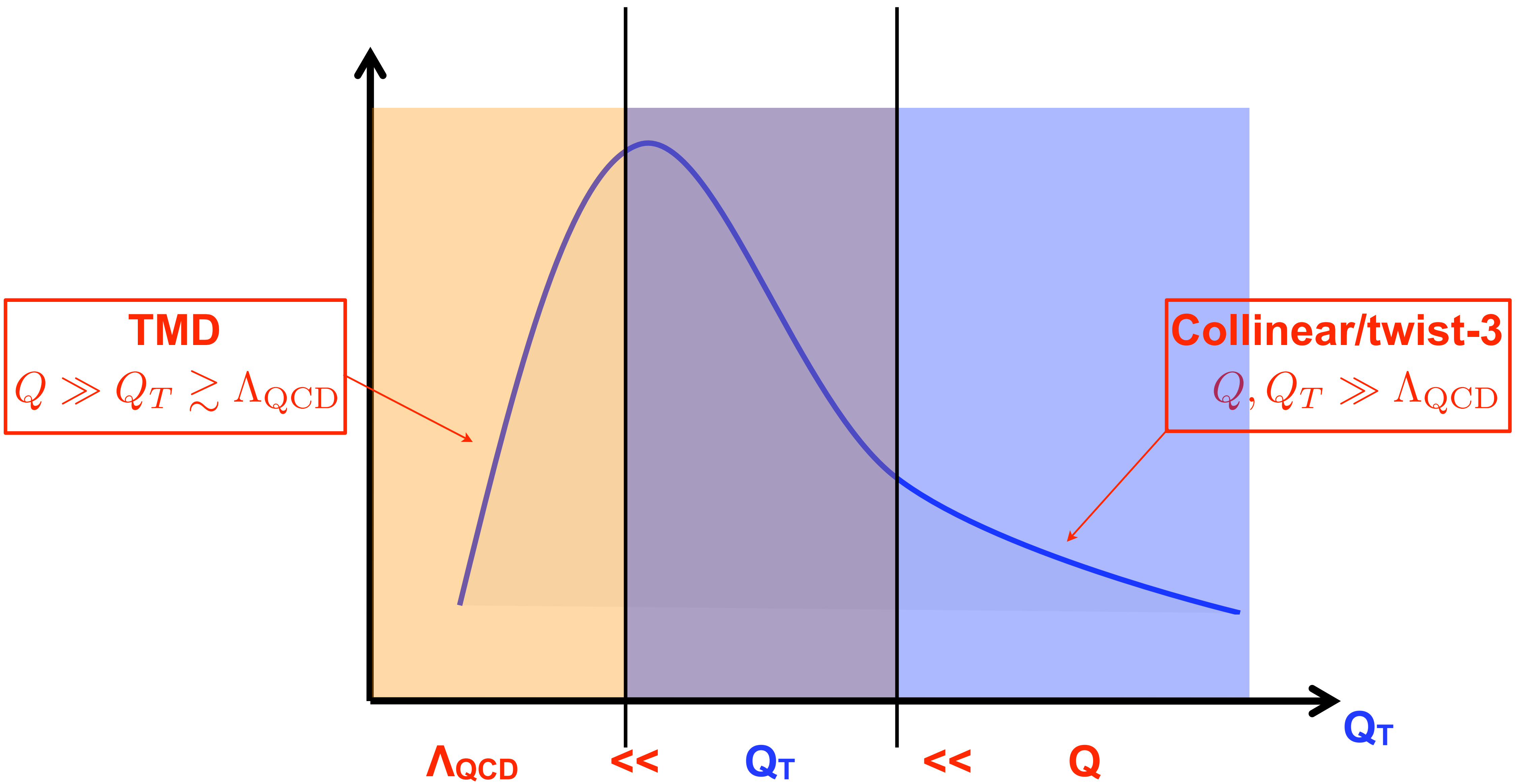

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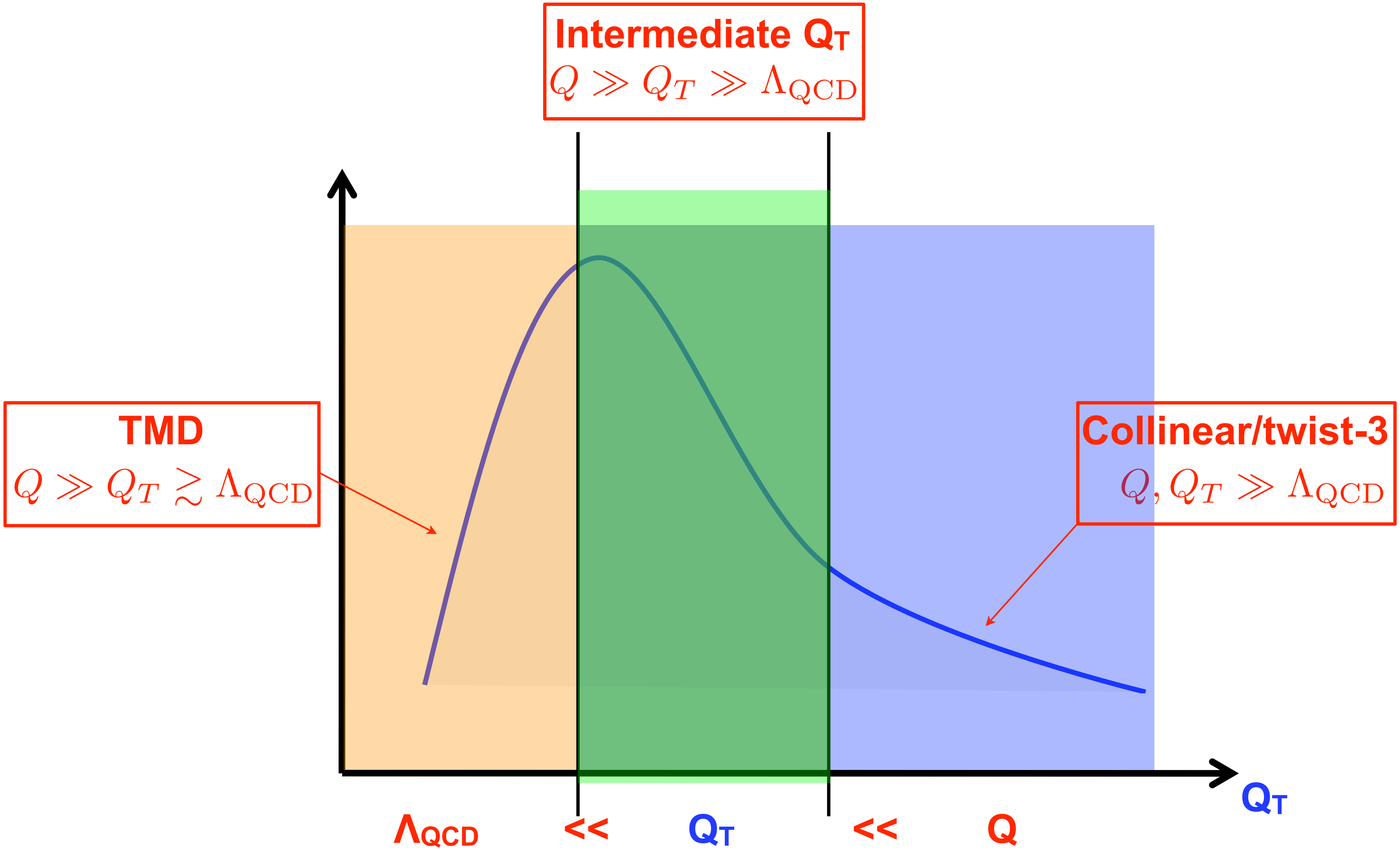


Major difference in these two approaches

- Collinear factorization approach:
  - All the twist-3 correlation functions (both in distribution and fragmentation side) are universal
  - Any process-dependent part is in the hard-part, which is calculable
- However, the TMD function in TMD approach MIGHT not be universal
  - Sivers function is NOT universal

    Collins 02, Boer, Mulders, Pijlman, 03, Collins, Metz, 04, Kang, Qiu, 09, …
  - Collins function is universal

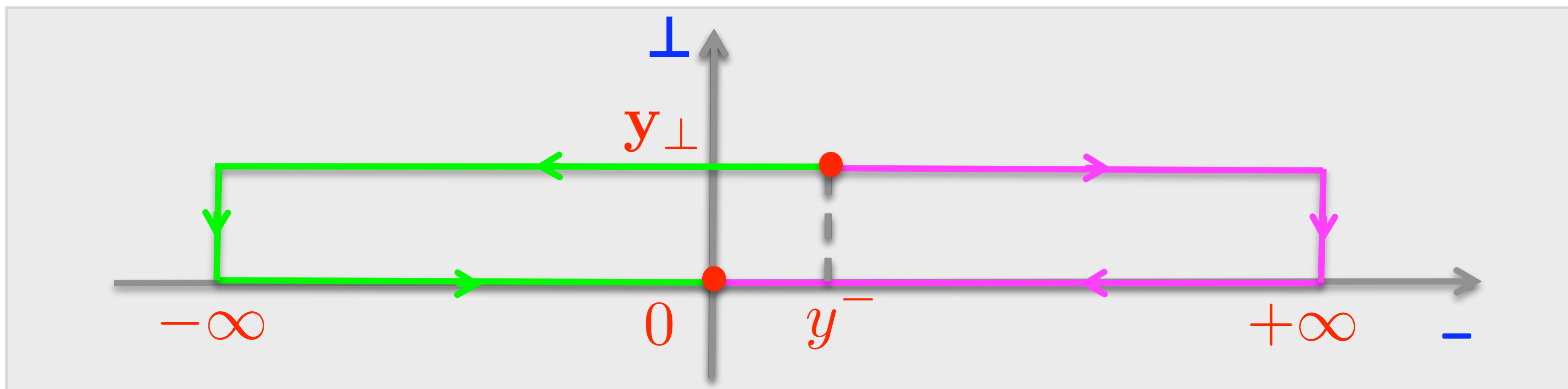
    Metz 02, Collins, Metz, 04, Yuan, 08, Gamberg, Mukerjee, Mulders, 08, Meissner, Metz, 08, Zhou, Yuan, 09, …

Non-universality of the Sivers function

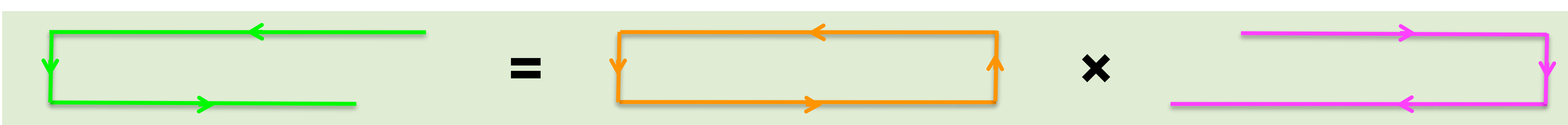
- Different gauge link for gauge-invariant TMD distribution in SIDIS and DY

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

  - 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



- For a fixed spin state:

$$f_{q/h^\uparrow}^{\text{SIDIS}}(x,\mathbf{k}_\perp,\vec{S}) \neq f_{q/h^\uparrow}^{\text{DY}}(x,\mathbf{k}_\perp,\vec{S})$$

Time-reversal modified universality of the Sivers function

- Relation between Sivers functions in SIDIS and DY
  - From P and T invariance:

$$f_{q/h^\uparrow}^{\rm SIDIS}(x, \mathbf{k}_\perp, \vec{S}) = f_{q/h^\uparrow}^{\rm DY}(x, \mathbf{k}_\perp, -\vec{S})$$

    - **Spin-averaged parton distribution function is universal**

$$f_{q/h}(x, k_\perp) = \frac{1}{2}\left[f_{q/h^\uparrow}(x, \mathbf{k}_\perp, \vec{S}) + f_{q/h^\uparrow}(x, \mathbf{k}_\perp, -\vec{S})\right]$$

  - From the definition of Sivers function:

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

  - One can derive:

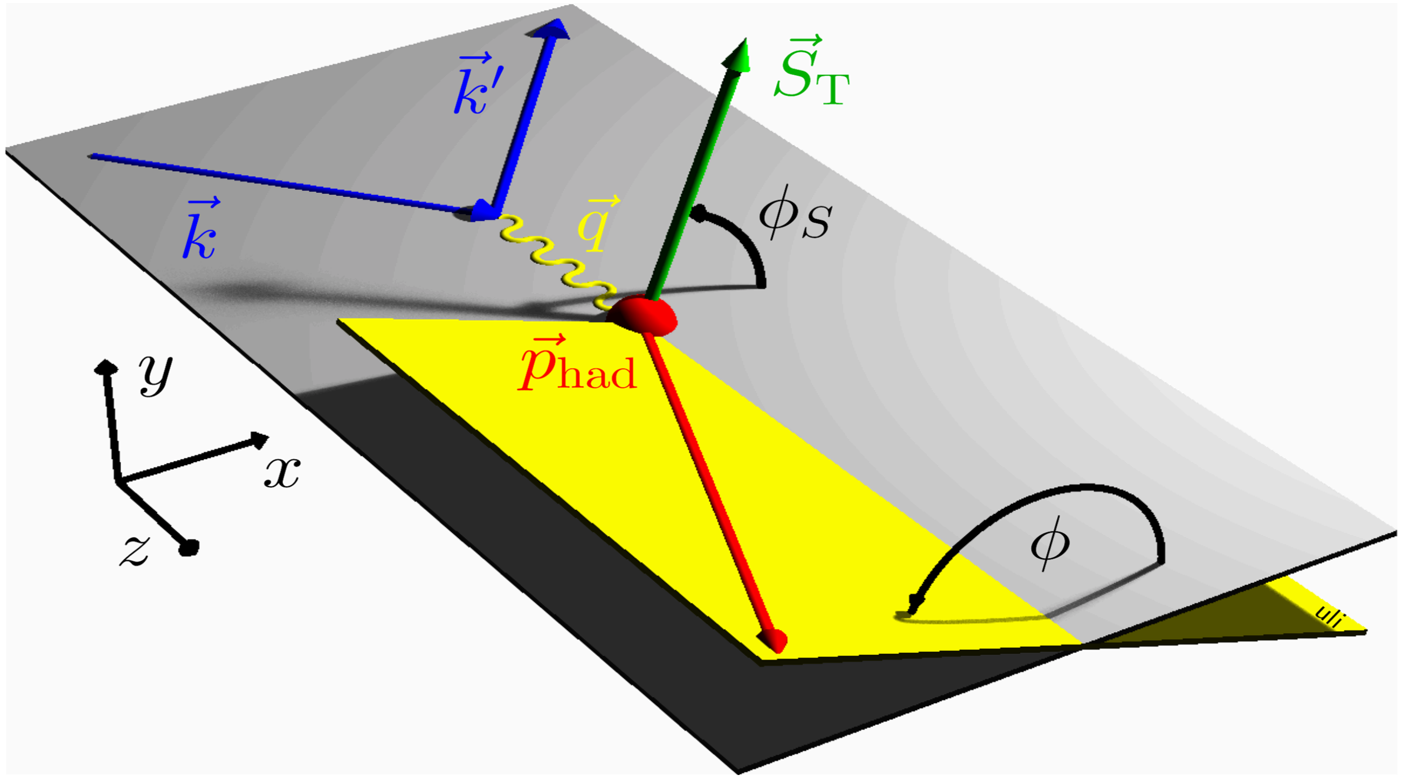
$$\Delta^N f_{q/h^\uparrow}^{\rm SIDIS}(x, k_\perp) = -\Delta^N f_{q/h^\uparrow}^{\rm DY}(x, k_\perp)$$

Most critical test for TMD approach to SSA

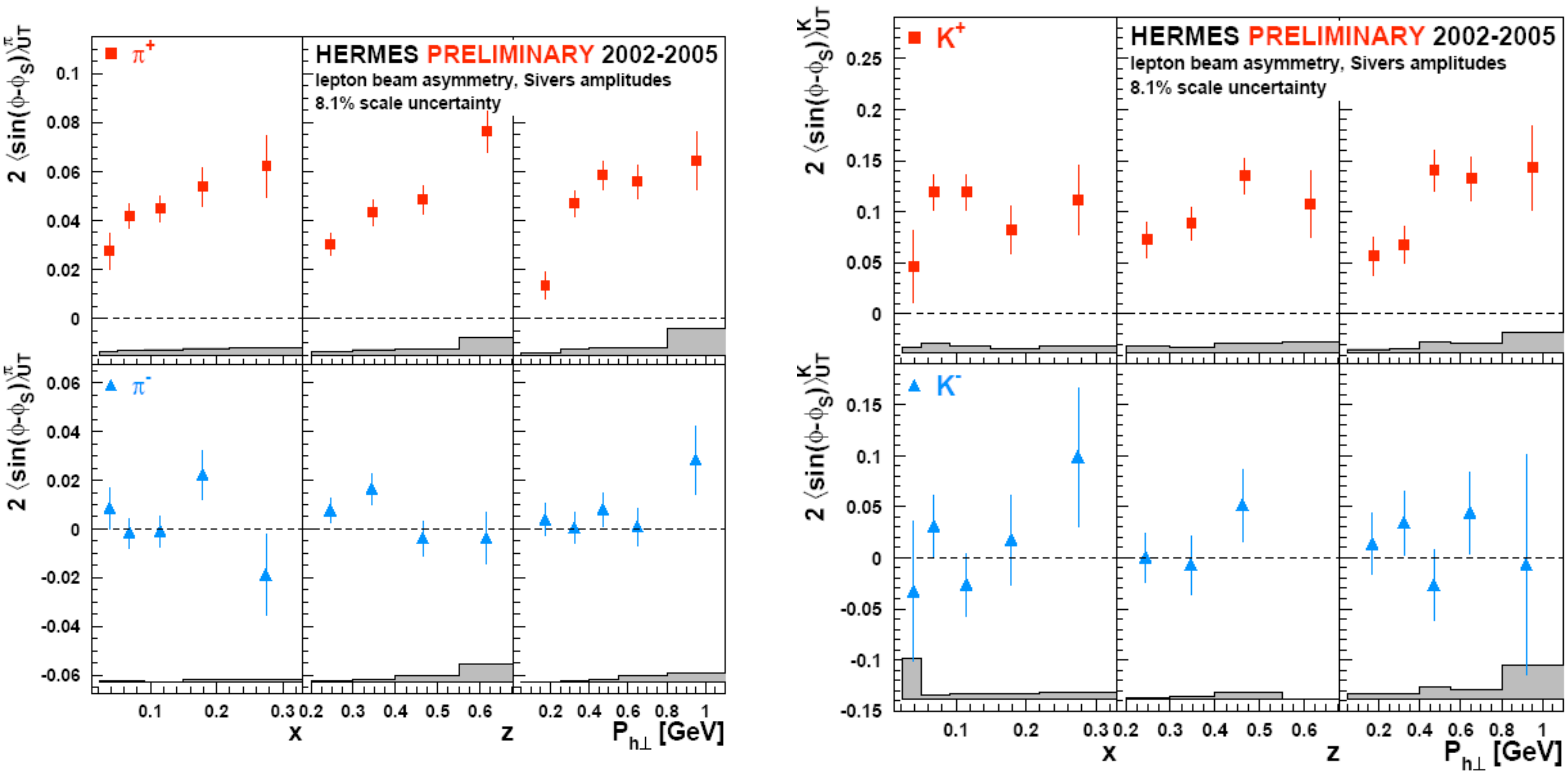
Current Sivers function from SIDIS

- Sivers and Collins can be separately extracted from SIDIS

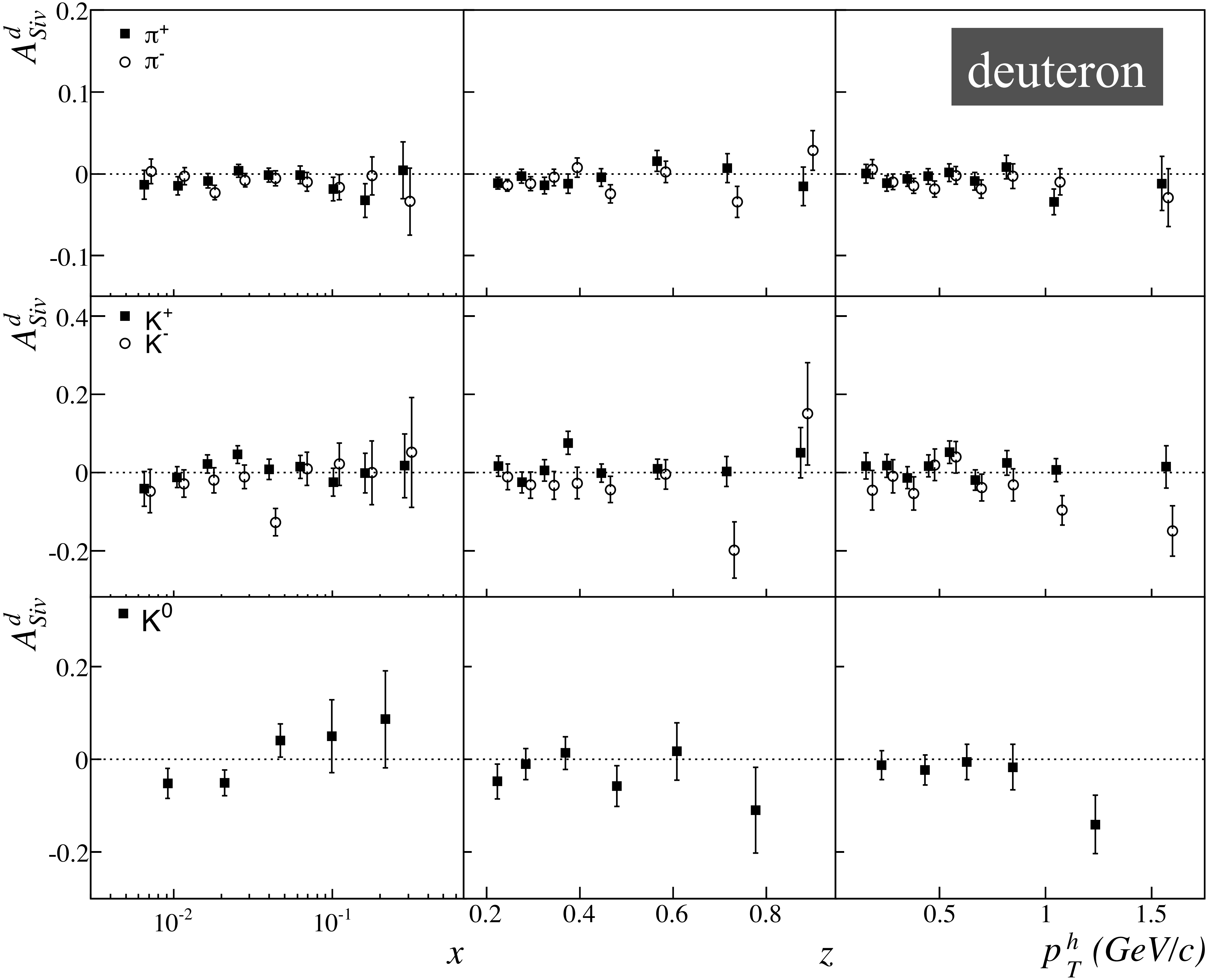
$$\Delta\sigma \propto A_{UT}^{Collins}\sin(\phi+\phi_S) + A_{UT}^{Sivers}\sin(\phi-\phi_S)$$



HERMES: Preliminary results on Proton (NOT zero)



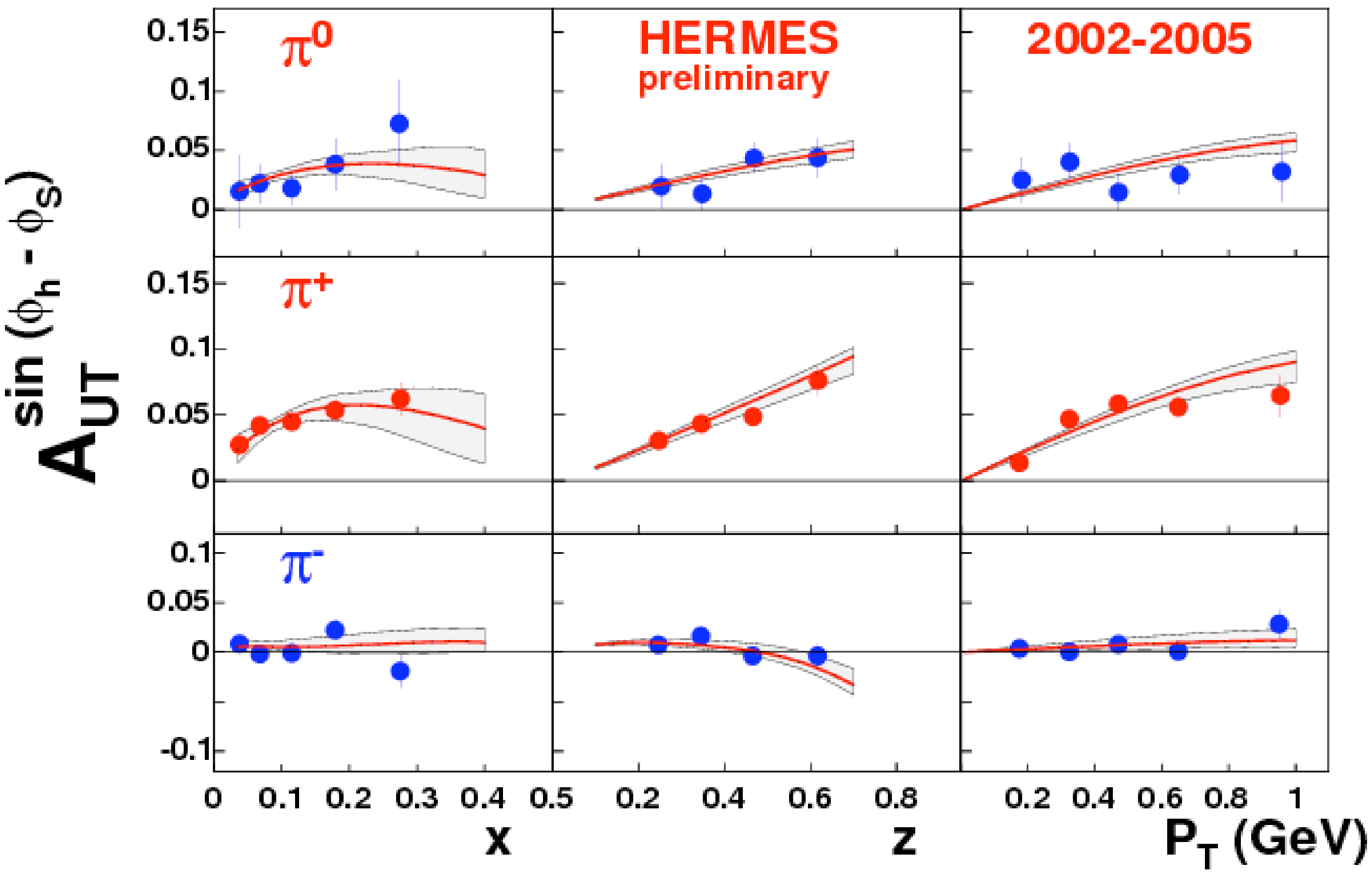
COMPASS: Deuteron target (small or zero)

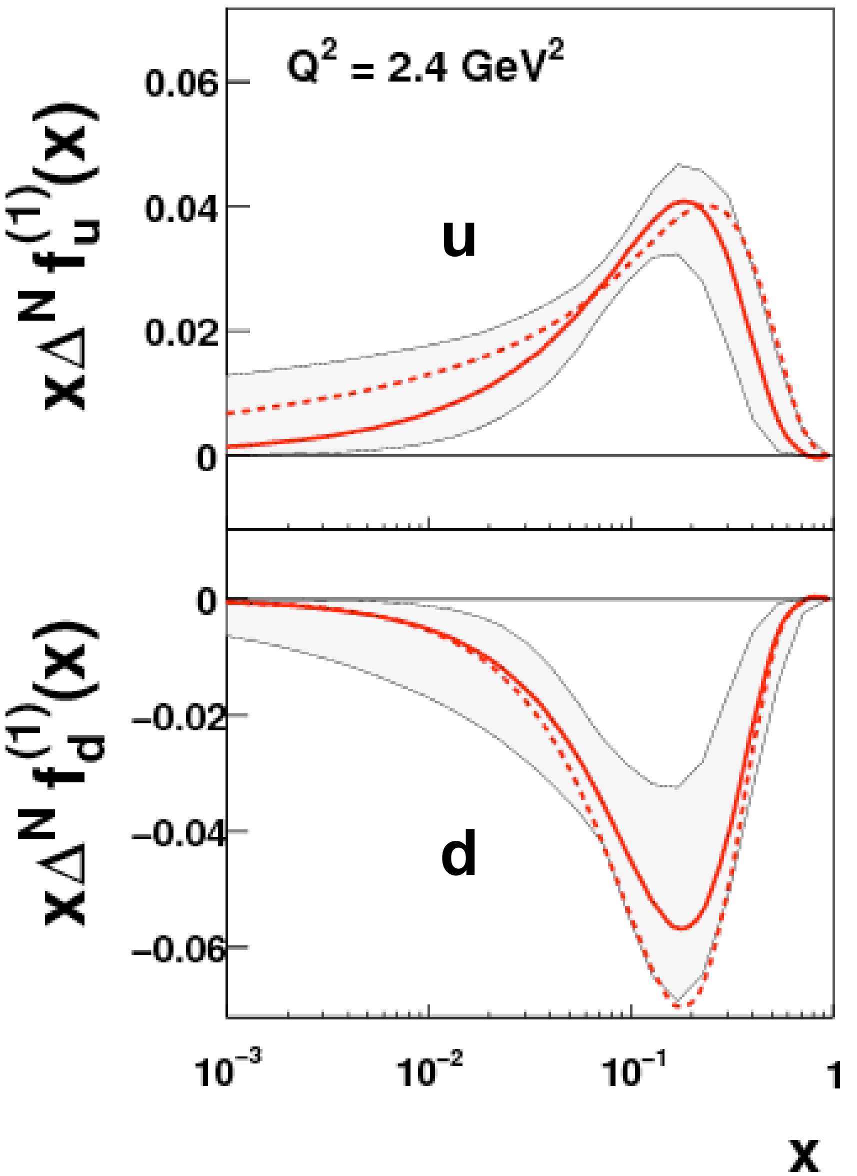


Sivers function from SIDIS: Current Global Analysis

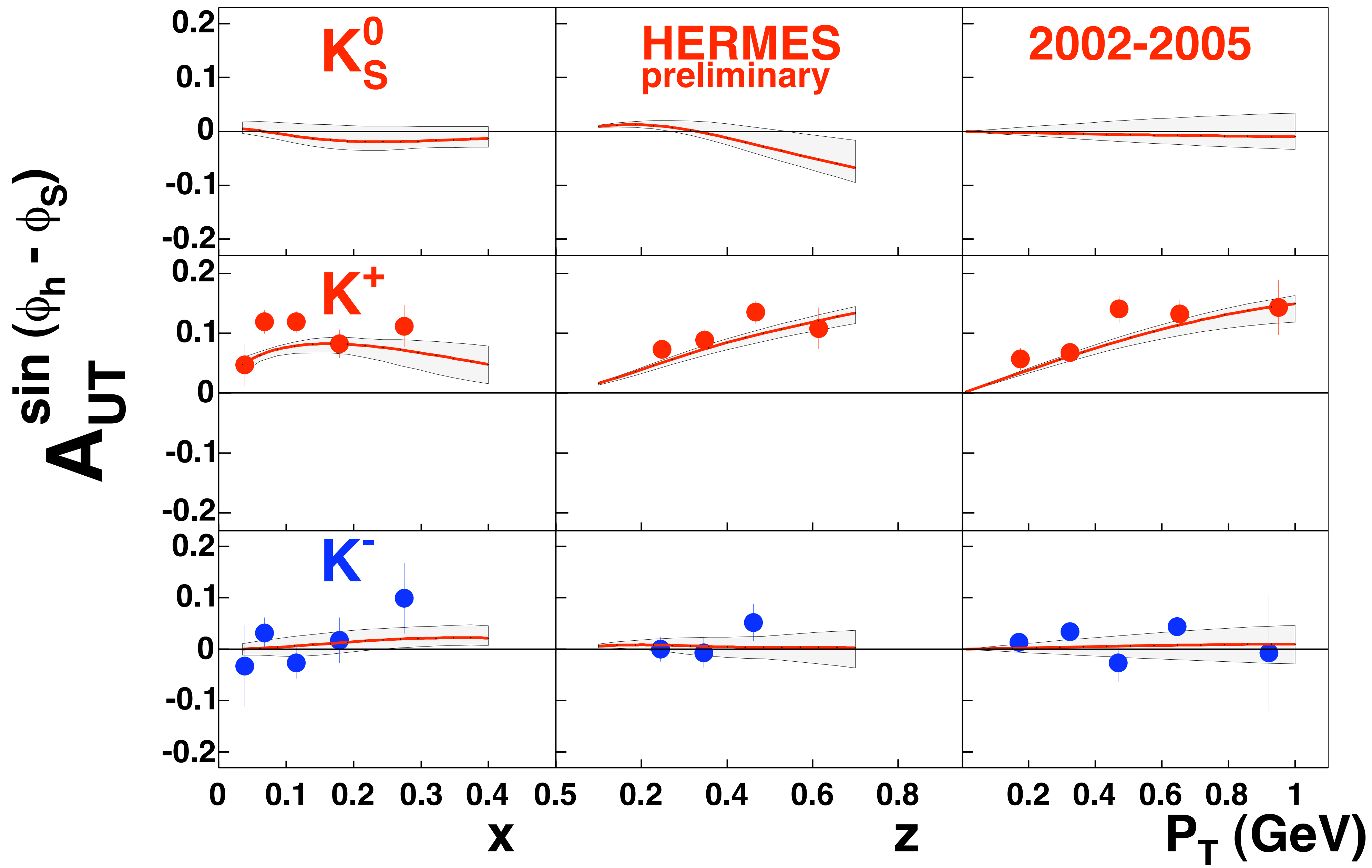
- Includes HERMES Proton data and COMPASS Deuteron data

Anselmino, et.al., 2009

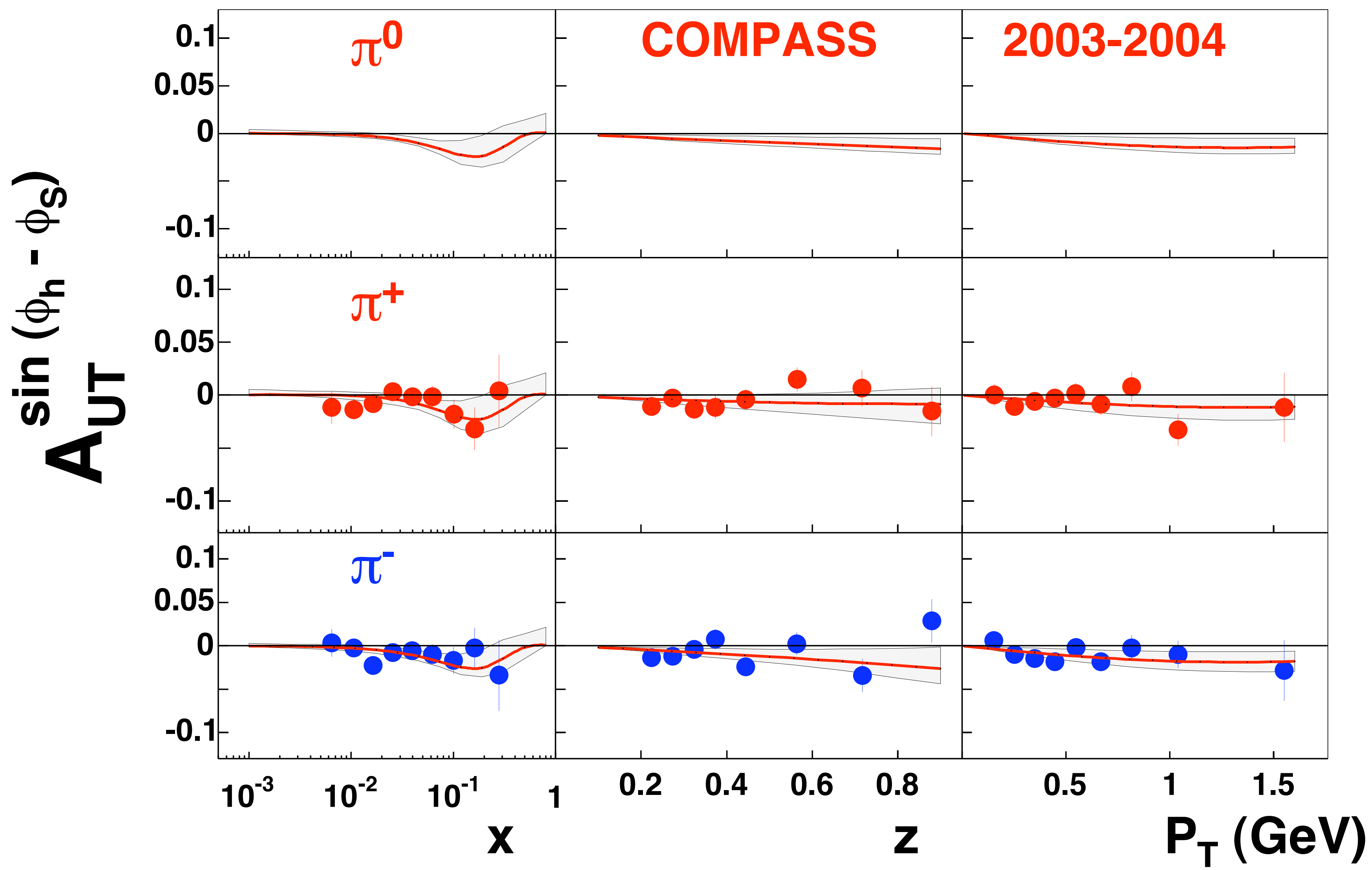




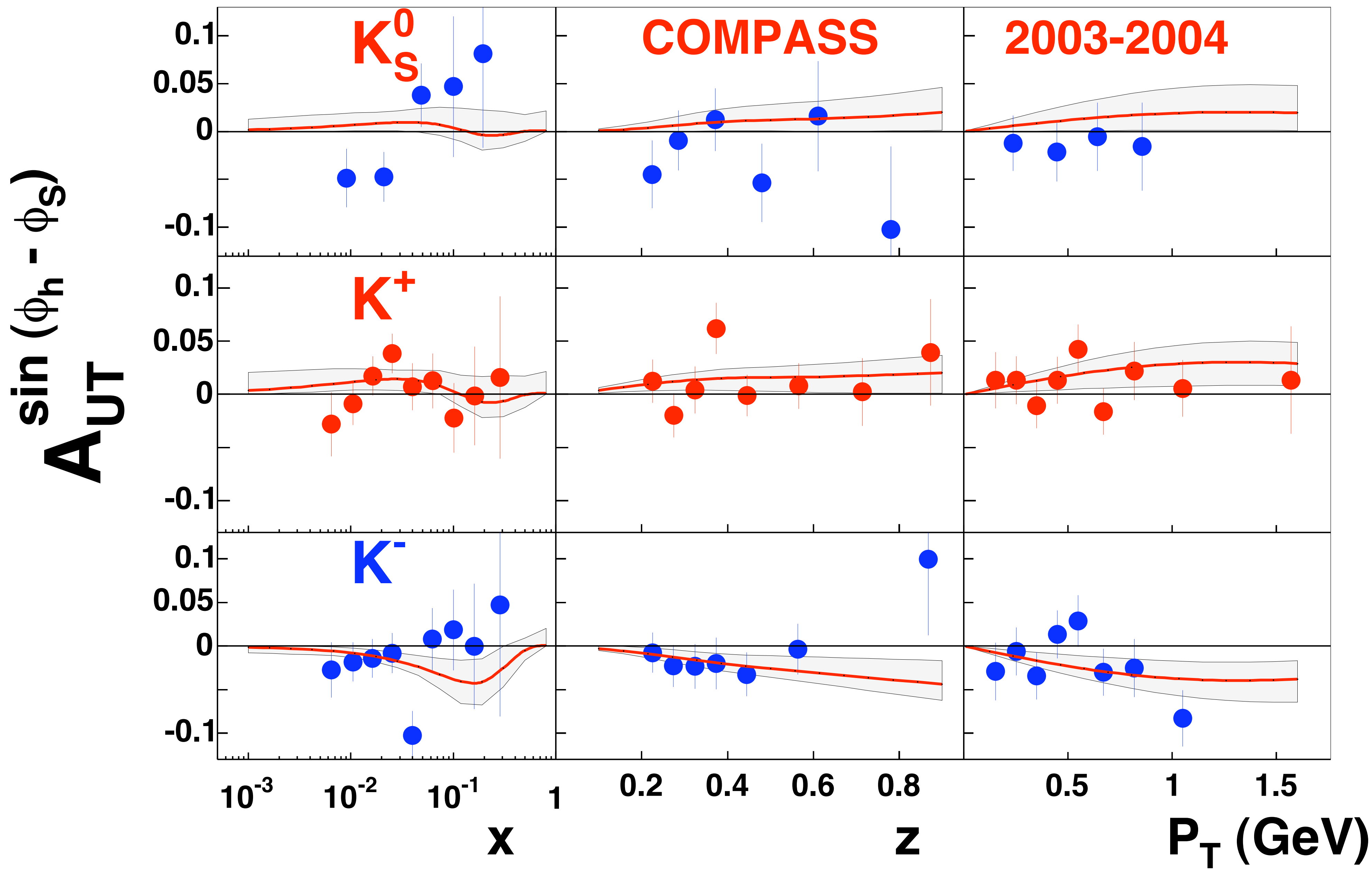
Comparison with HERMES Proton: Kaons



Comparison with COMPASS Deutron: Pions

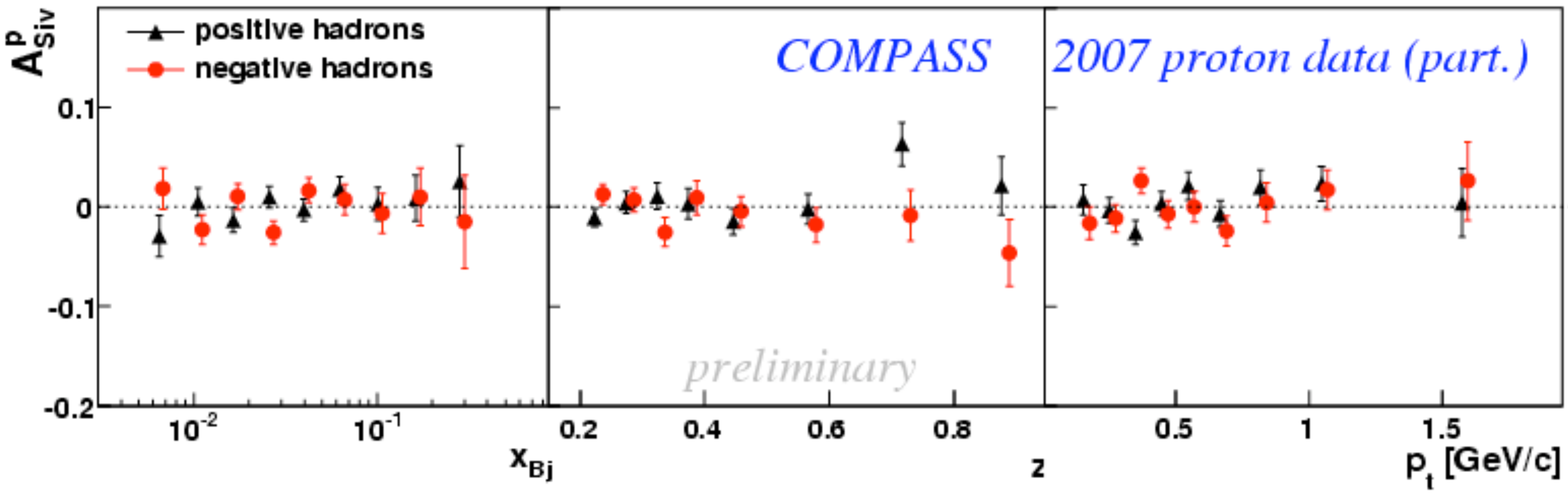


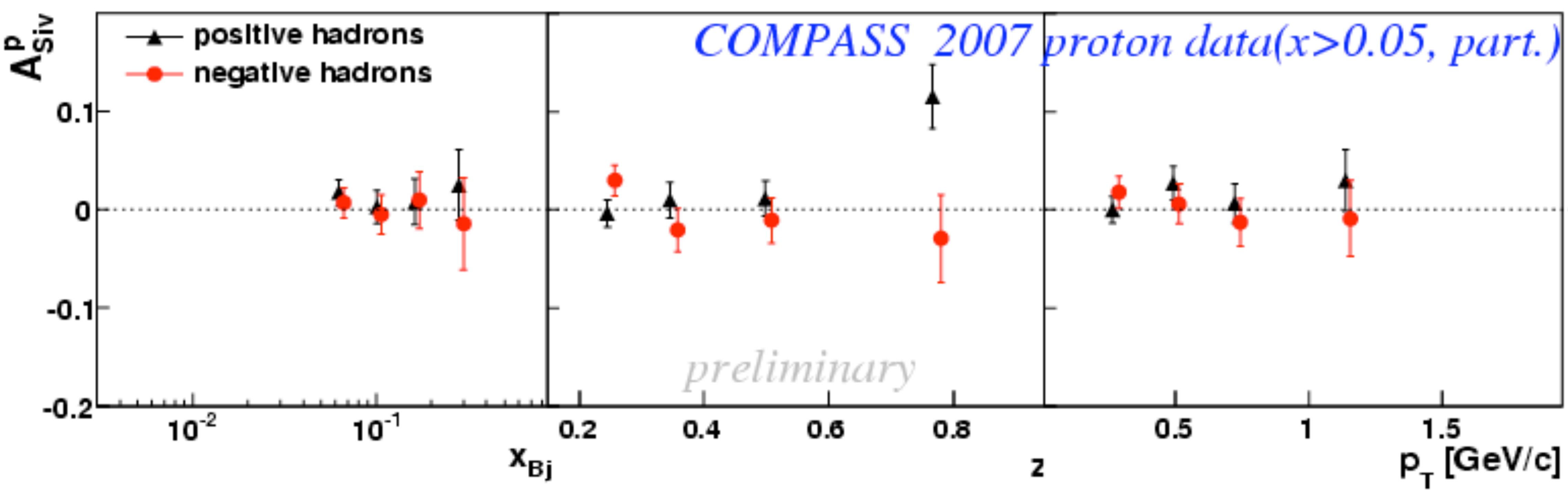
Comparison with COMPASS Deuteron: Kaons



What about COMPASS proton?

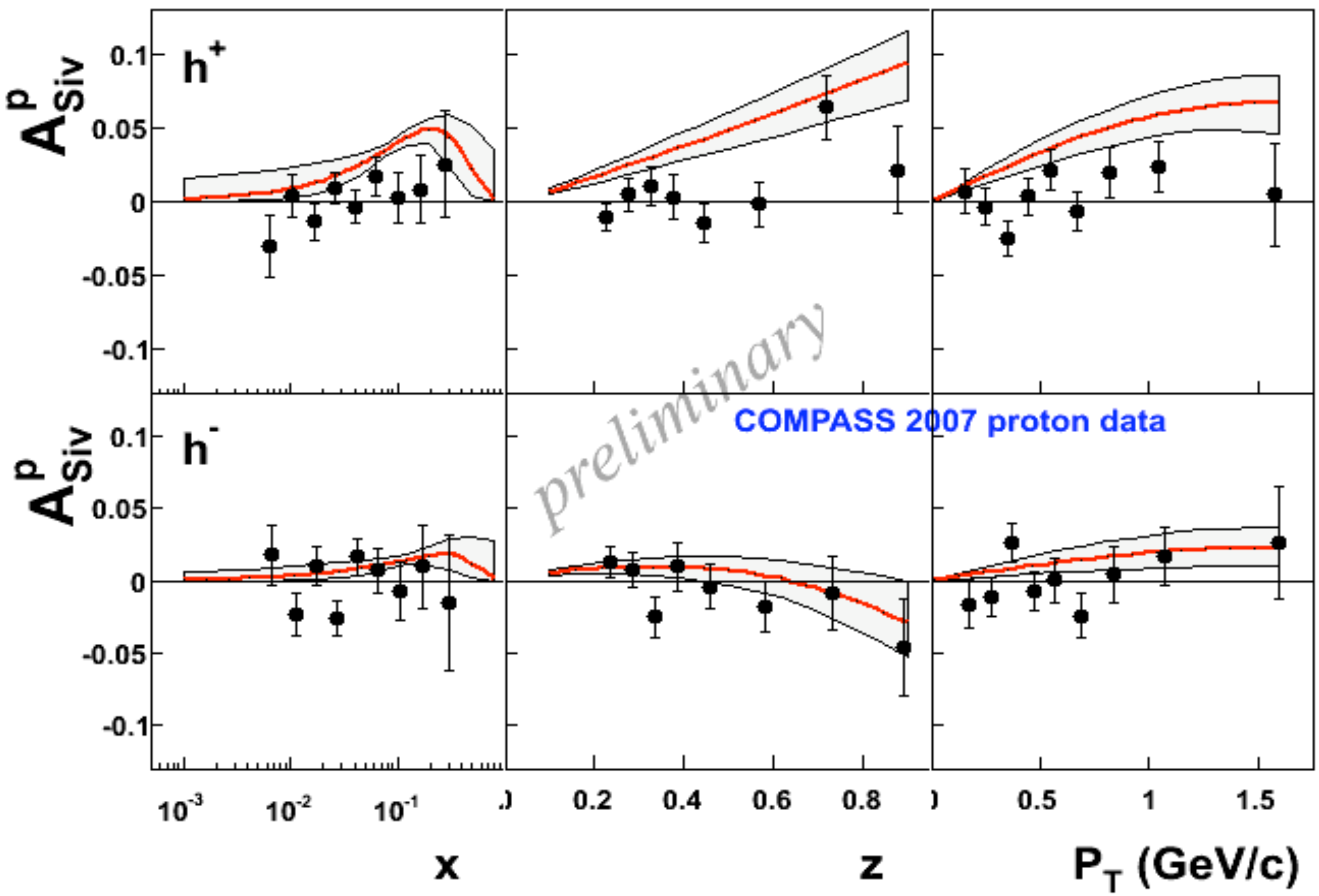
COMPASS: proton (small or zero)





COMPASS Proton compare with theory

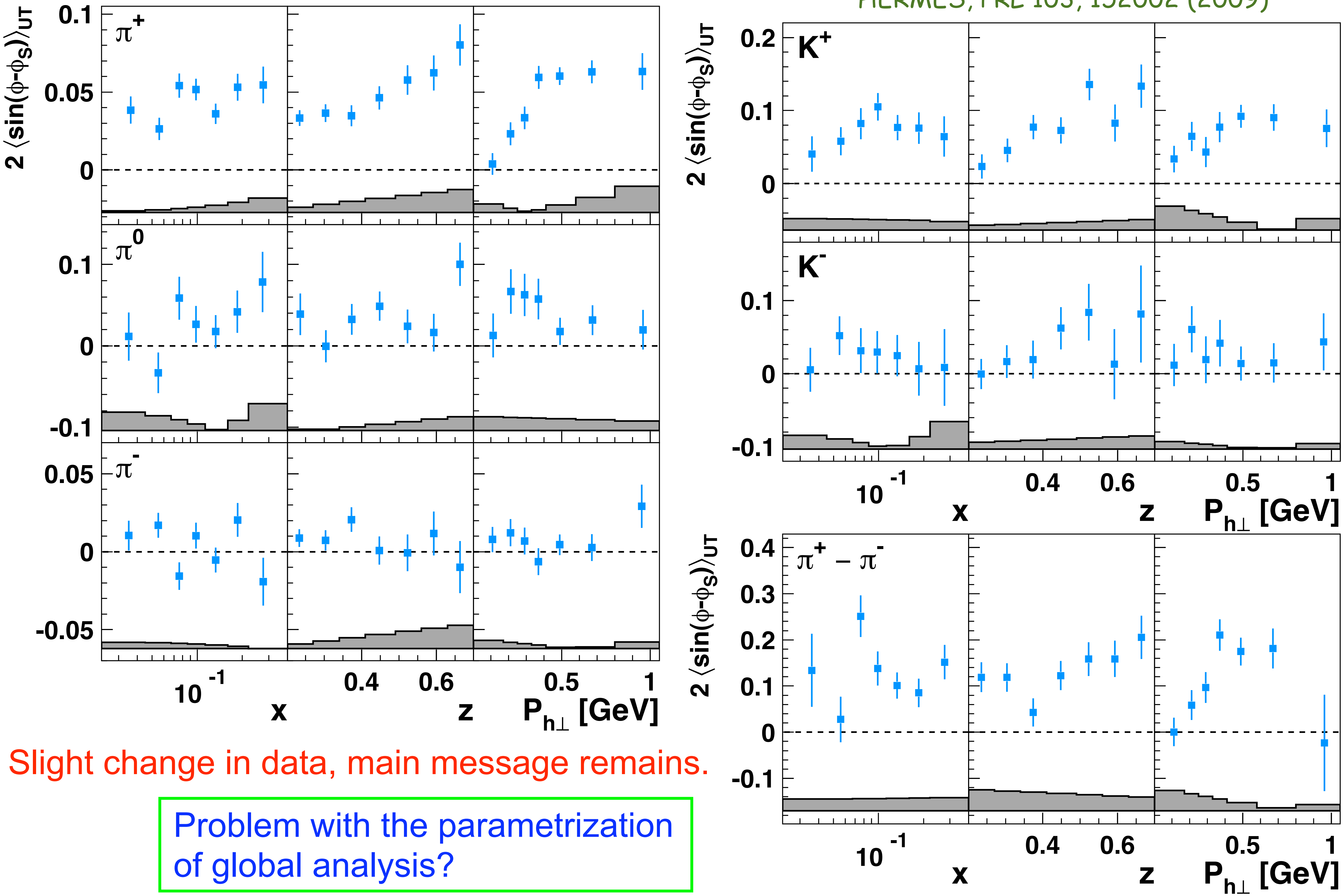
- The predictions do not seem consistent with COMPASS proton data



Preliminary HERMES data wrong?

Final published HERMES Proton: (NOT zero)

HERMES, PRL 103, 152002 (2009)



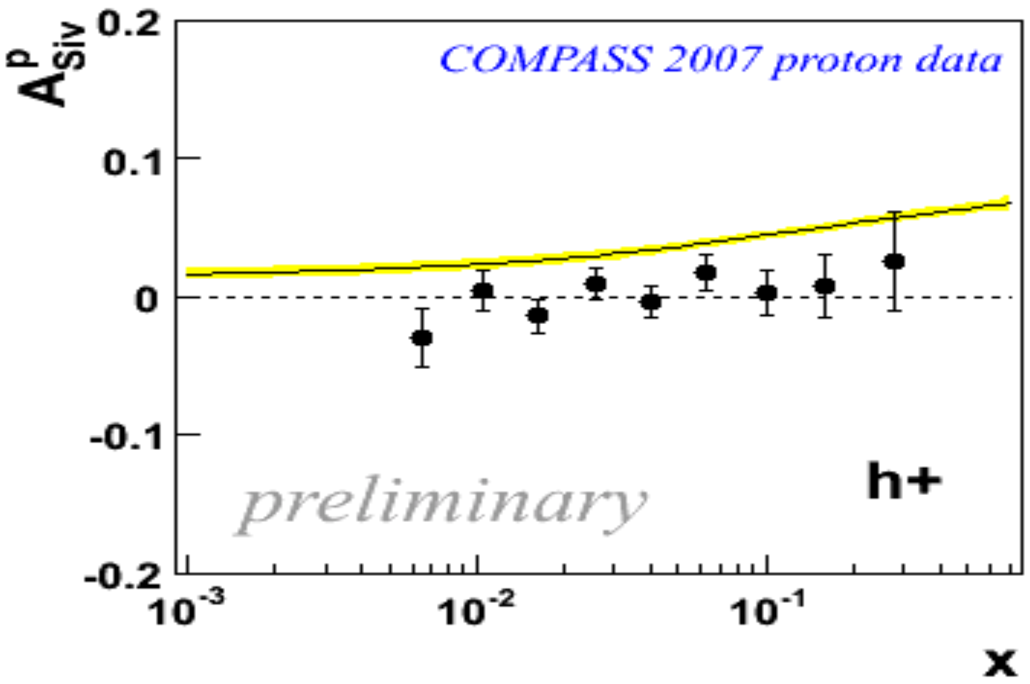
Slight change in data, main message remains.

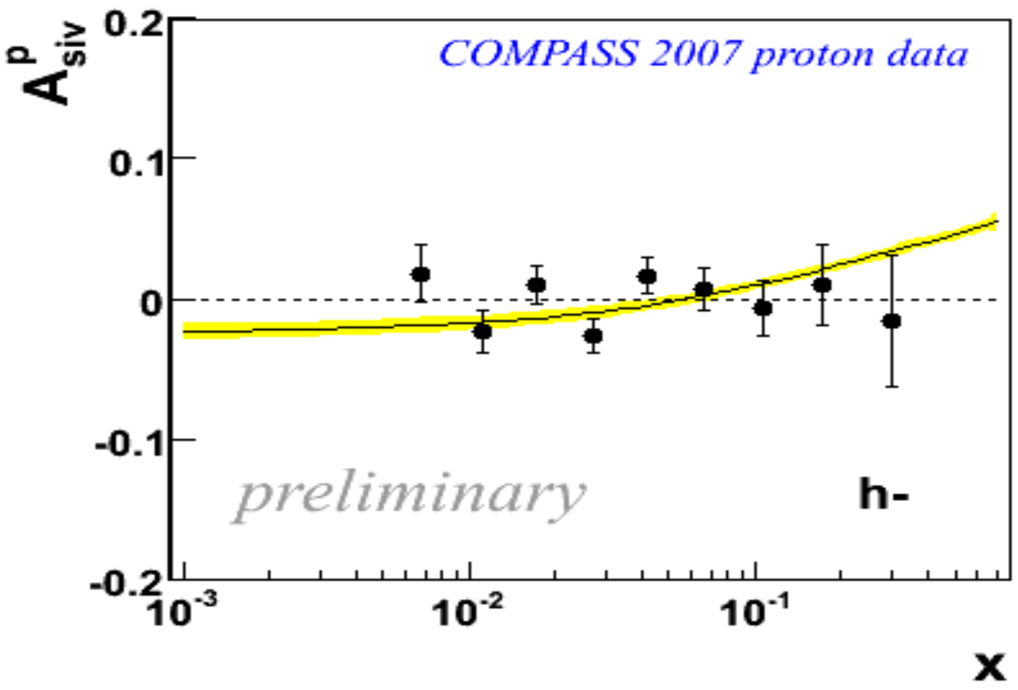
Problem with the parametrization of global analysis?

A slightly different parametrizations for Sivers

- Different parametrization doesn't help

Arnold, Efremov, Goeke, Schlegel, Schweitzer, arXiv: 0805.2137

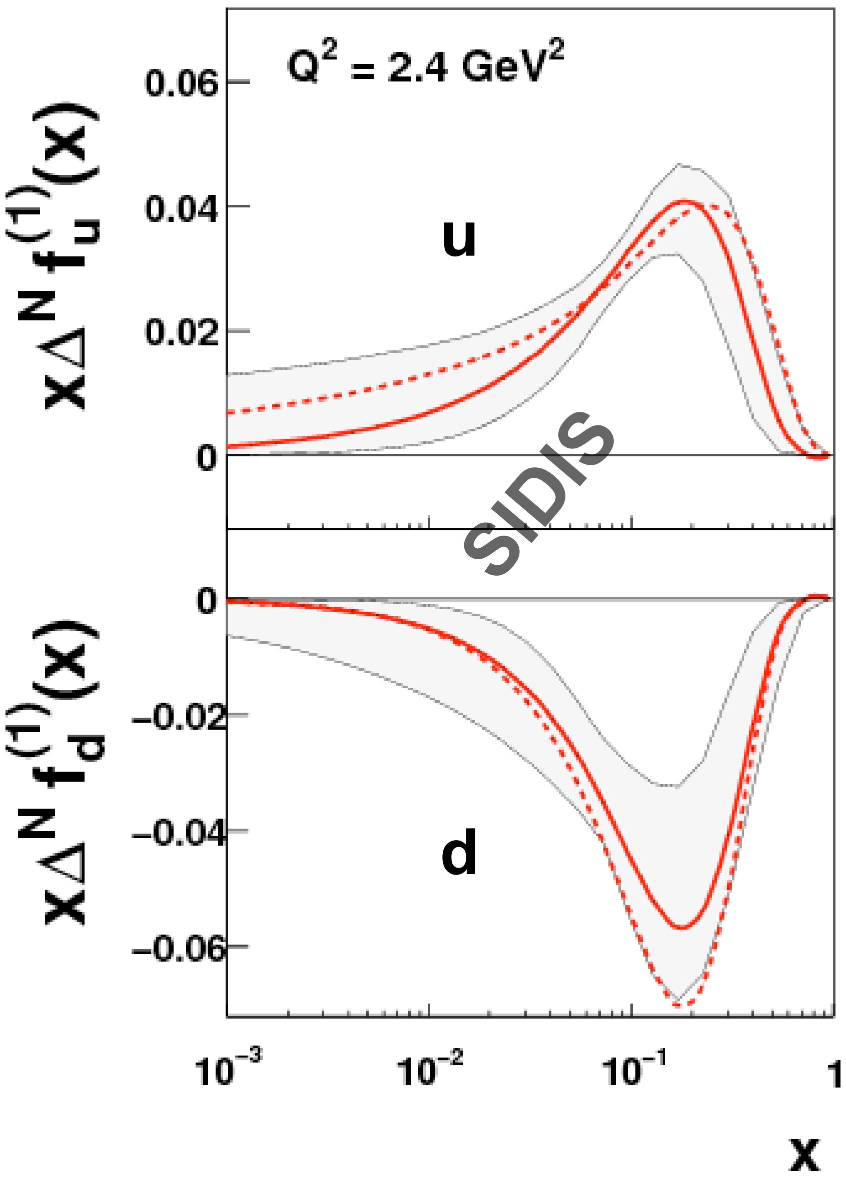




Assume HERMES is correct

- Since theory doesn't prevent the existence of the Siver functions:

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



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

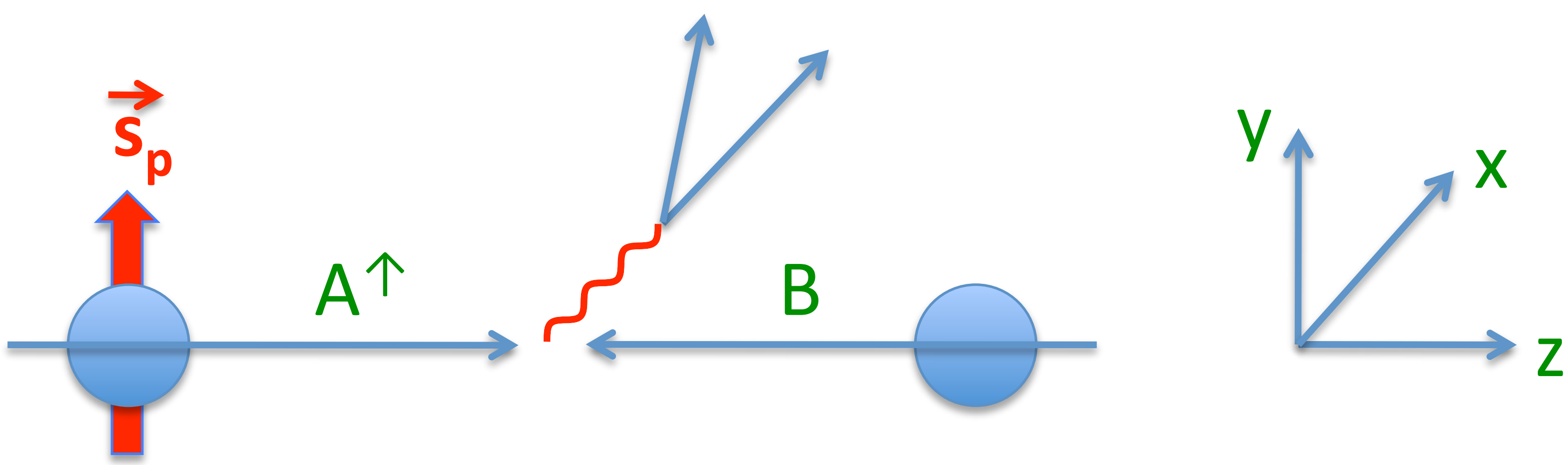
Sivers effect in Drell-Yan process

- Formula in TMD approach: weighted sum of u and d-Sivers

$$A_N = \frac{\sum_q e_q^2 \int \Delta^N f_{q/A^\uparrow}(x_1, \mathbf{k}_{\perp 1}) f_{\bar{q}/B}(x_2, k_{\perp 2})}{2\sum_q e_q^2 \int f_{q/A}(x_1, k_{\perp 1}) f_{\bar{q}/B}(x_2, k_{\perp 2})} \propto \frac{4}{9}\Delta^N u + \frac{1}{9}\Delta^N d$$

➡ $A_N < 0$

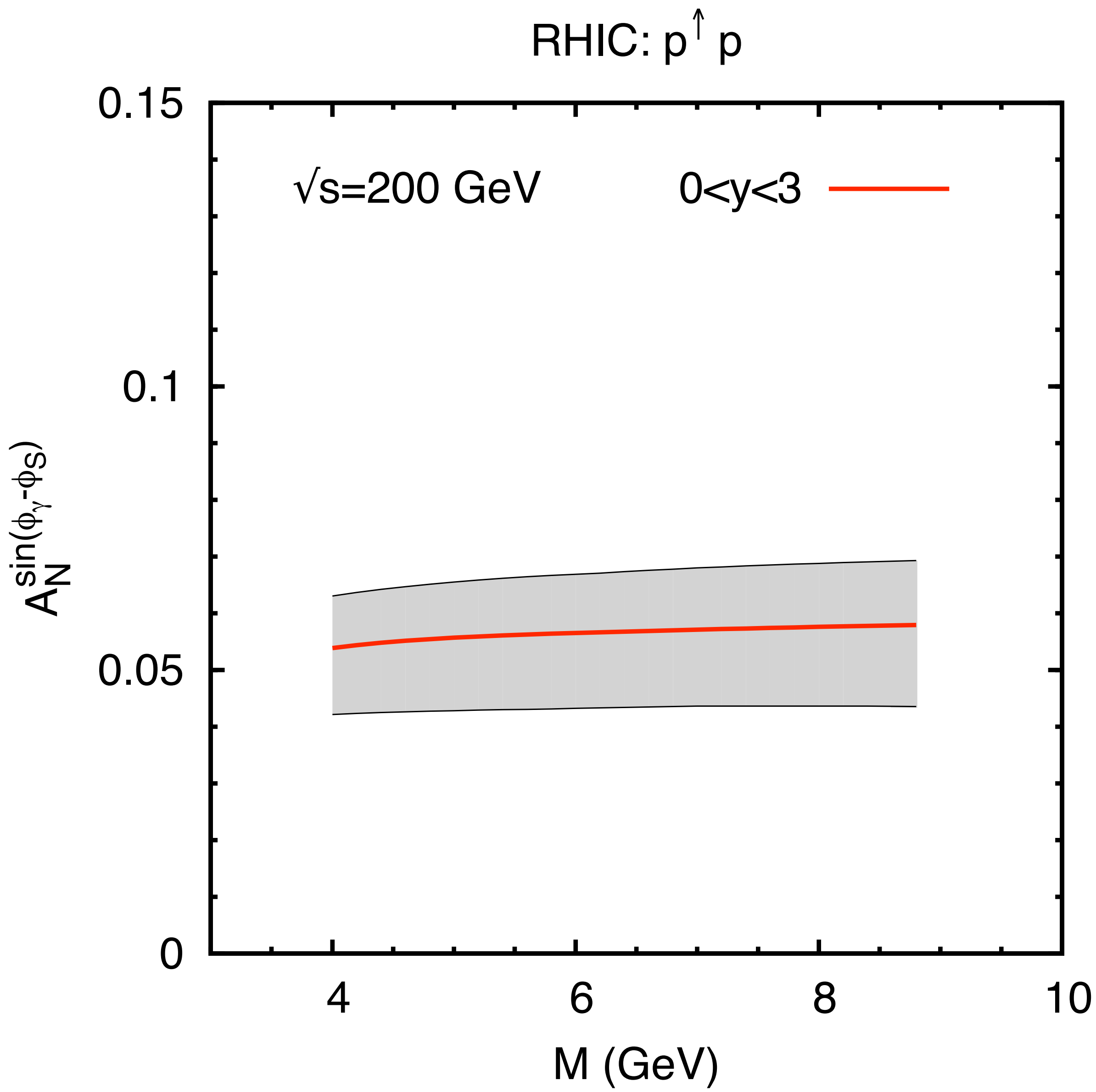
- Careful about the frame: $A^\uparrow + B \to [\gamma^* \to \ell^+\ell^-] + X$
  - In A-B CM frame: $A^\uparrow$ along z-direction, B is opposite to it. "up" (↑) polarization direction is along y-axis

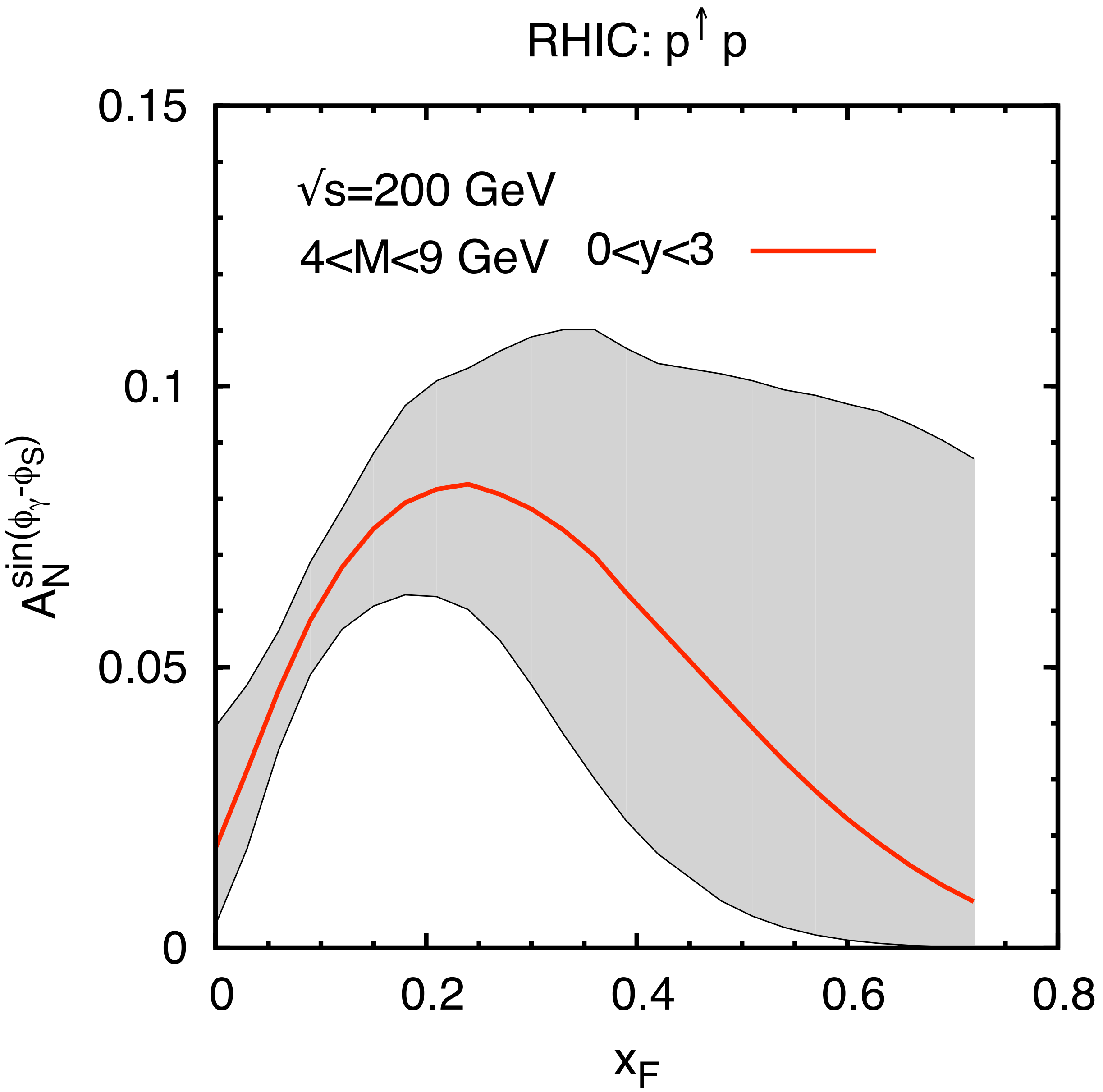


➡ $A_N^{\sin(\phi_\gamma - \phi_s)} = -A_N > 0$

Predictions from Anselmino's parametrizations: weighted

- Uncertainty band: 1-σ error of the fitted parameters in Sivers function

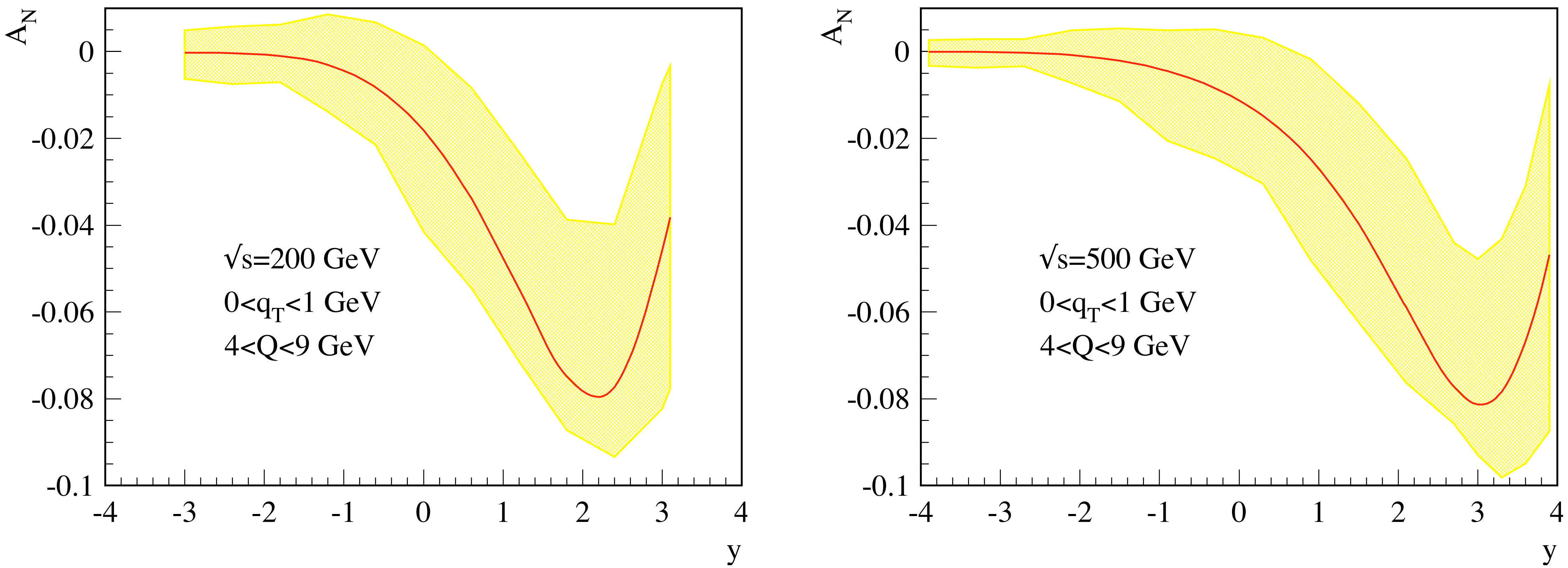




Anselmino,et.al, PRD79: 054010 (2009)

Rapidity dependence at 200 and 500 GeV: unweighted

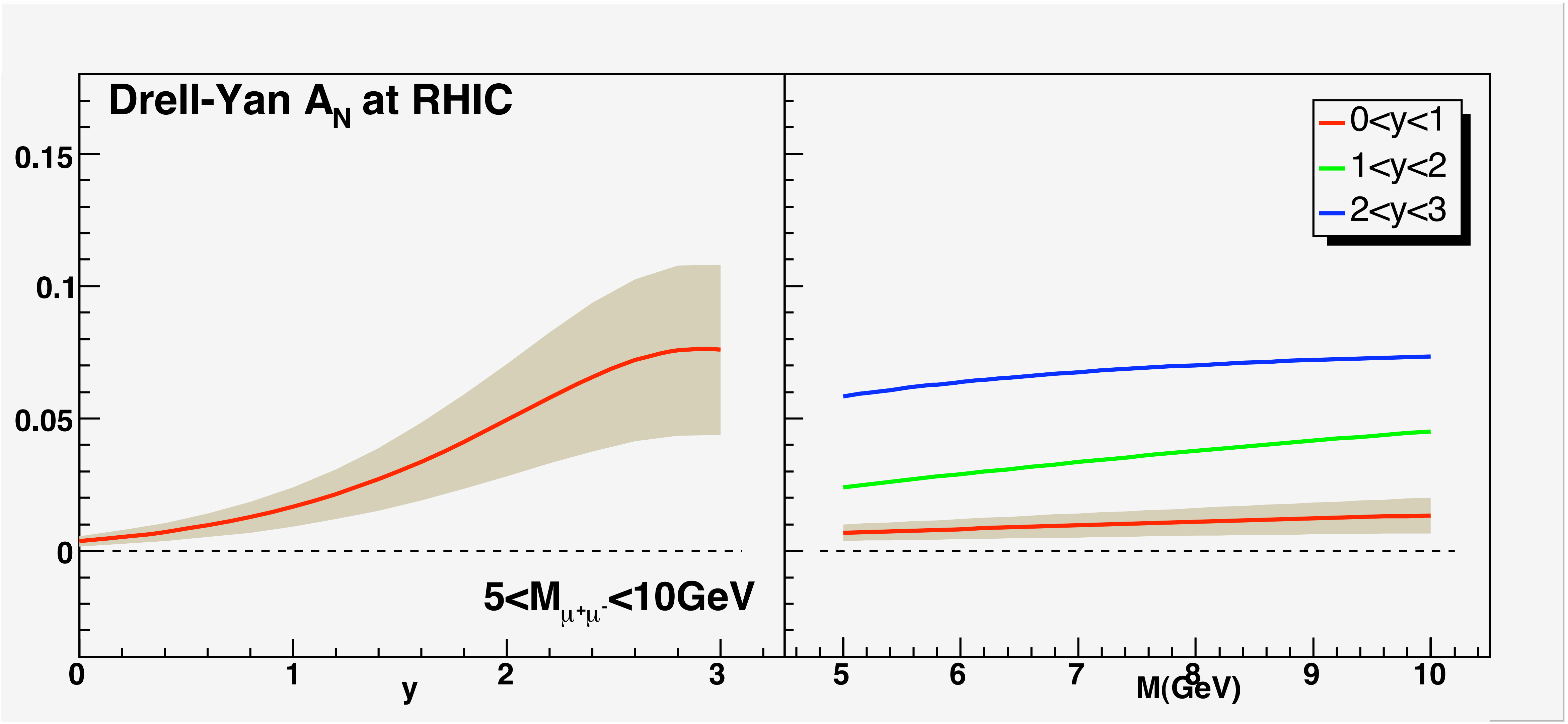
A_N ~ 2-3% in mid-rapidity y=0



Kang, Qiu, PRD81: 054020 (2010)

Different parametrization of Sivers functions - I

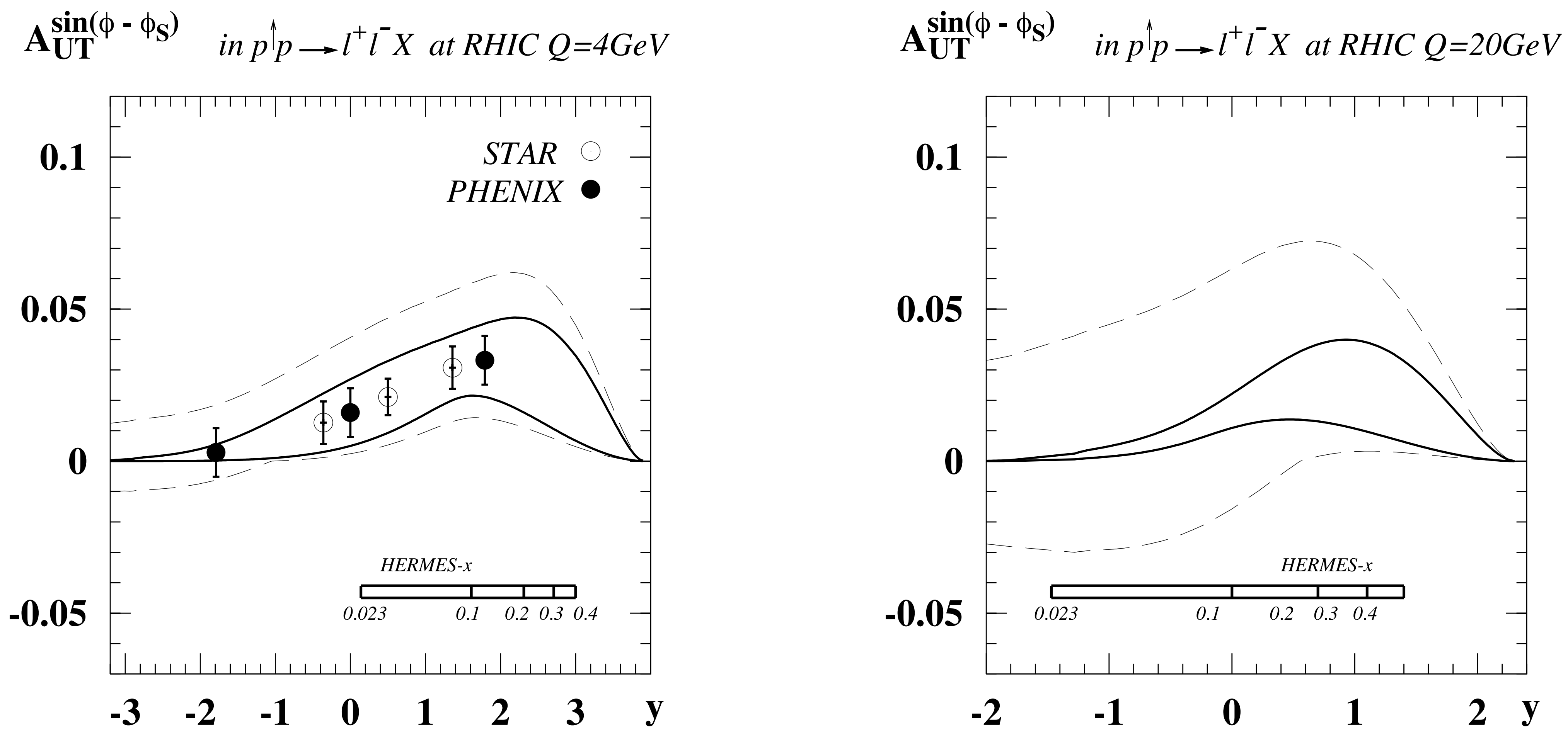
- Prediction from Yuan and Vogelsang: sign convention different



Vogelsang, Yuan, PRD72: 054028 (2005)

Different parametrization of Sivers functions - II

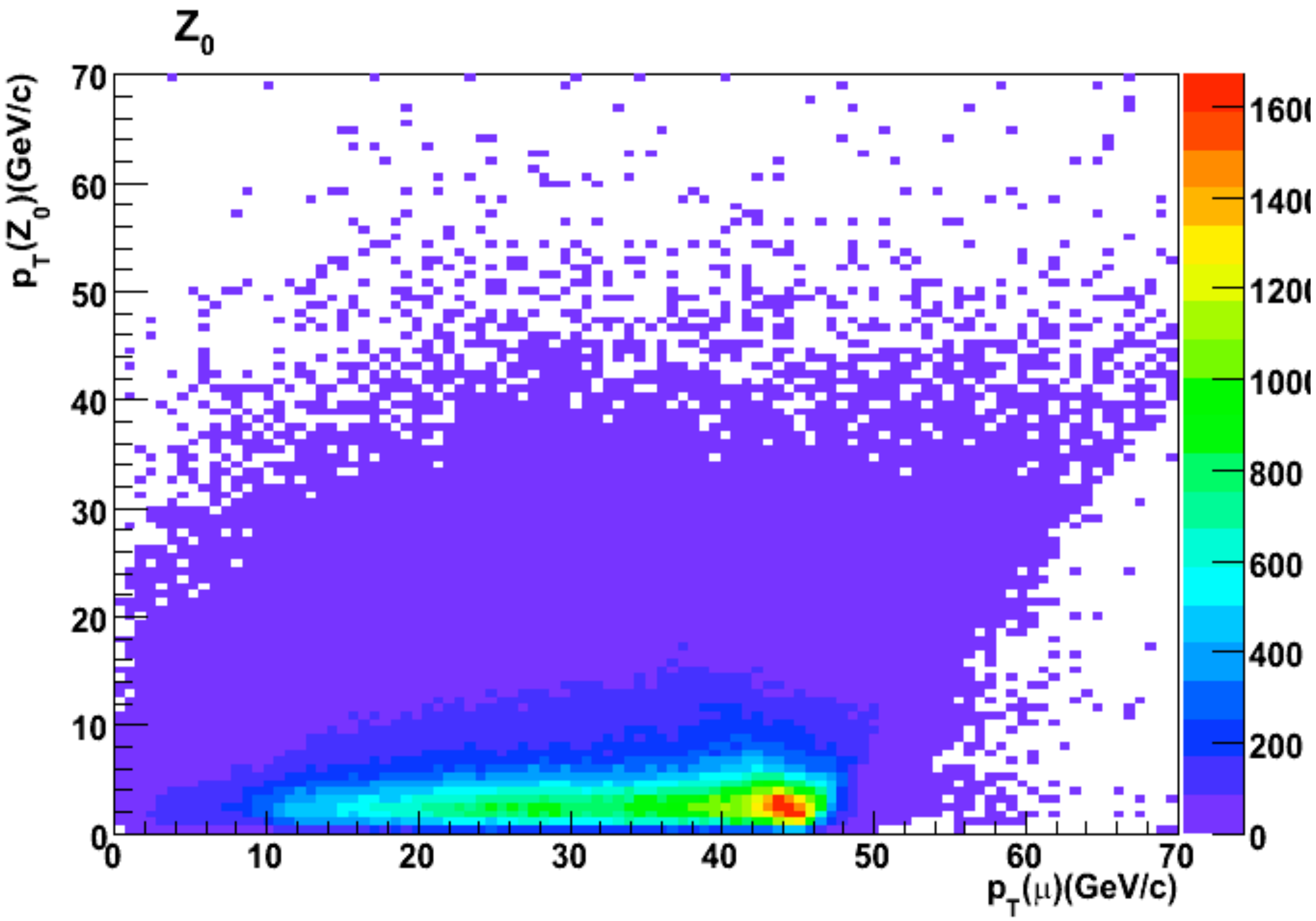
Collins, Efremov, Goeke, Menzel, et.al 2006

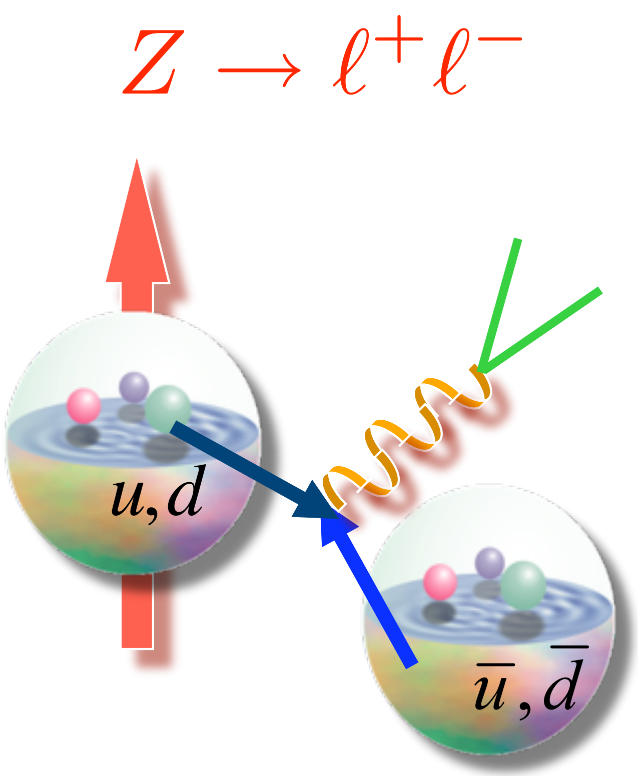


- Error band: 1-σ uncertainty of the fit of Sivers function
- Size is consistent with different parameterization

Outlook: Z boson

- RHIC can reconstruct Z boson





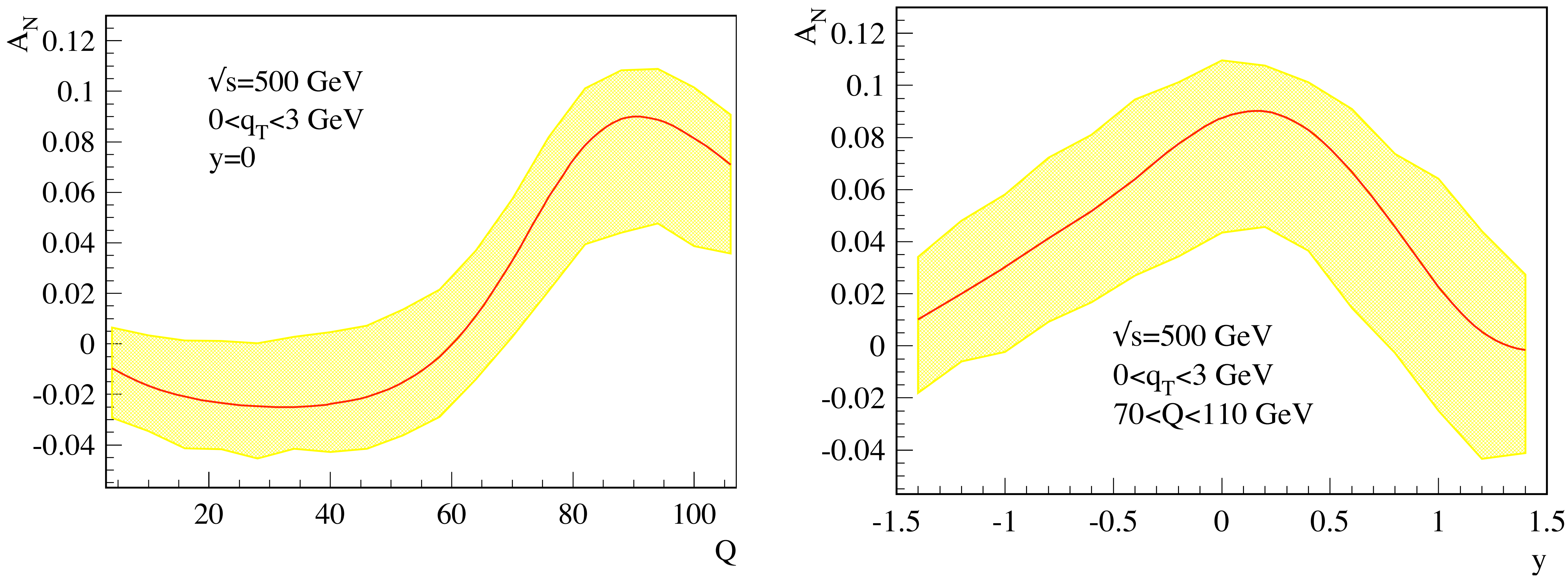
Courtesy of Kempel, Lajoie (PHENIX)

- Events down by an order of magnitude compared to W boson:
  - ~1000

SSA of Z boson at RHIC: test relative sign of u and d

- Why Z boson: change from virtual photon to Z boson, the weight of the u and d-Sivers function changes, the sign of A_N changes

Kang, Qiu, PRD81: 054020 (2010)



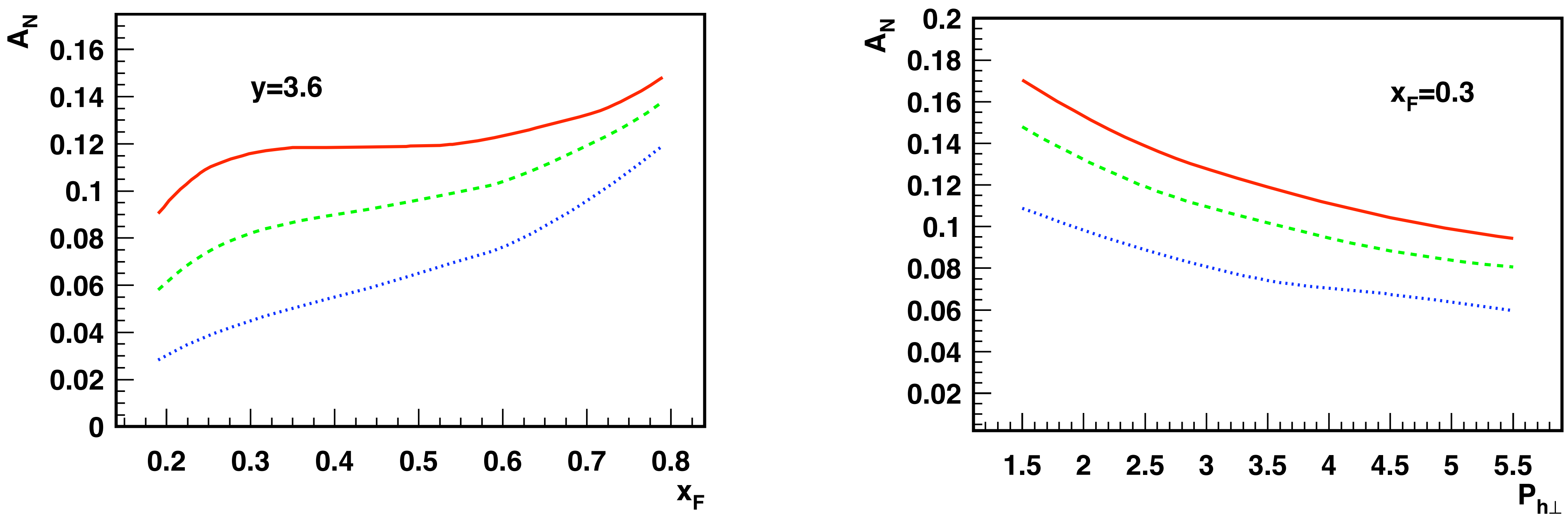
- Different weights: $e_q^2 \Rightarrow v_q^2 + a_q^2$

$$
\begin{aligned}
v_u &= \frac{1}{2} - \frac{4}{3}\sin^2\theta_W \qquad a_u = \frac{1}{2} \quad \Rightarrow \quad v_u^2 + a_u^2 = 0.29 \\
v_d &= -\frac{1}{2} + \frac{2}{3}\sin^2\theta_W \qquad a_d = -\frac{1}{2} \quad \Rightarrow \quad v_d^2 + a_d^2 = 0.38
\end{aligned}
$$

What if COMPASS is correct?

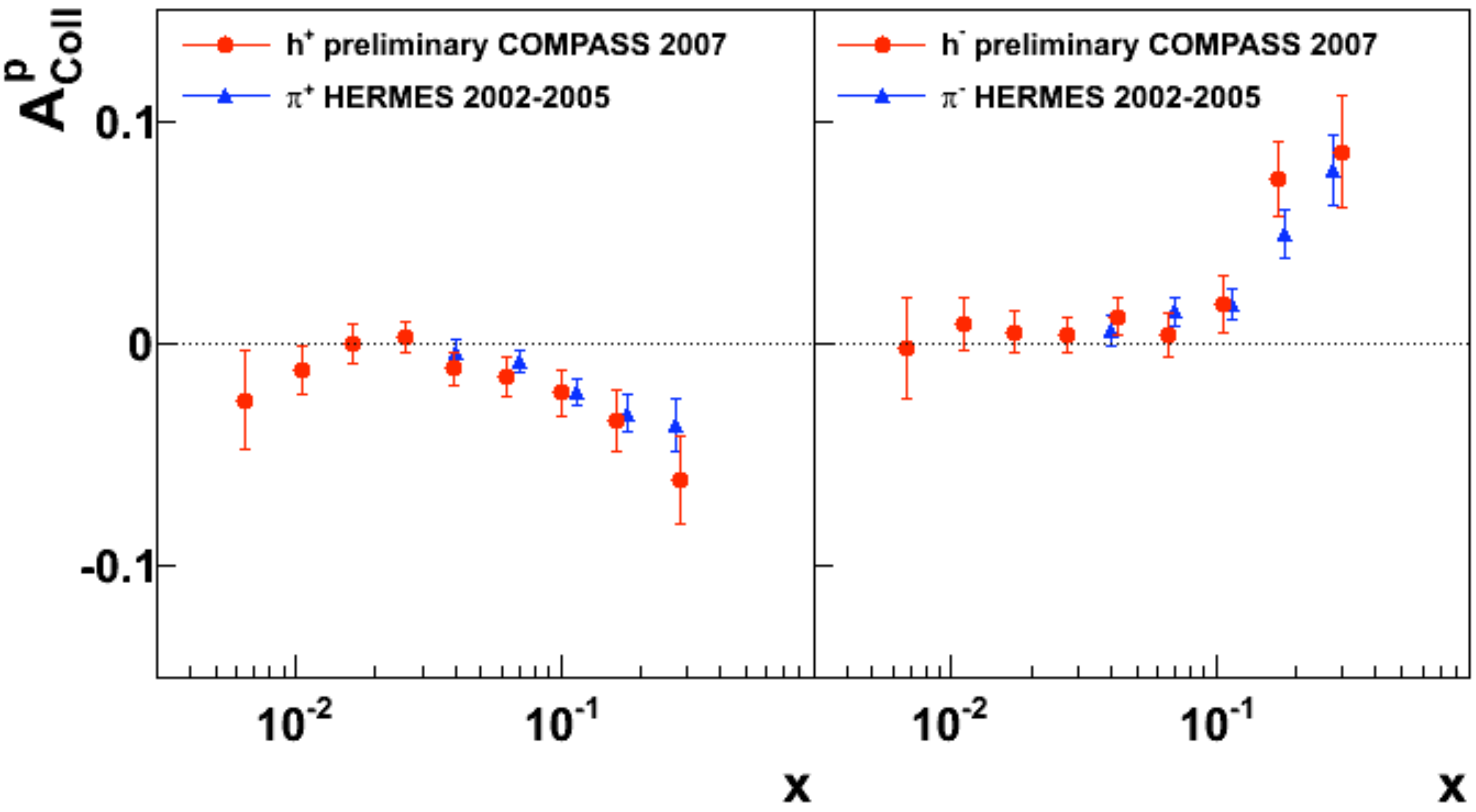
- If Sivers functions are zero, then HERMES has to be wrong, since one can distinguish Sivers and Collins effects from angle-dependence

- It won't cause serious damage to inclusive pion data from E704, BRAHMAS, PHENIX, and STAR. A non-vanishing asymmetry could still come from Collins effect.
  - A_N from fragmentation contribution in collinear approach: π^0



Kang, Yuan, Zhou, 2010

Collins is consistent between COMPASS and HERMES



Possibilities from RHIC DY measurements:

- A_N is zero:
  - Fine. COMPASS is correct, HERMES is wrong. No big deal!

- A_N doesn't follow the sign change of the Sives function:
  - Trouble: what's wrong?

  - The problem of TMD factorization: firm.
  - If remember the Collinear approach is consistent with TMD approach in the intermediate region, so at least in this region, the Collinear approach also predict the same sign of the SSA as from TMD, if indeed conclude with no sign change, then even the problem of Collinear factorization, too??
    - The collinear factorization has been tested in many different processes and so far so good
    - It should be the problem of our current understanding of the SSA: probably the SSA phenomenon has completely different origin, not described in perturbative formalism at all, from non-perturbative physics?
  - It is not the problem of QCD Lagrangian: that's too far.
- A_N is exactly expected by the sign change: should we be happy?

Summary

- Sign change of Sivers function between DY and SIDIS is the most critical test for our current understanding of SSAs

- Let's hope we have this result as soon as possible

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Thank you