# $A_N$ of W Production in Polarized pp collisions

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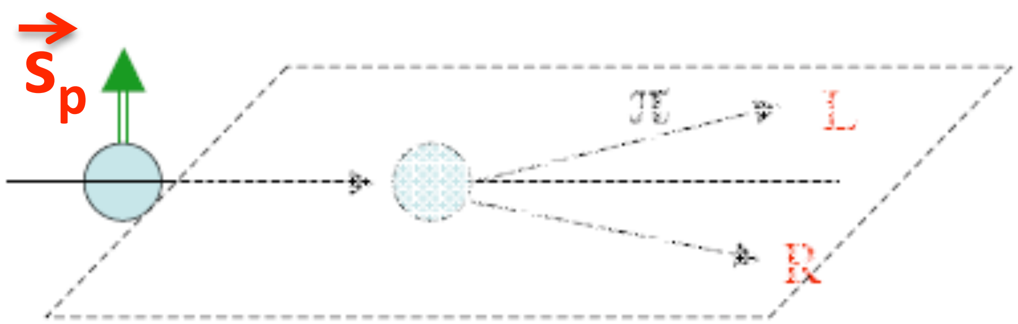
# Outline

- Introduction
  - $A_N$: single transverse-spin asymmetry (SSA)
  - Transverse motion
- Sivers function
  - Modified universality: sign change between SIDIS and DY processes
- W production
- Summary

# $A_N$ Definition: Single Transverse Spin Asymmetry (SSA)

- Consider the scattering of a transversely polarized nucleon with another nucleon, observe a particle going left or right: left-right asymmetry




$$A_N = \frac{N_L - N_R}{N_L + N_R}$$

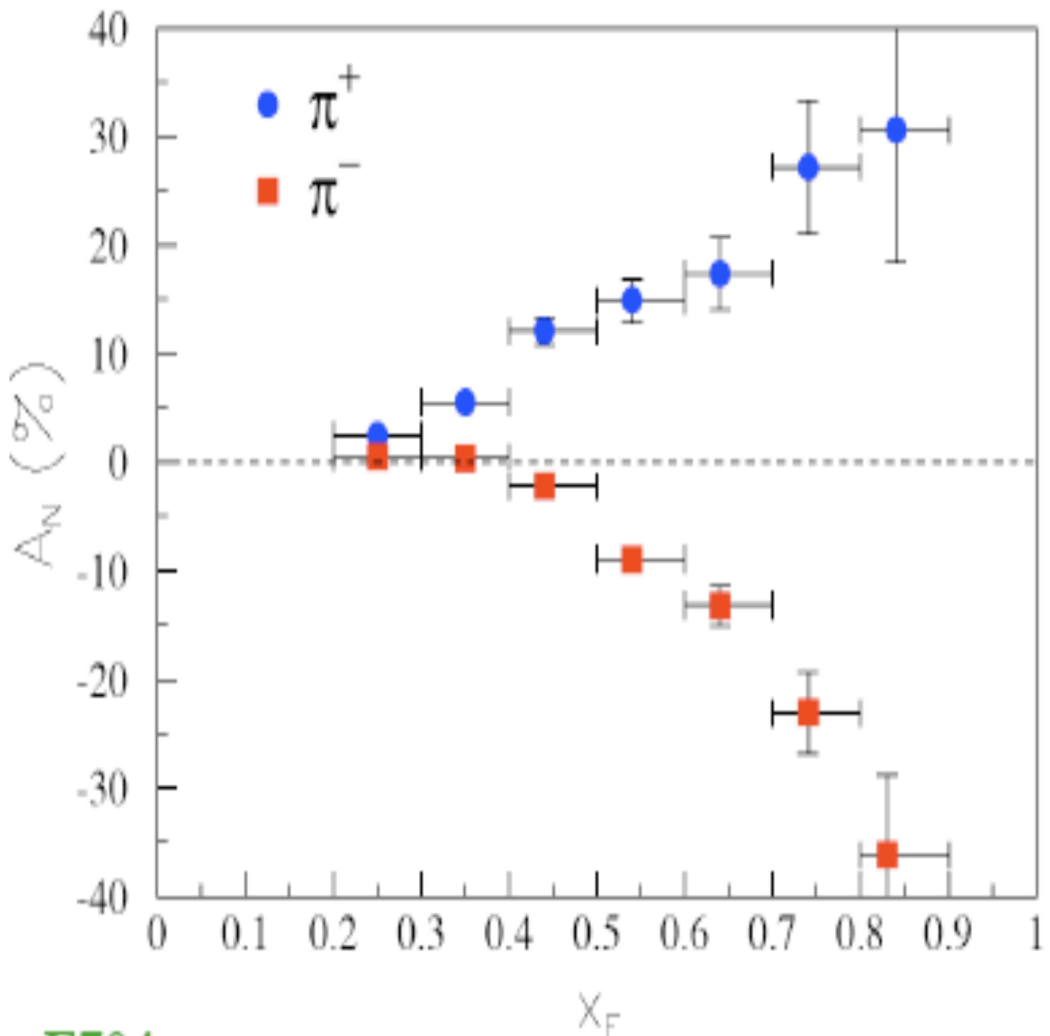
- Because of rotational symmetry, this corresponds to an asymmetry relate to the difference of the cross section when the spin of the incoming nucleon is flipped
  - Spin-averaged cross section: $\sigma(\ell) = \frac{1}{2}\left[\sigma(\ell, \vec{s}) + \sigma(\ell, -\vec{s})\right]$
  - Spin-dependent 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):

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

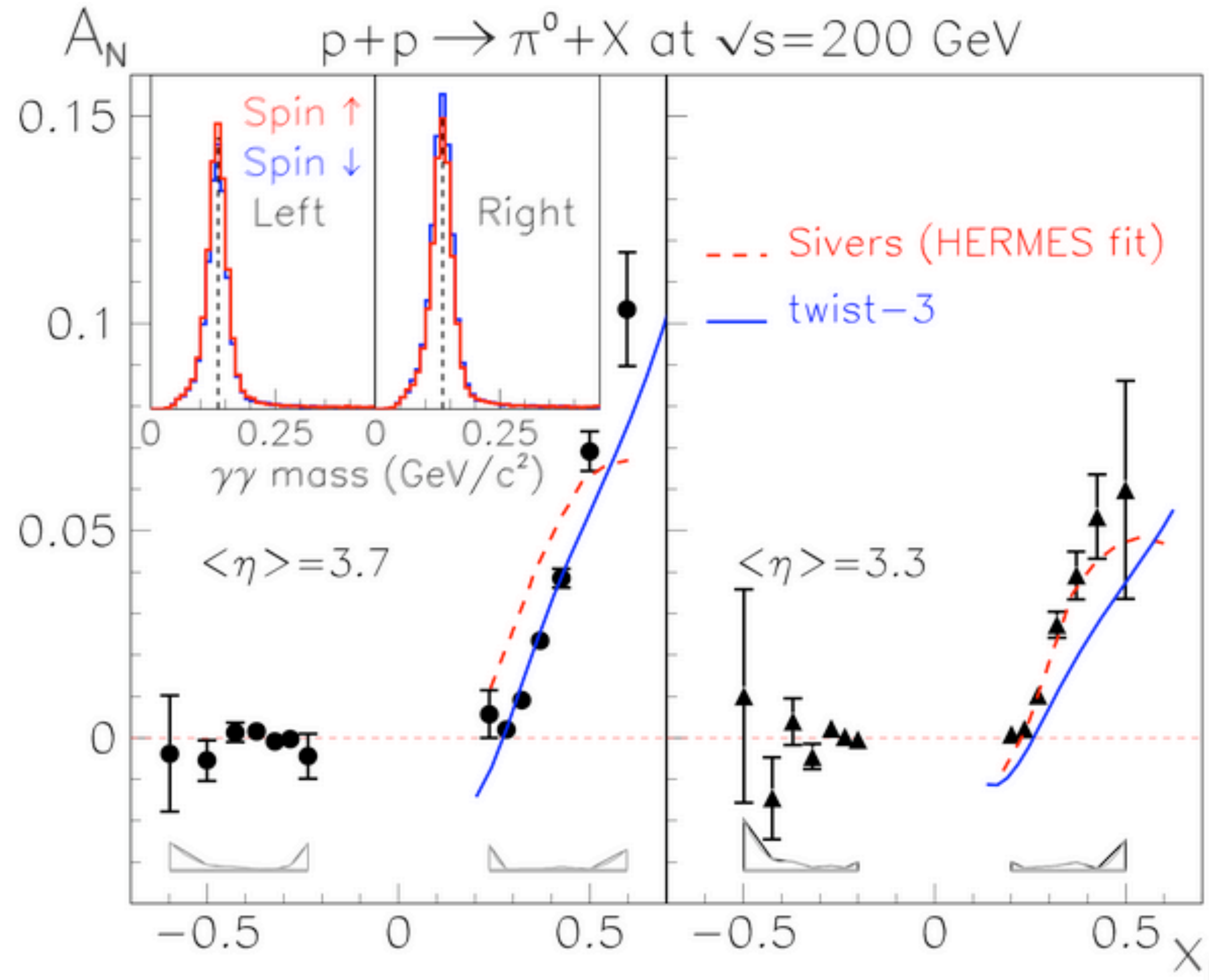
# Experiment: Single Spin Asymmetries

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

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




E704



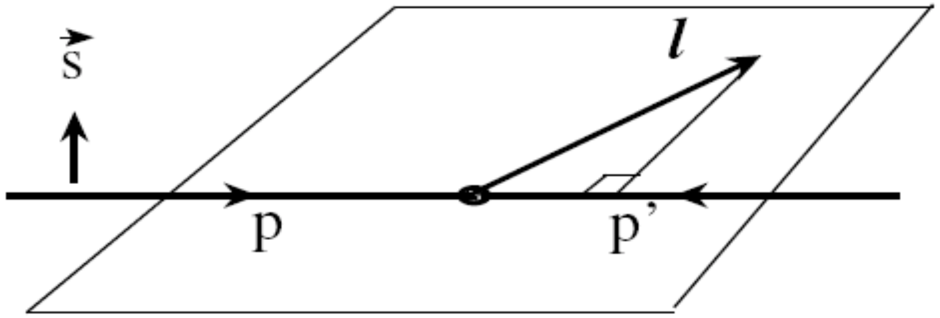

STAR

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 (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

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

  - the phase "$i$" is required by time-reversal invariance
  - covariant form: $A_N \propto i\epsilon^{\mu\nu\alpha\beta} p_\mu s_\nu \ell_\alpha p'_\beta$

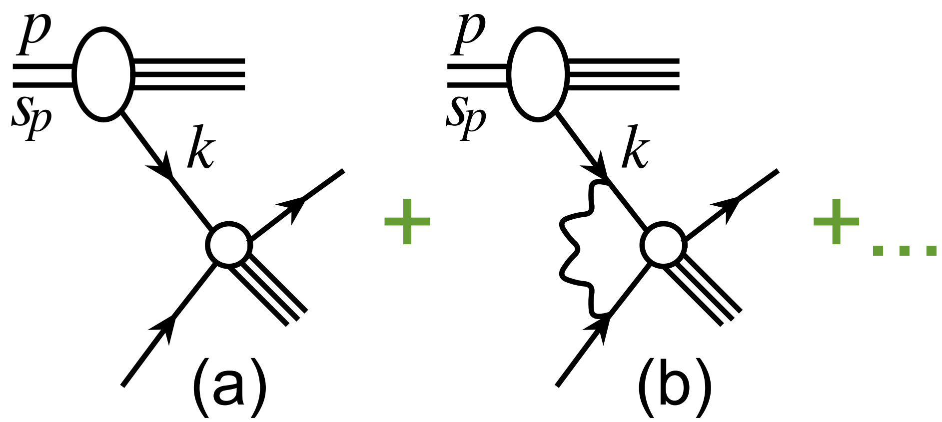
**Nonvanishing $A_N$ requires a phase, a helicity flip, and enough vectors to fix a scattering plane**

# SSA vanishes at leading twist in collinear factorization

- At leading twist formalism: partons are collinear

Kane, Pumplin, Repko, 1978

$\sigma(s_T) \sim \Big|$




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

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

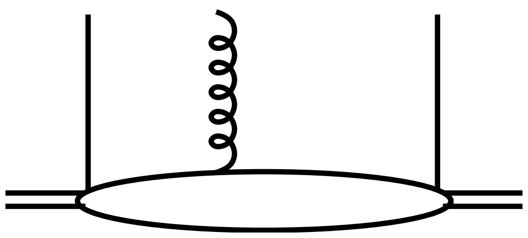
Therefore we have

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

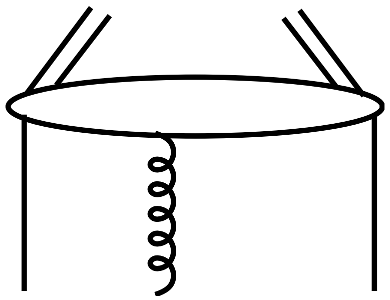
- $A_N \neq 0$: result of parton's transverse motion or correlations!

# Two mechanisms to generate SSA in QCD

- 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, 09, Kang, Zhou, Yuan, 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 $q_T$

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

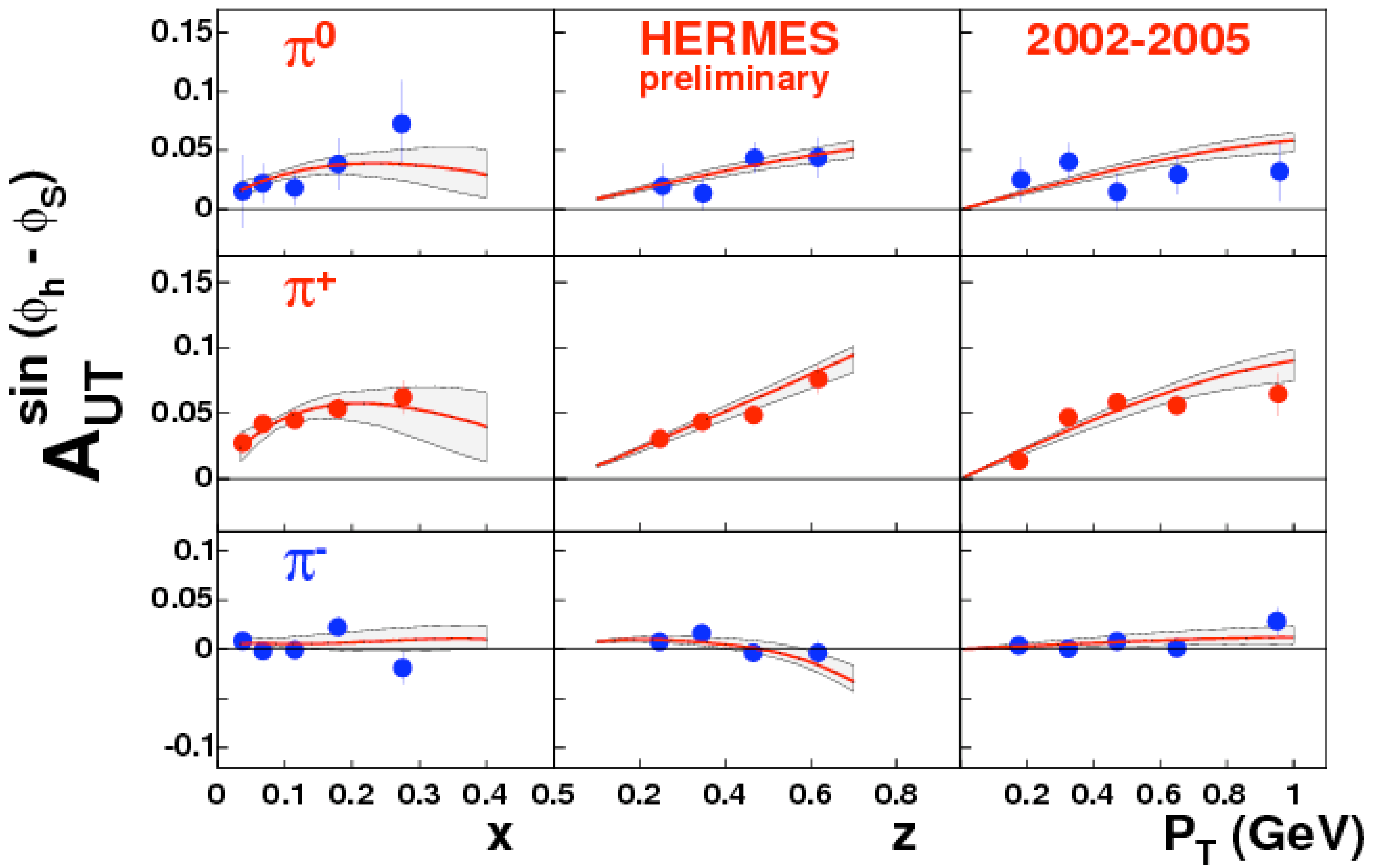
  - Collinear factorization approach: more relevant for single scale hard process: inclusive pion production at pp collision
- They generate same results in the overlap region when they both apply:
  - Twist-3 three-parton correlation in distribution $\longleftrightarrow$ Sivers function

    Ji, Qiu, Vogelsang, Yuan, 06, ...
  - Twist-3 three-parton correlation in fragmentation $\longleftrightarrow$ Collins function

    Zhou, Yuan, 09

# Current formalisms work well: TMD approach

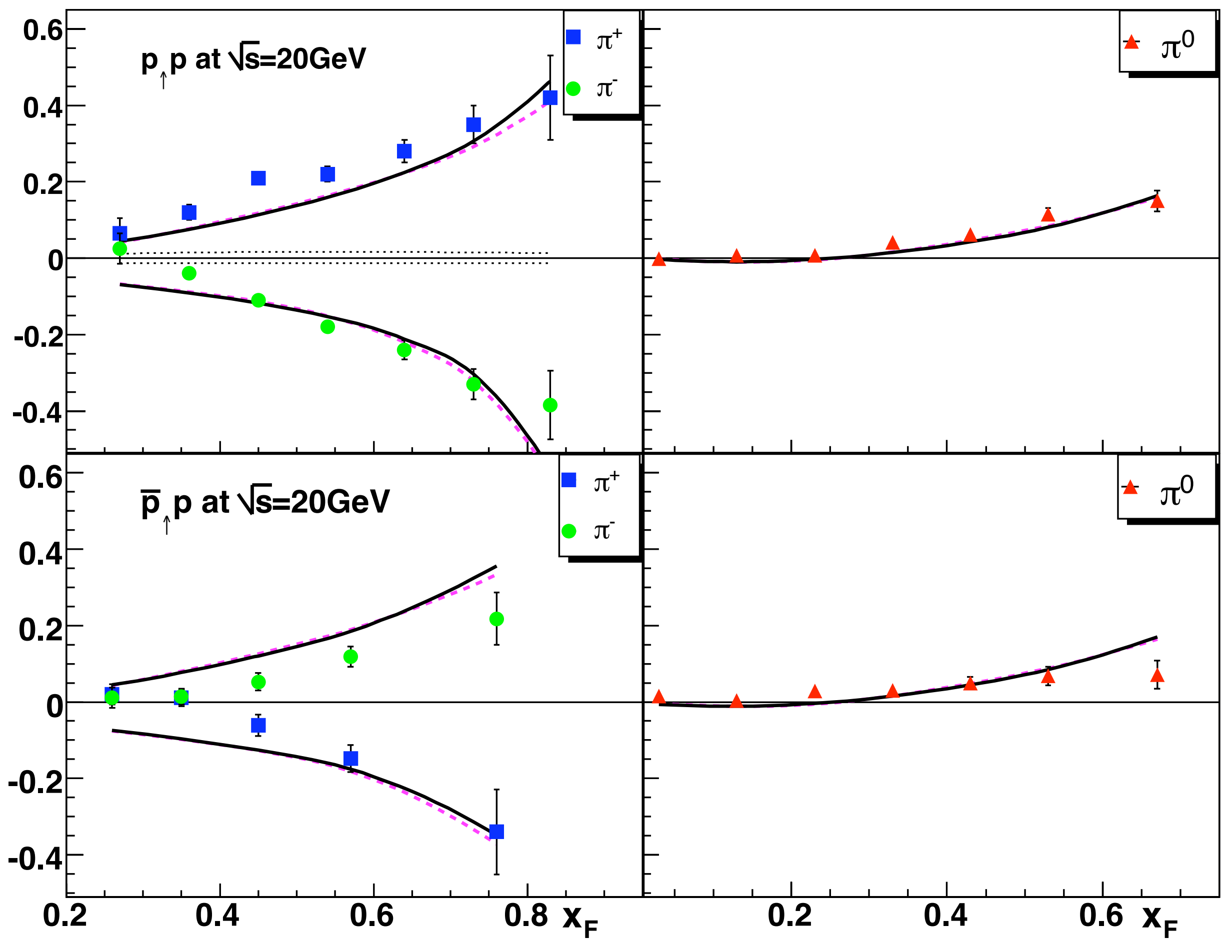
- TMD approach for SIDIS process: $\ell + p^{\uparrow} \rightarrow \ell + \pi + X$

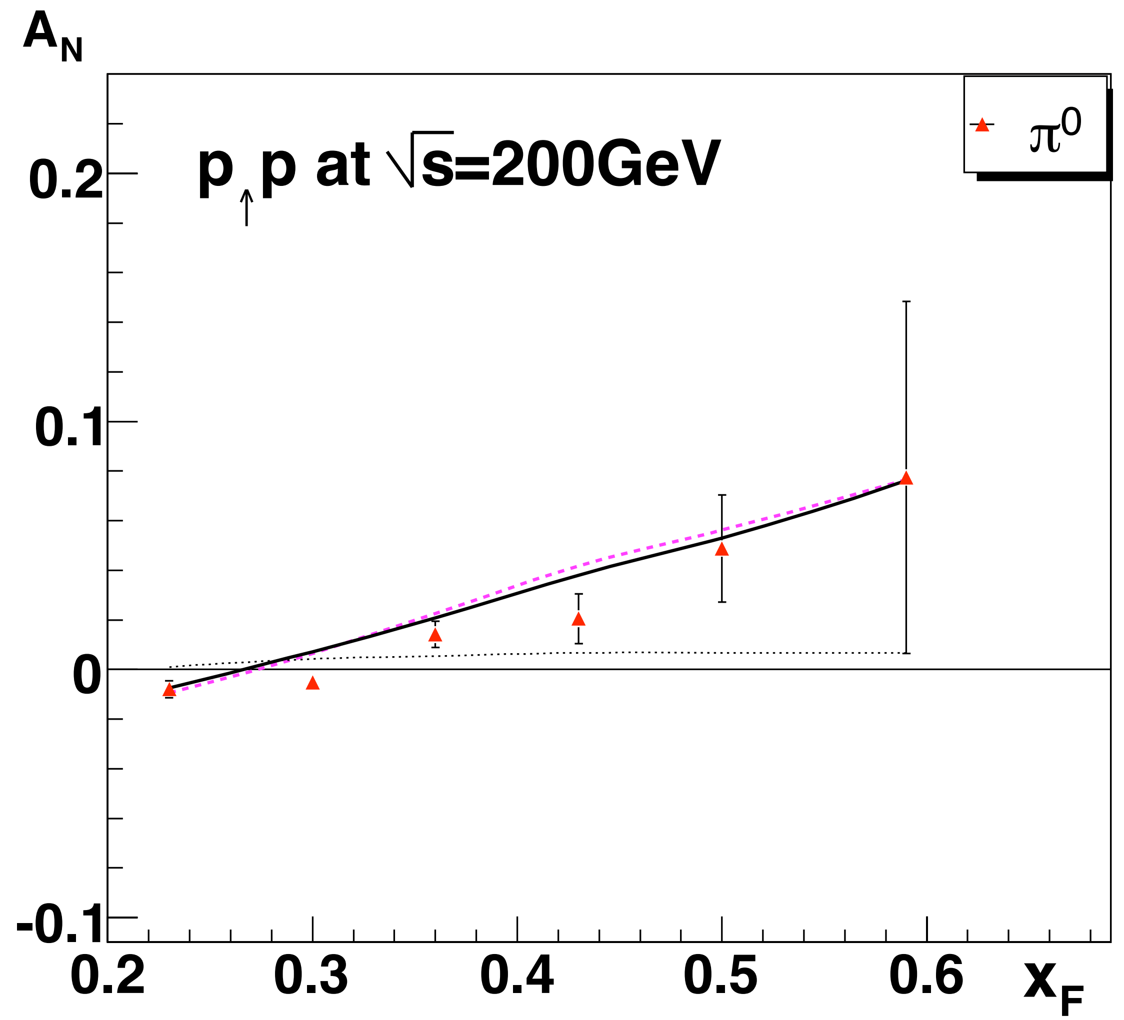


# Current formalisms work well: Twist-3 approach

- Twist-3 collinear approach for inclusive hadron production:

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



# 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

# Major difference in these two approaches

- Collinear factorization approach:
  - All the twist-3 correlation functions (both in distribution and fragmentation side) are universal
- 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

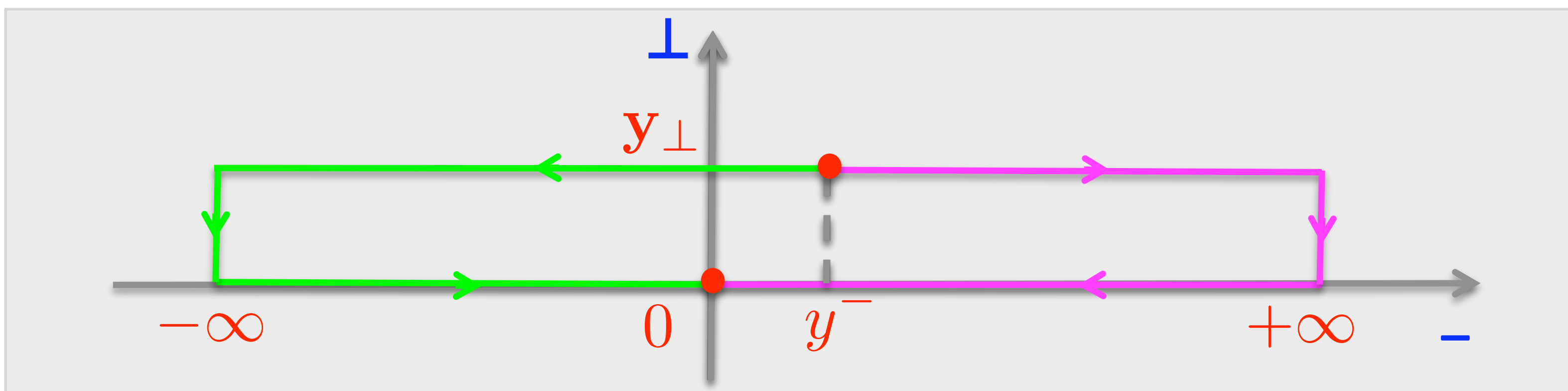
    Metz 02, Collins, Metz, 04, Yuan, 08, Gamberg, Mukerjee, Mulders, 08, Meissner, Metz, 08, Zhou, Yuan, 09, ...

# Non-universality of the Sivers function

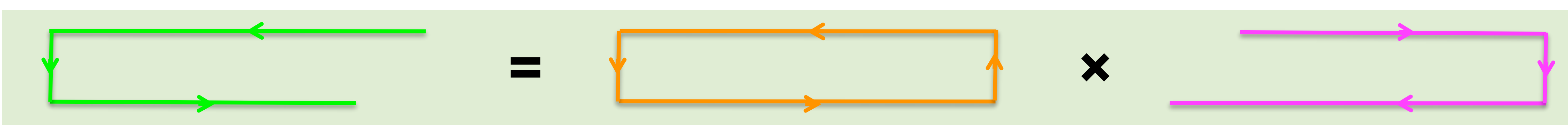
- Different gauge link for gauge-invariant TMD distribution in SIDIS and DY

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

  - 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:

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

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

  - From definition:

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

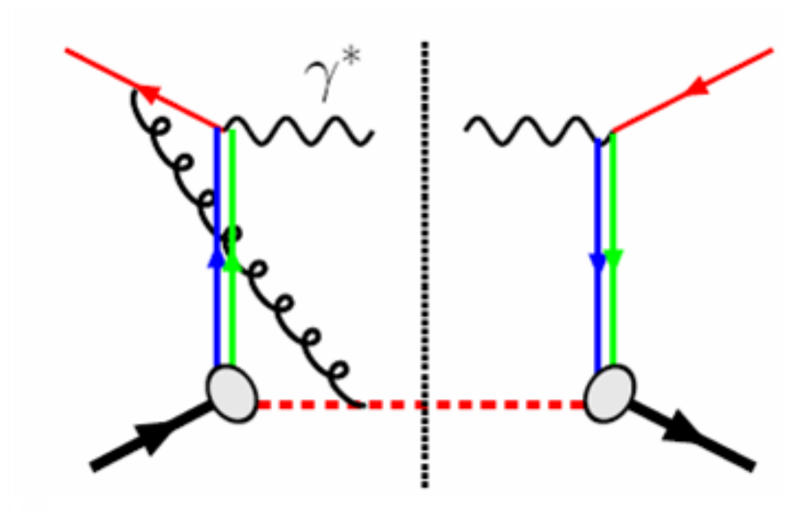
  - One can derive:

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

Most critical test for TMD approach to SSA

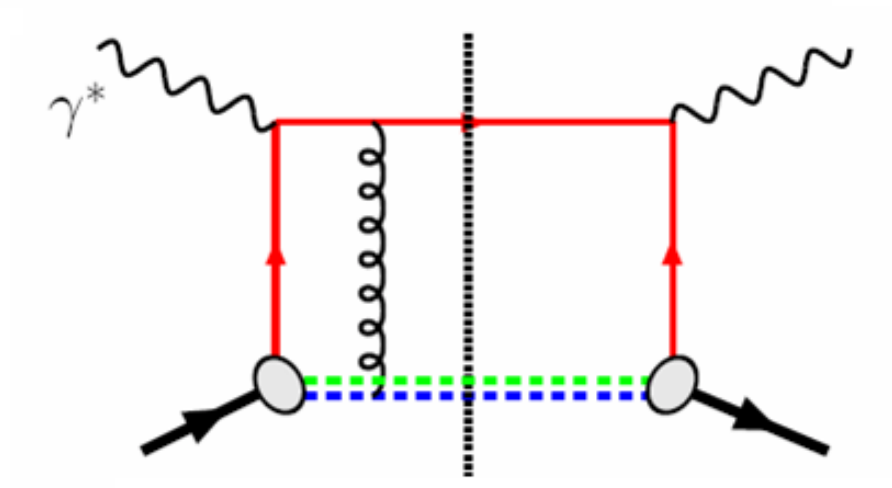
# Intuitive understanding of the sign change

- Difference between initial and final state interactions




$$p^\uparrow + p \to \left[\gamma^* \to \ell^+\ell^-\right] + X$$

**DY: repulsive**




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

**SIDIS: attractive**

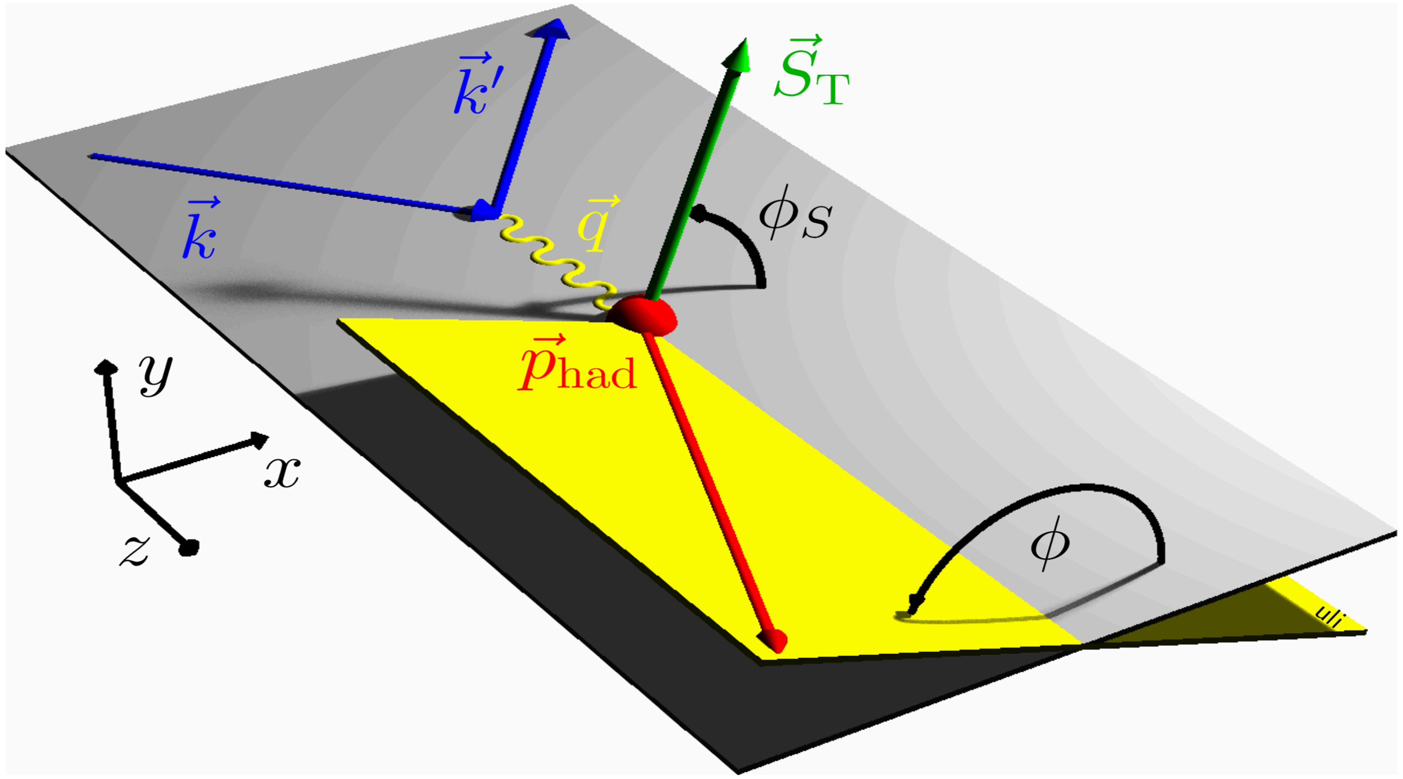
$$\Delta^N f_{q/h^\uparrow}^{\rm SIDIS}(x, k_\perp) = -\Delta^N f_{q/h^\uparrow}^{\rm DY}(x, k_\perp)$$

- Sign change:
  - Test of TMD factorization
  - Test of current understanding of SSA

# Current Sivers function from SIDIS

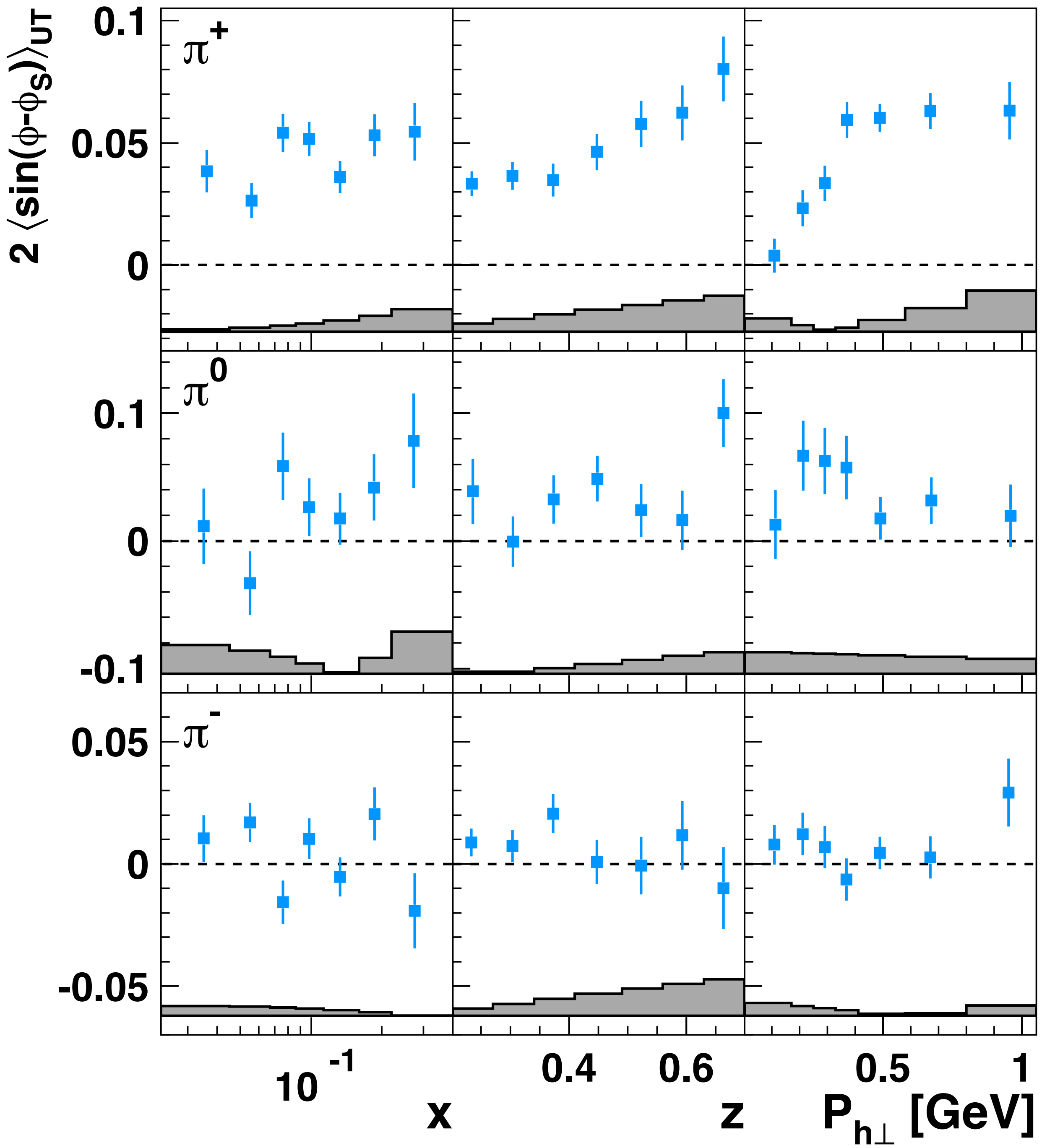
- Sivers and Collins can be separately extracted from SIDIS

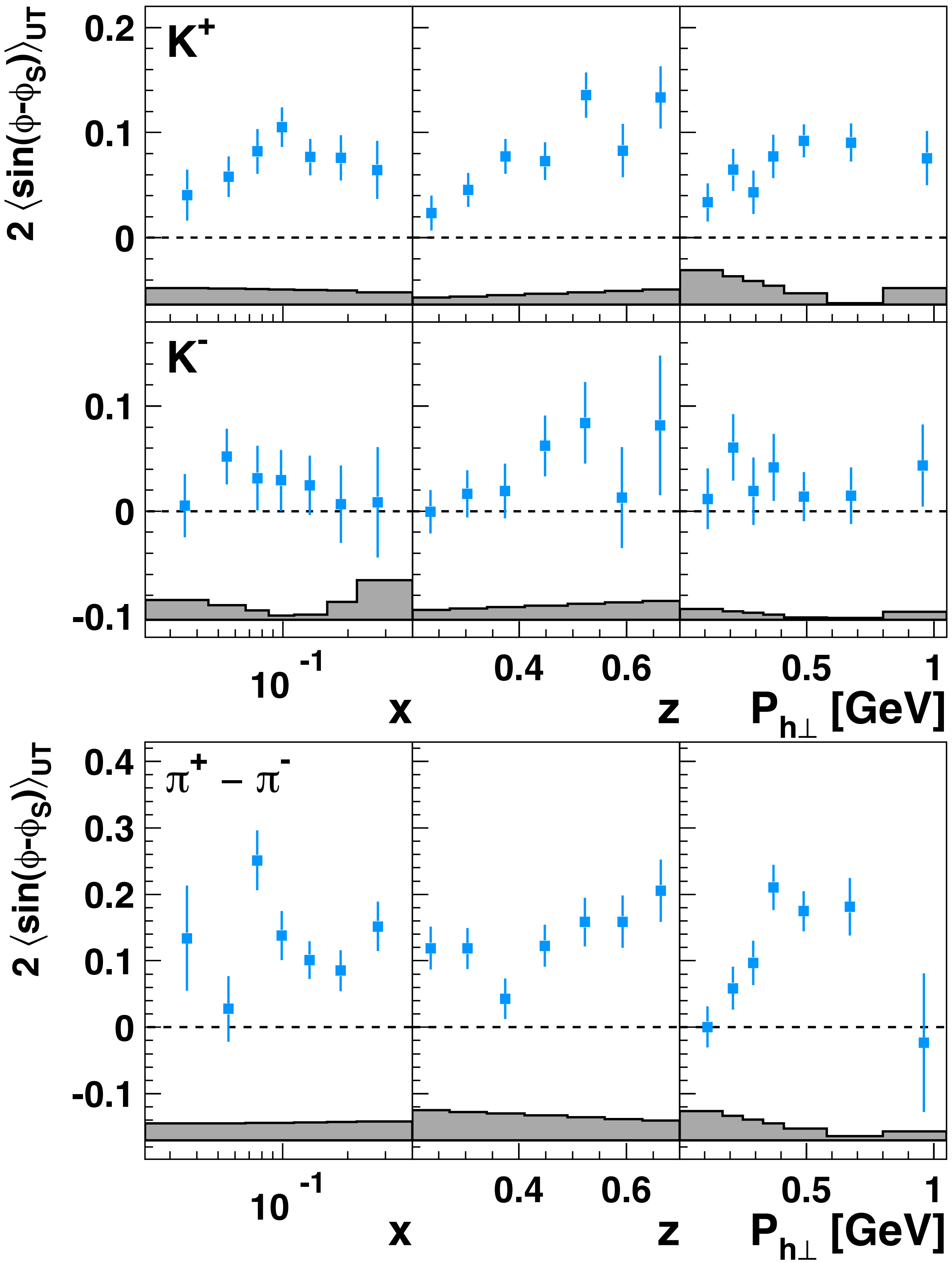
$$\Delta\sigma \propto A_{UT}^{\text{Collins}} \sin(\phi + \phi_S) + A_{UT}^{\text{Sivers}} \sin(\phi - \phi_S)$$



# Sivers effect has been observed in SIDIS

- Sivers effect from HERMES

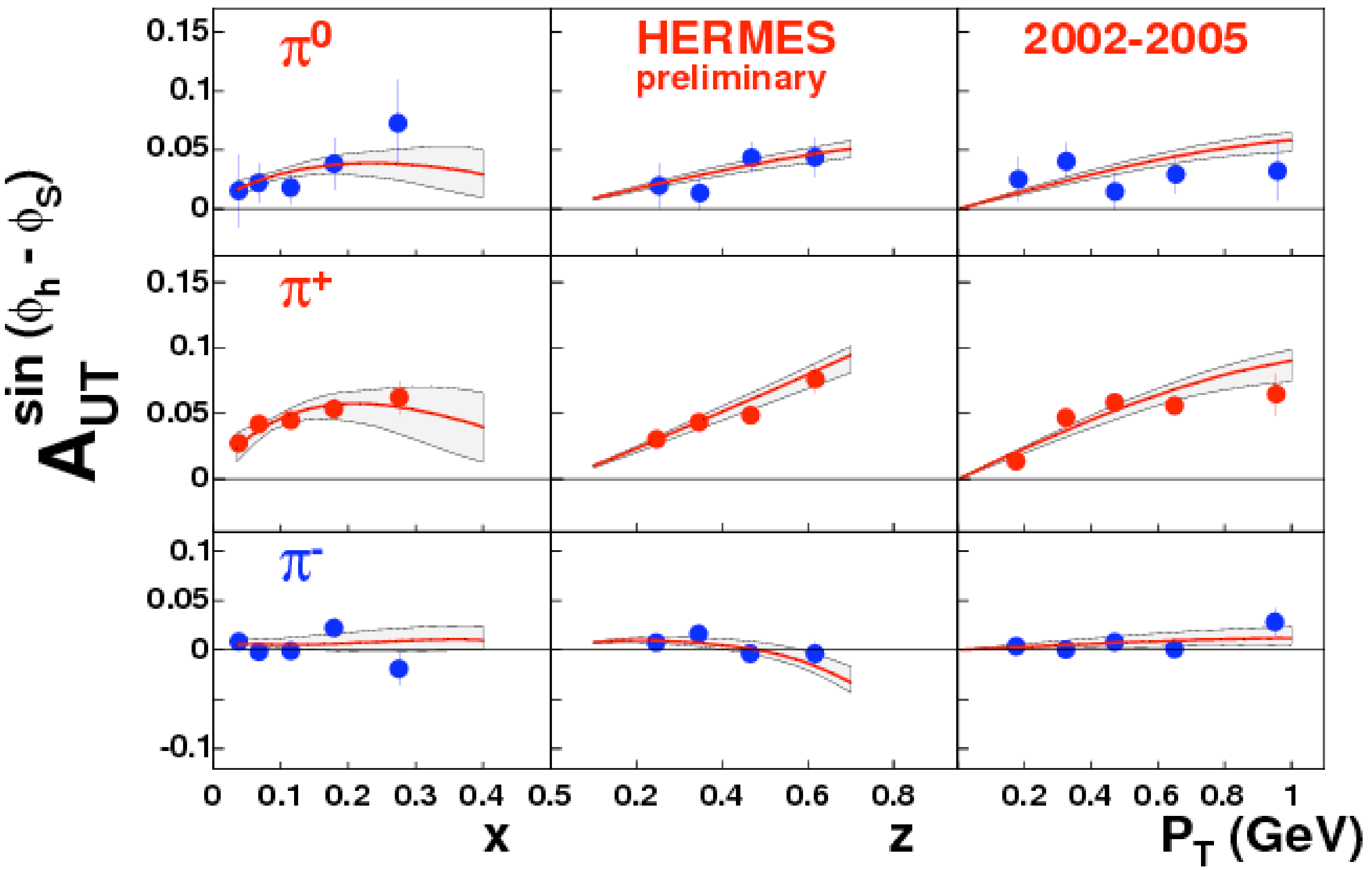


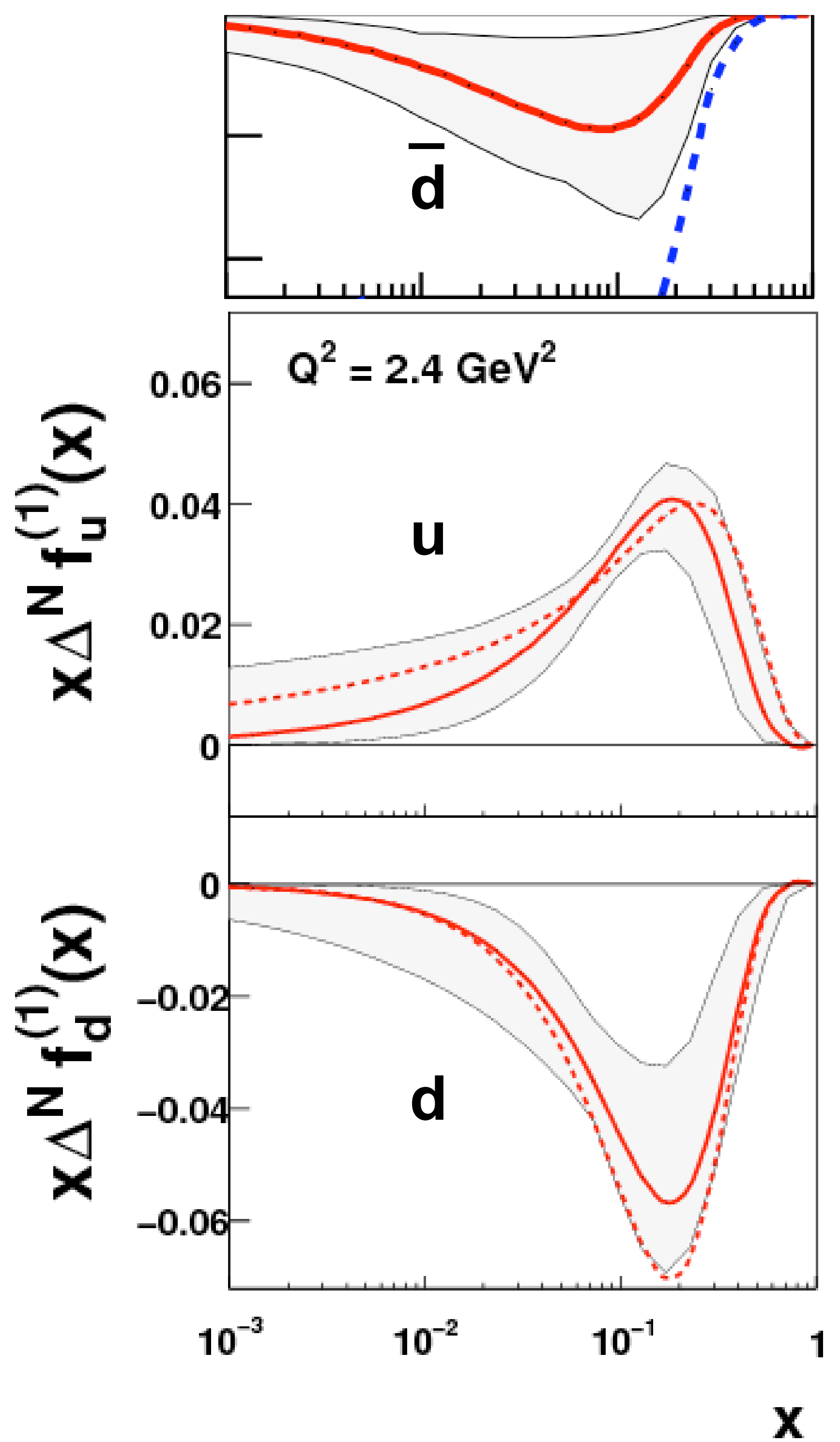



# Sivers function from SIDIS

- Extract Sivers function from SIDIS

Anselmino, et.al., 2009



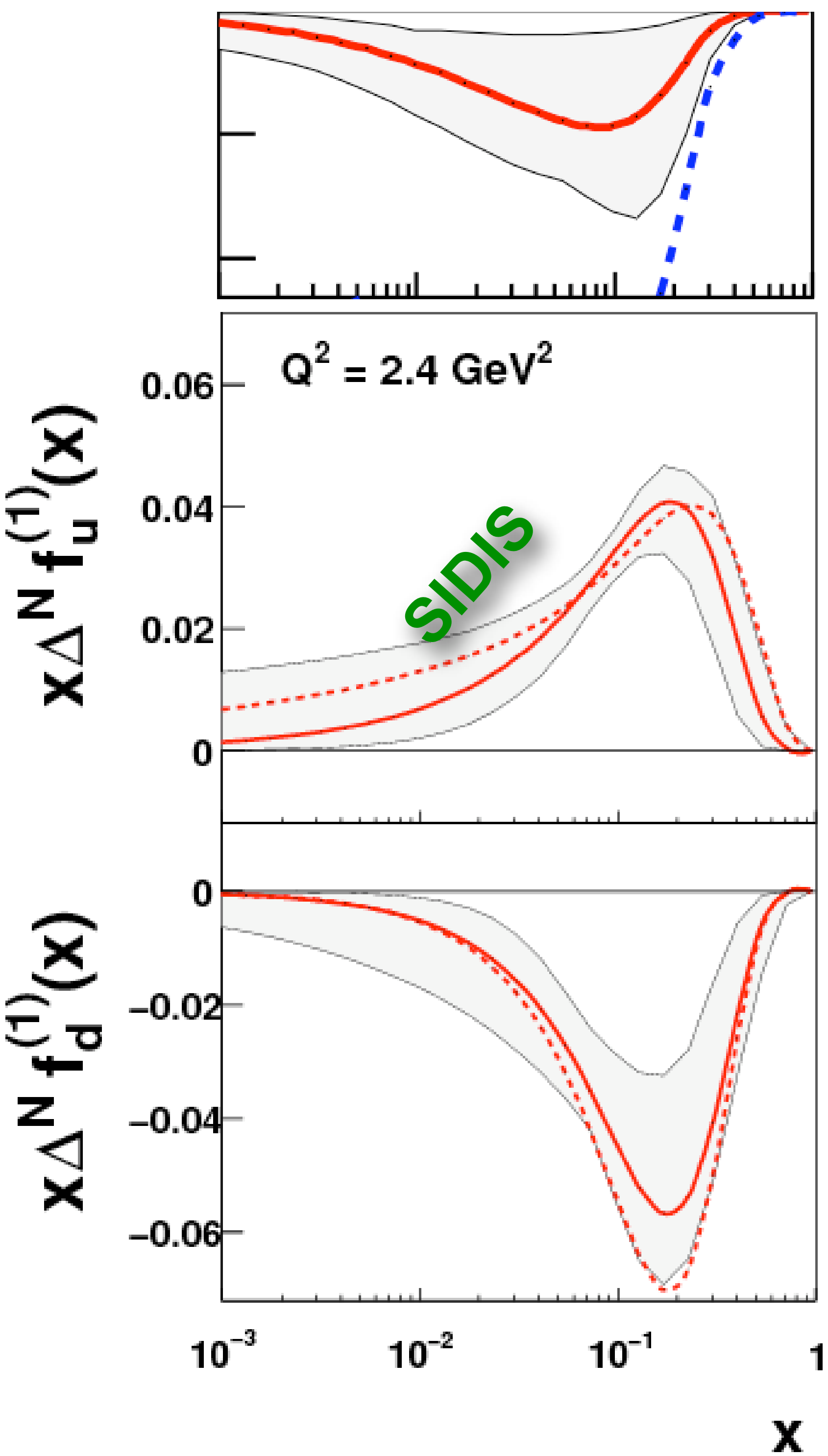




- u and d almost equal size, different sign
- d-Sivers is slightly larger
- d-bar Sivers is negative

# Sivers function in DY

- After sign change:

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




- d-Sivers is positive, larger
- u-Sivers is negative, smaller
- d-bar Sivers is positive, small

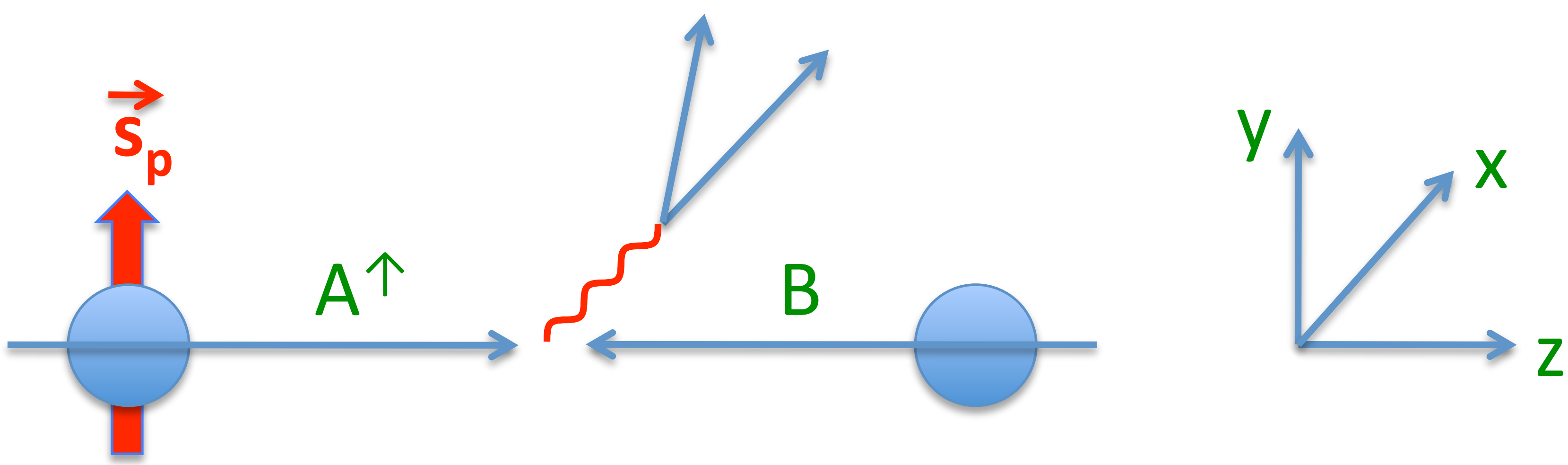
# Sivers effect in Drell-Yan process

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

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

➡ $A_N < 0$

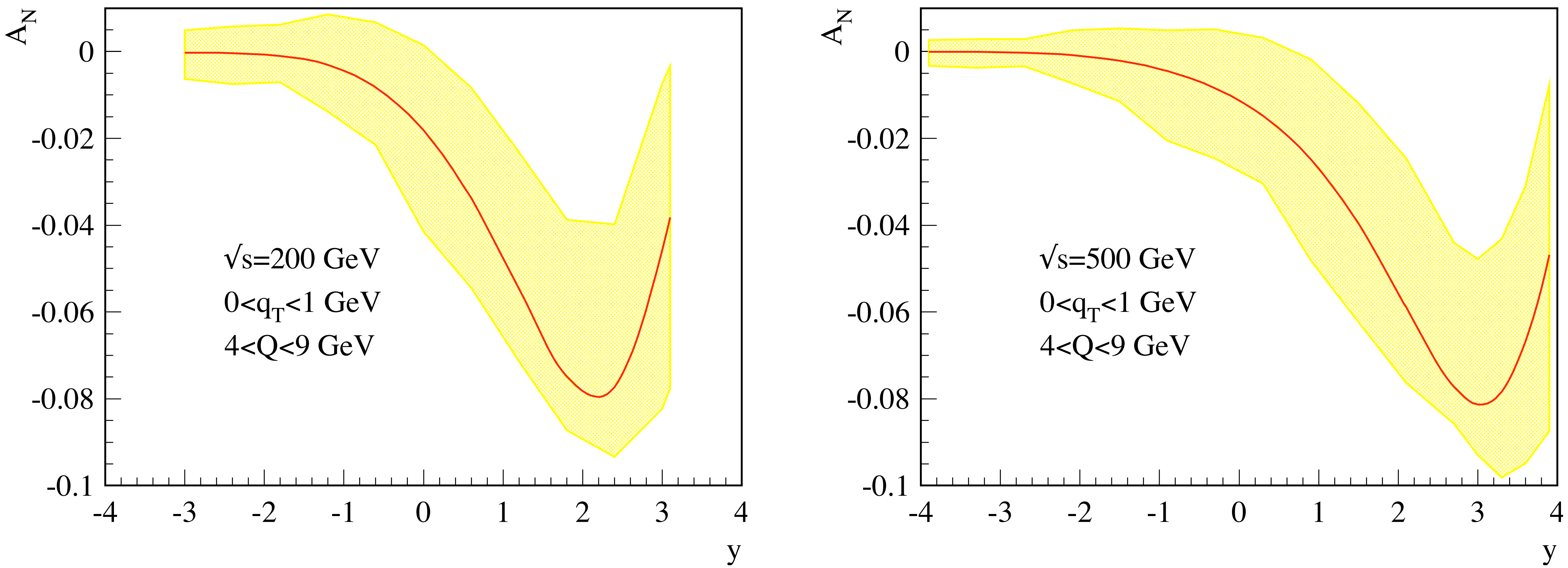
- Careful about the frame: $A^\uparrow + B \to [\gamma^* \to \ell^+\ell^-] + X$
  - In A-B CM frame: $A^\uparrow$ along $z$-direction, $B$ is opposite to it. "up" (↑) polarization direction is along $y$-axis




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

# SSA for Drell-Yan dilepton production at RHIC

$A_N \sim$ 2-3% in mid-rapidity y=0

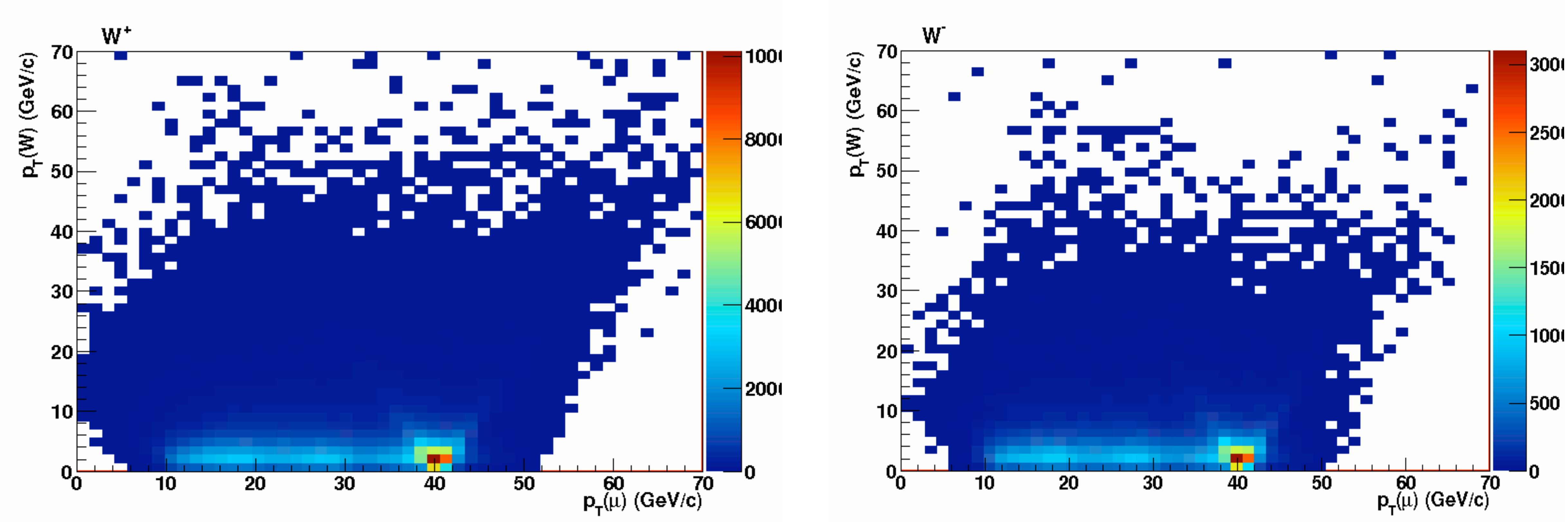



Kang, Qiu, PRD81: 054020 (2010)

- When will Drell-Yan be available: 2016?
  - Separate check of u and d Sivers function?

# Production of $W^+$, $W^-$ at RHIC

- W boson are primarily produced at the region: $M_W >> q_T \sim 2$ GeV
  - Lepton $p_T \sim M_W/2$




Courtesy of Kempel, Lajoie (PHENIX)

- TMD approach could be used
  - W events ~ 10, 000

# SSA of W boson

- Collinear factorization will have problems: Sudokov logarithm, resummation, CSS formalism
- Results in TMD approach:
  - Spin-dependent:

$$\frac{d\Delta\sigma_{A^\uparrow B\to W}(\vec{S}_\perp)}{dy_W\, d^2\mathbf{q}_\perp} = \frac{\sigma_0}{2}\sum_{a,b}|V_{ab}|^2\int d^2\mathbf{k}_{a\perp} d^2\mathbf{k}_{b\perp}\, \vec{S}_\perp\cdot(\hat{p}_A\times\hat{\mathbf{k}}_{a\perp})$$
$$\times\Delta^N f^{\rm DY}_{a/A^\uparrow}(x_a,k_{a\perp}) f_{b/B}(x_b,k_{b\perp})\,\delta^2(\mathbf{q}_\perp-\mathbf{k}_{a\perp}-\mathbf{k}_{b\perp})$$

$$x_a = \frac{M_W}{\sqrt{s}}\,e^{y_W}, \quad x_b = \frac{M_W}{\sqrt{s}}\,e^{-y_W}$$

W⁻: $ab = d\bar{u}, \bar{u}d, \cdots$ W⁺: $ab = u\bar{d}, \bar{d}u, \cdots$

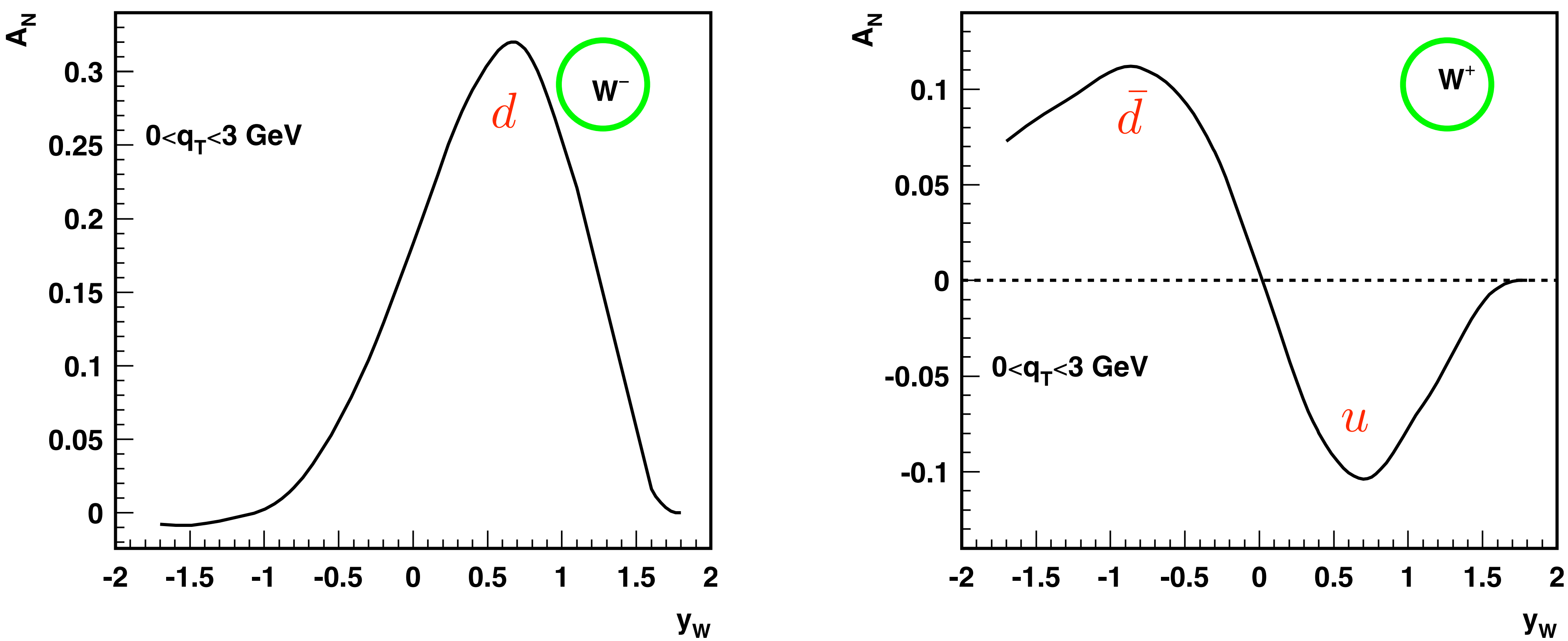
  - W- sensitive to d and u-bar Sivers function, W+ sensitive to u and d-bar Sivers function

$$A_N^{(W)} \equiv \frac{d\Delta\sigma(\vec{S}_\perp)_{A^\uparrow B\to W}}{dy_W\, d^2\mathbf{q}_\perp} \Bigg/ \frac{d\sigma_{AB\to W}}{dy_W\, d^2\mathbf{q}_\perp}$$

# SSA of W bosons: rapidity dependence

Brodsky, Hwang, Schmidt, 2002,
Schmidt, Soffer, 03, Kang, Qiu, 09

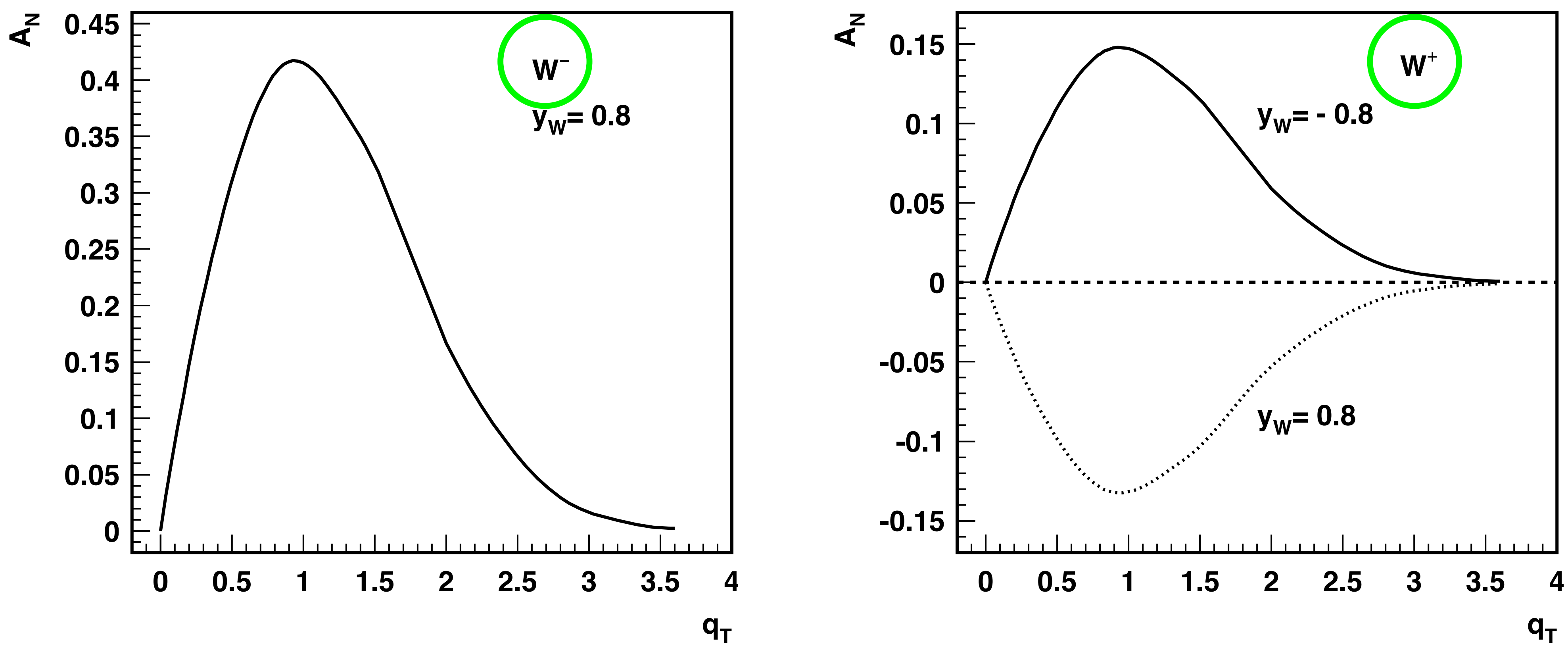
- Use the Sivers functions extracted by Anselmino et al.
- SSAs of W production at RHIC:
  - Sivers function same as DY, different from SIDIS by a sign




  - Good flavor separation

# SSA of W bosons: $q_T$ dependence

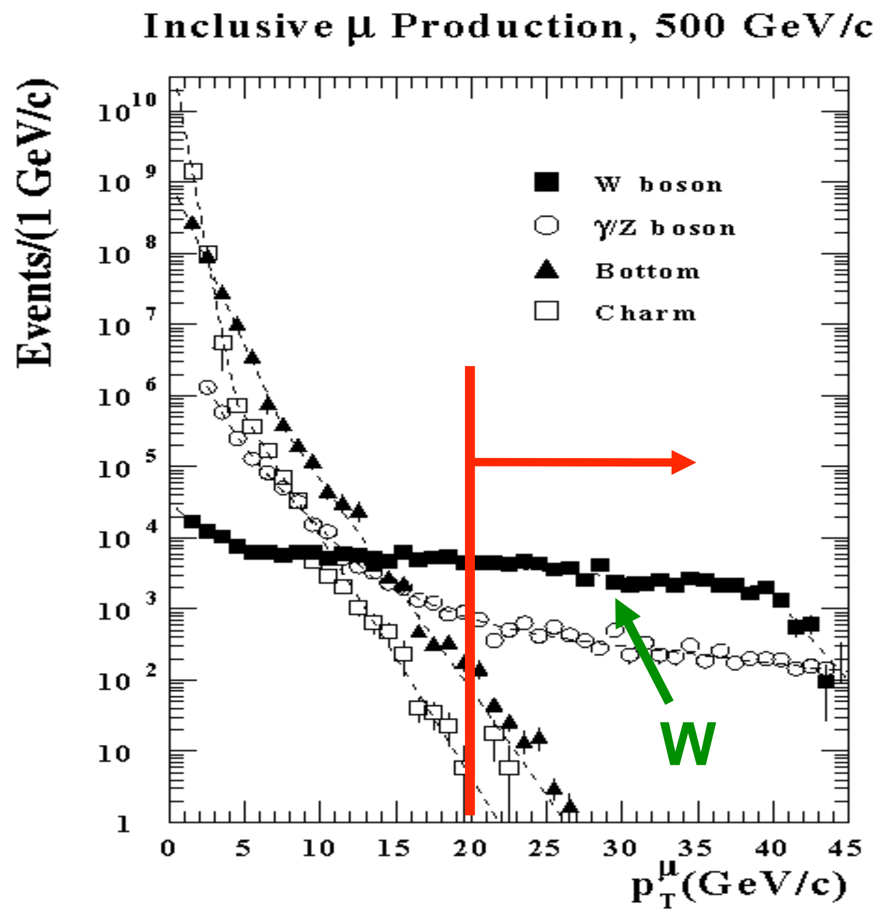
- Large asymmetry: should be able to see sign change




- But, the detectors at RHIC cannot reconstruct the W's

# Lepton from W decay: $W \to \mu\, \nu$

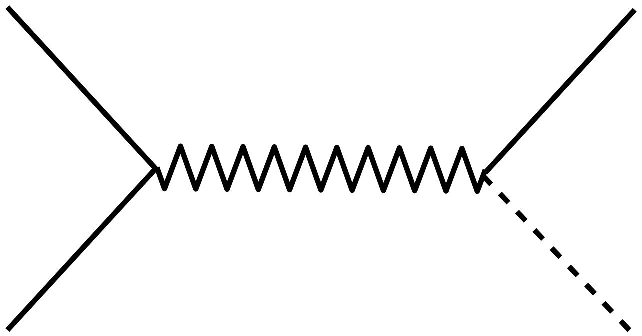
- Inclusive lepton background from Charm/Bottom dies when $p_T > 20$ GeV




- Idea: integrate out the neutrino to measure SSA of inclusive high $p_T$ lepton
- However, $\sin(\Phi_S - \Phi_W)$ dependence of the SSA of W's could dilute the SSA of inclusive lepton

# SSA of lepton from W decay: formula

- Spin-dependent:



$$\frac{d\Delta\sigma_{A^\uparrow B\to\ell(p)}(\vec{S}_\perp)}{dy\, d^2\mathbf{p}_\perp} = \sum_{a,b} |V_{ab}|^2 \int dx_a\, d^2\mathbf{k}_{a\perp} \int dx_b\, d^2\mathbf{k}_{b\perp} \vec{S}_\perp \cdot (\hat{p}_A \times \hat{\mathbf{k}}_{a\perp}) \Delta^N f^{\rm DY}_{a/A^\uparrow}(x_a, k_{a\perp})$$

$$\times f_{b/B}(x_b, k_{b\perp}) \frac{1}{16\pi^2 \hat{s}} \left|\overline{\mathcal{M}}_{ab\to\ell}\right|^2 \delta(\hat{s}+\hat{t}+\hat{u})$$

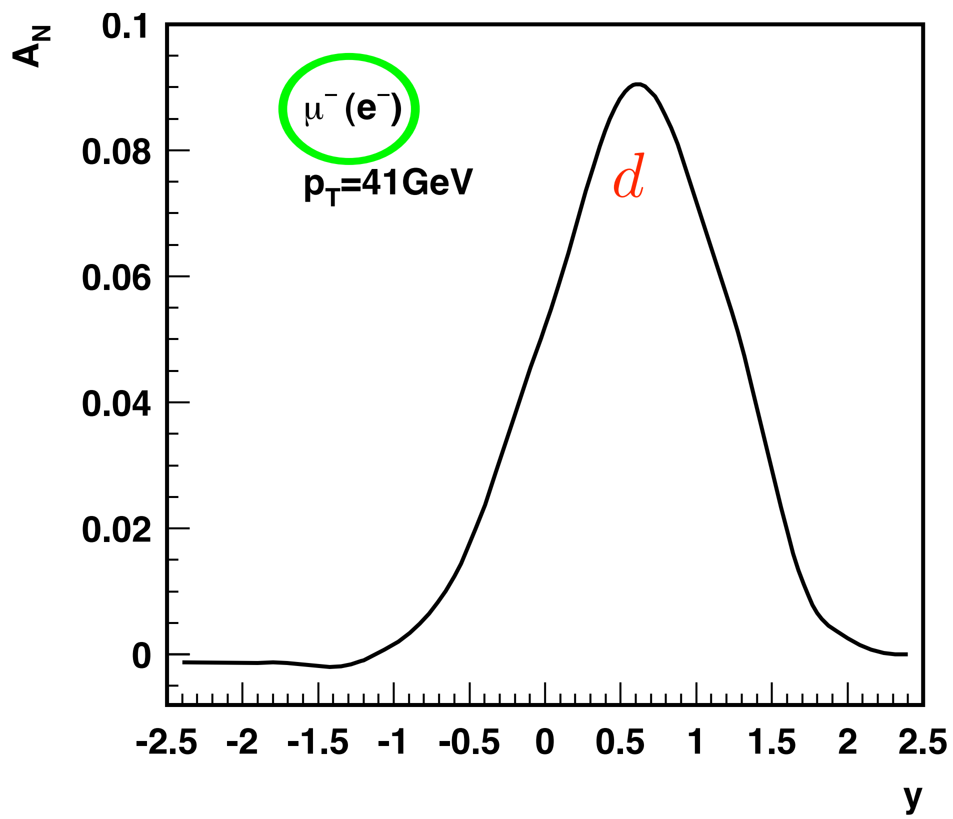
$$\left|\overline{\mathcal{M}}_{ab\to\ell}\right|^2 = \frac{8(\mathrm{G}_F M_W^2)^2}{3} \frac{\hat{t}^2}{(\hat{s}-M_W^2)^2 + M_W^2\,\Gamma_W^2} \qquad ab = \bar{u}d, \bar{u}s, u\bar{d}, u\bar{s}$$

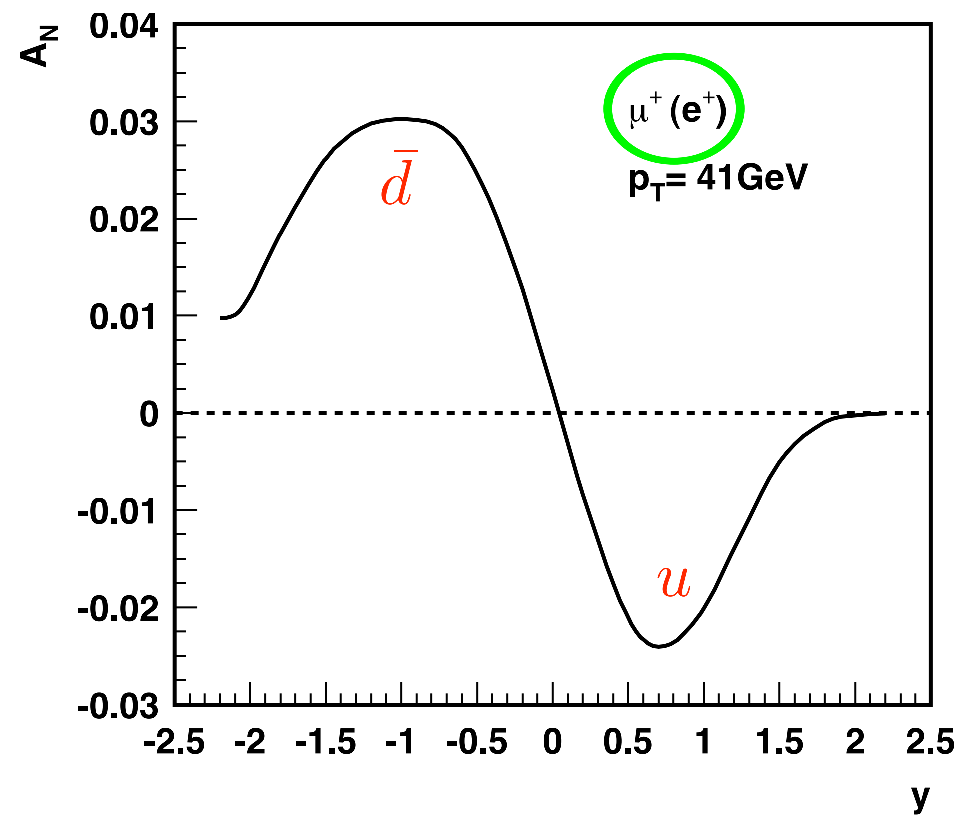
$$\left|\overline{\mathcal{M}}_{ab\to\ell}\right|^2 = \frac{8(\mathrm{G}_F M_W^2)^2}{3} \frac{\hat{u}^2}{(\hat{s}-M_W^2)^2 + M_W^2\,\Gamma_W^2} \qquad ab = d\bar{u}, s\bar{u}, \bar{d}u, \bar{s}u$$

# SSA of lepton from W decay: rapidity dependence

- SSA of inclusive lepton is still sufficient for measurement:

Kang, Qiu, PRL 103, 172001 (2009)

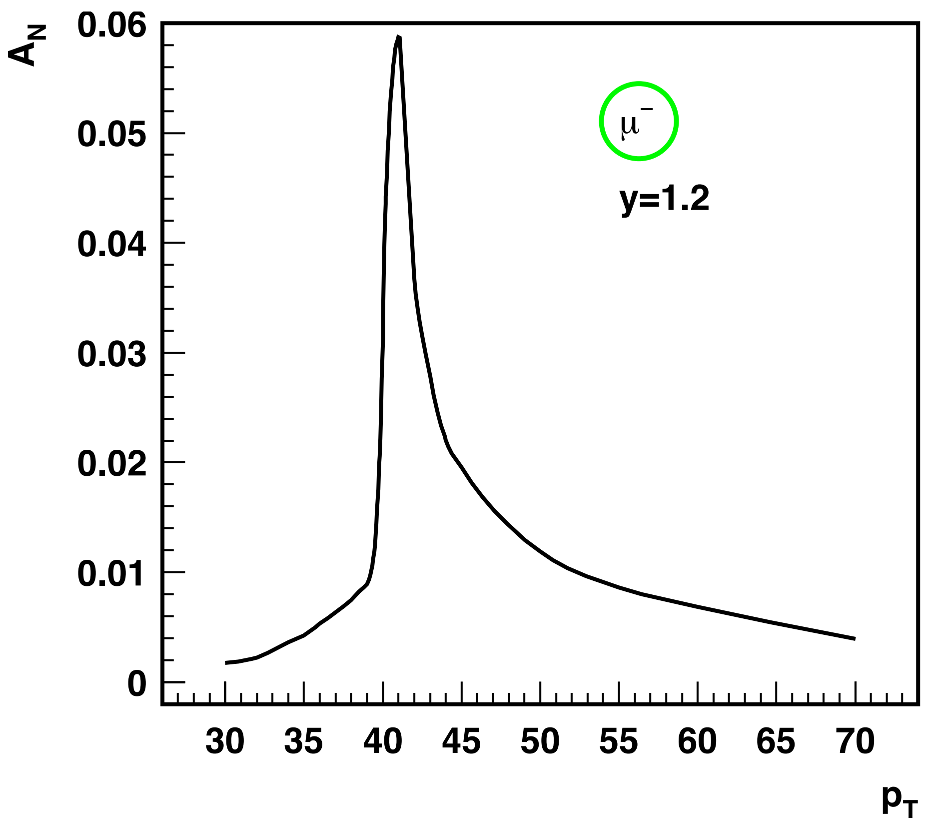


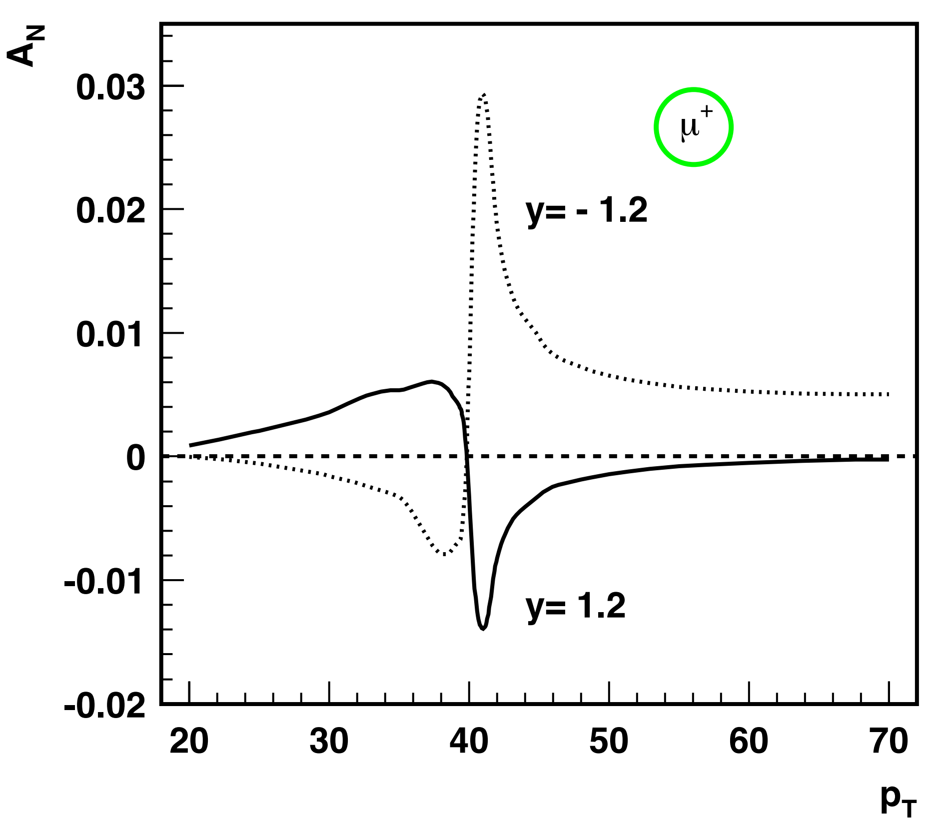




- Good flavor separation:
  - $\mu^-(e^-)$ at central-forward rapidity is sensitive to d Sivers function
  - $\mu+(e^+)$ at forward is sensitive to u Sivers function, at backward is sensitive to d-bar Sivers function

# SSA of lepton from W decay: $p_T$ dependence

- $p_T$ behavior of SSA of leptons:



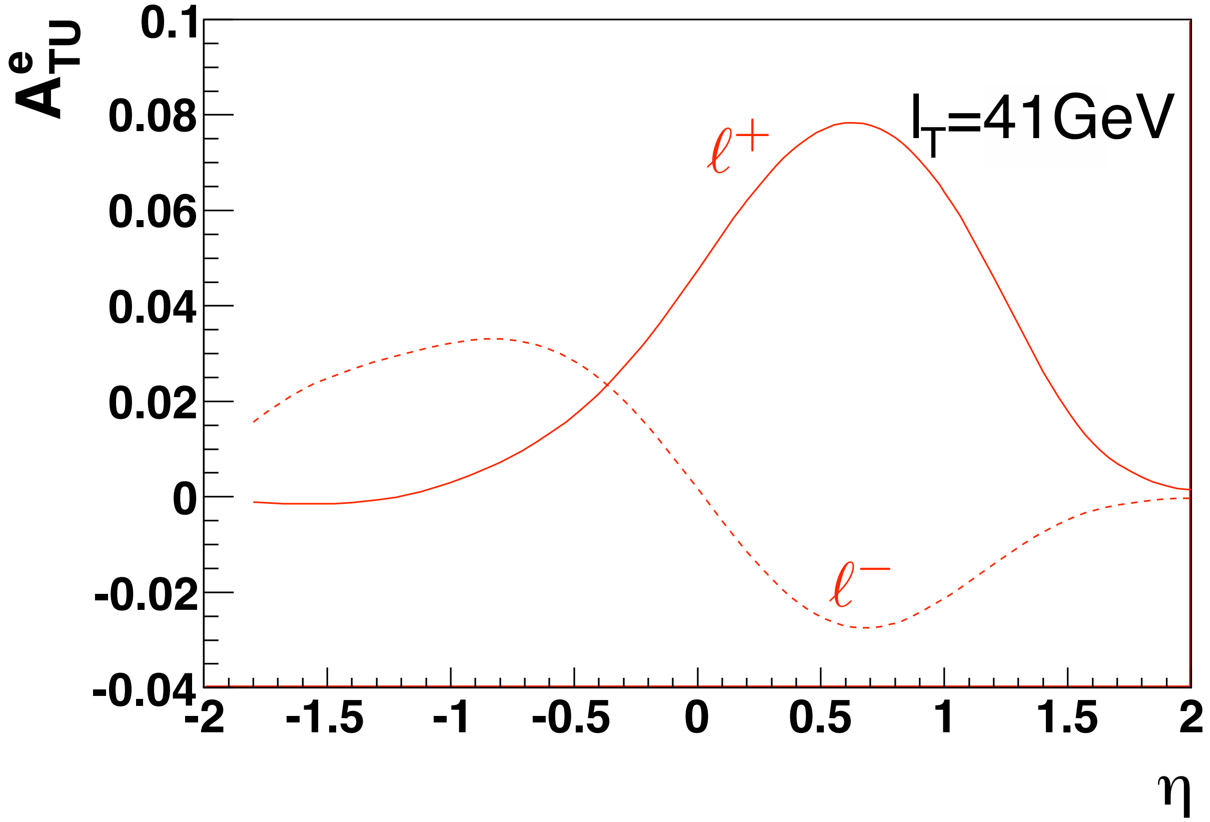



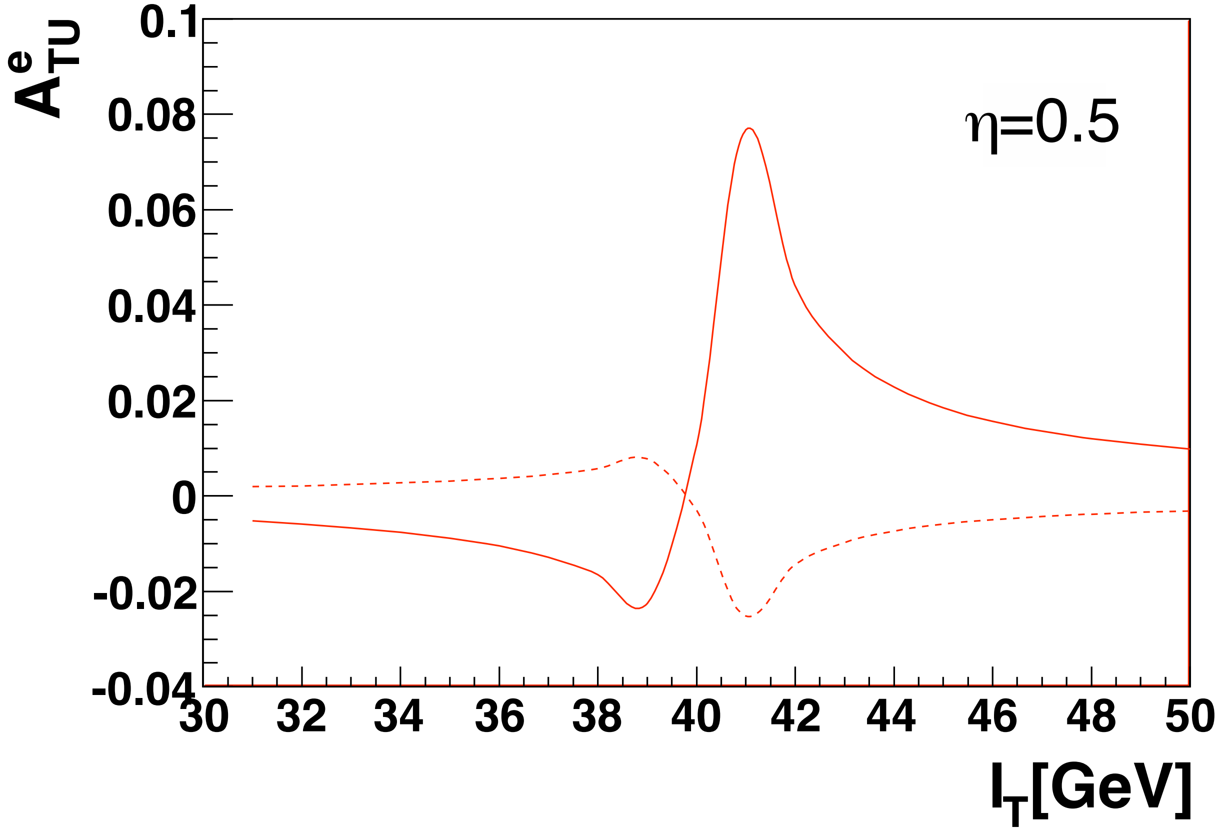

- inherit the key features of W asymmtry
- sharply peeked around $p_T \sim M_W/2$, should help control the potential background

# Another approach confirms our results

- Asymmetry of lepton decayed from W bosons

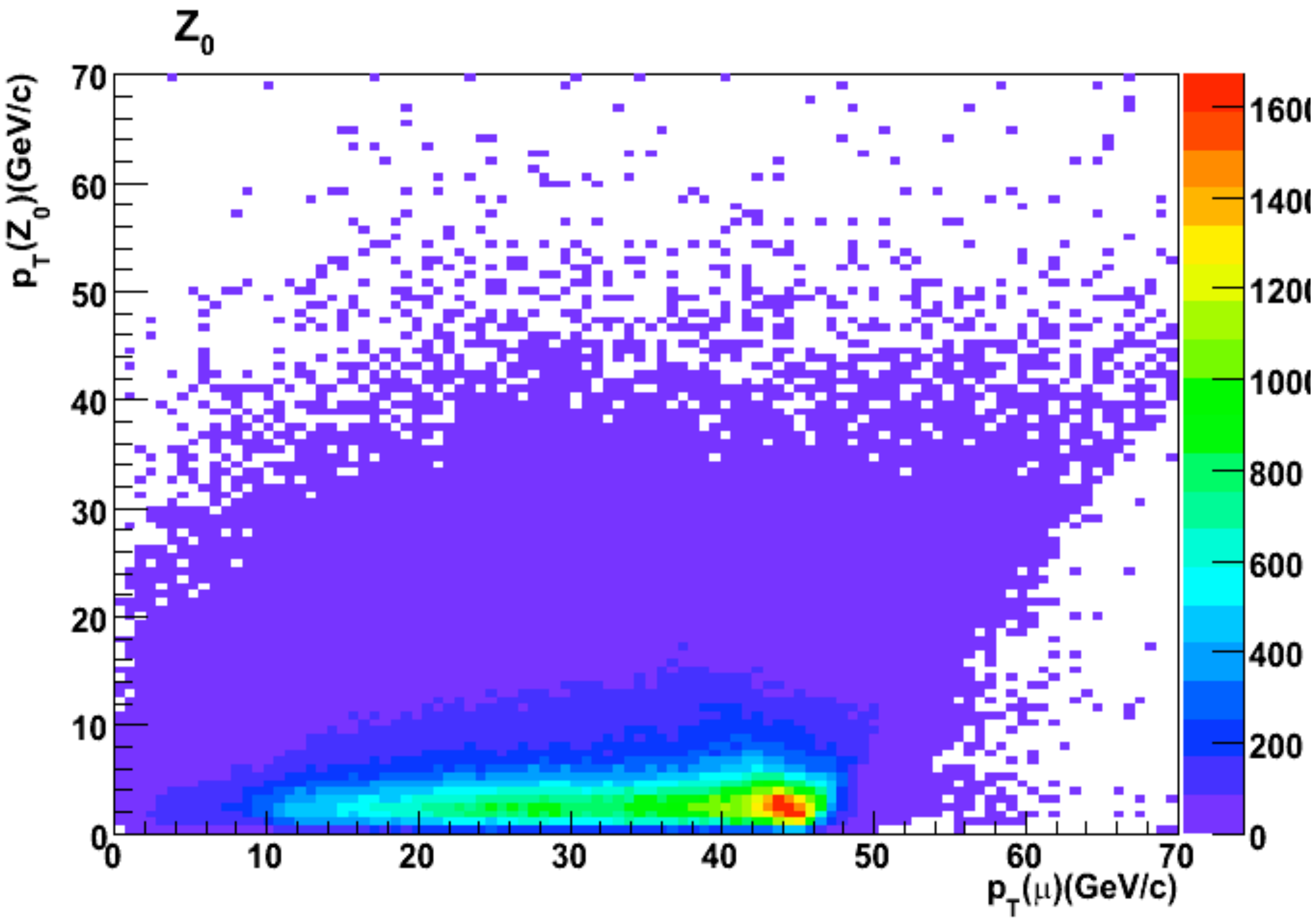
Metz, Zhou, 2010, arXiv:1006.3097



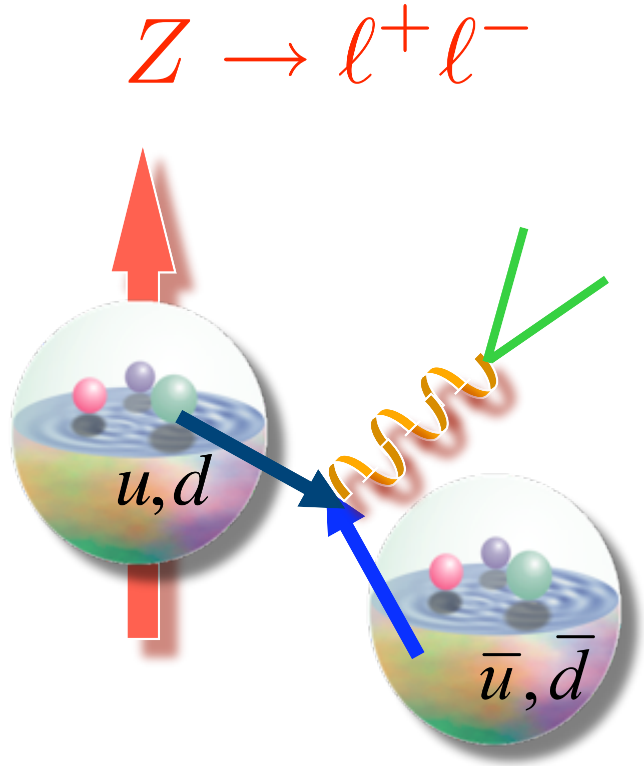



# What about Z boson?

- RHIC can reconstruct Z boson




Courtesy of Kempel, Lajoie (PHENIX)

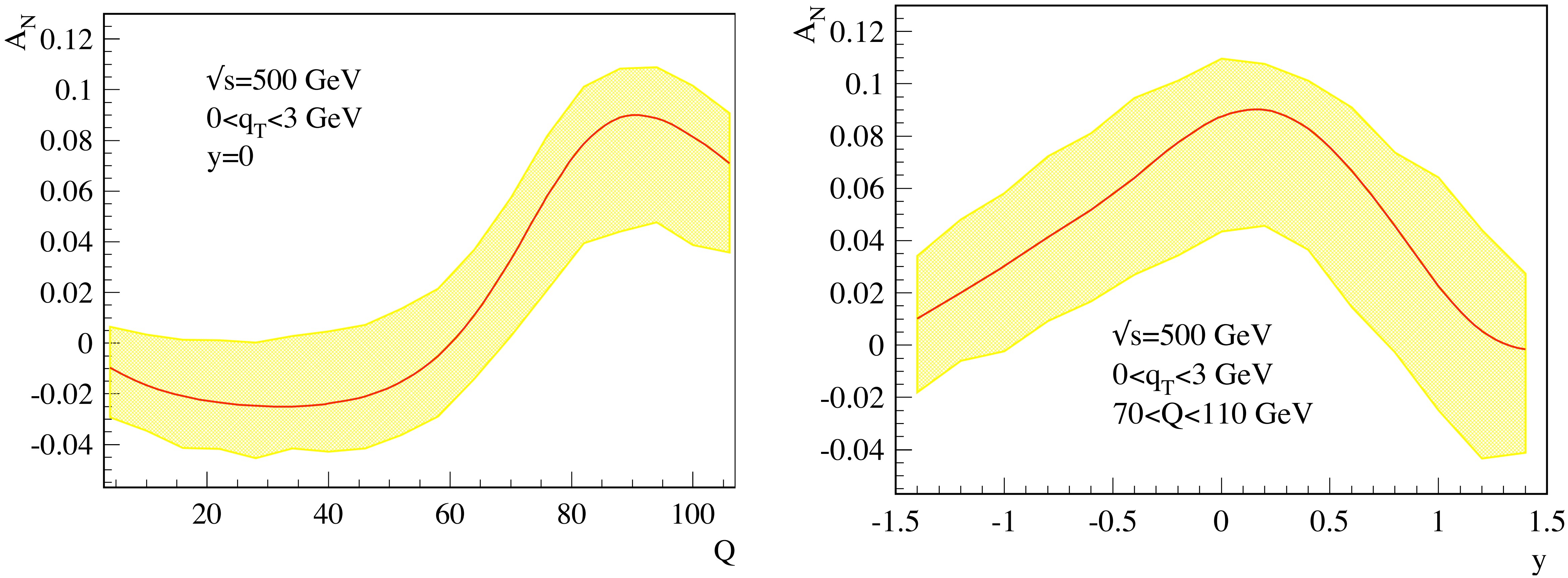



- Events down by an order of magnitude compared to W boson:
  - ~1000

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

- Prediction for RHIC kinematics: 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)




- Fairly large asymmetry, should be very good channel to test sign change if one can accumulate enough Z bosons

# Summary

- Sign change of Sivers function between DY and SIDIS is the most critical test for our current understanding of SSAs
- Besides the standard DY dilepton production, we propose to use the SSAs of W and/or Z boson production to test this sign change
- Lepton decayed from $W^+$, $W^-$ boson could give good flavor separation, give even separate tests for Sivers function of different flavors
- Z boson might also be a good channel if one could accumulate enough events

Thank you!