Single spin asymmetries in Semi-inclusive DIS

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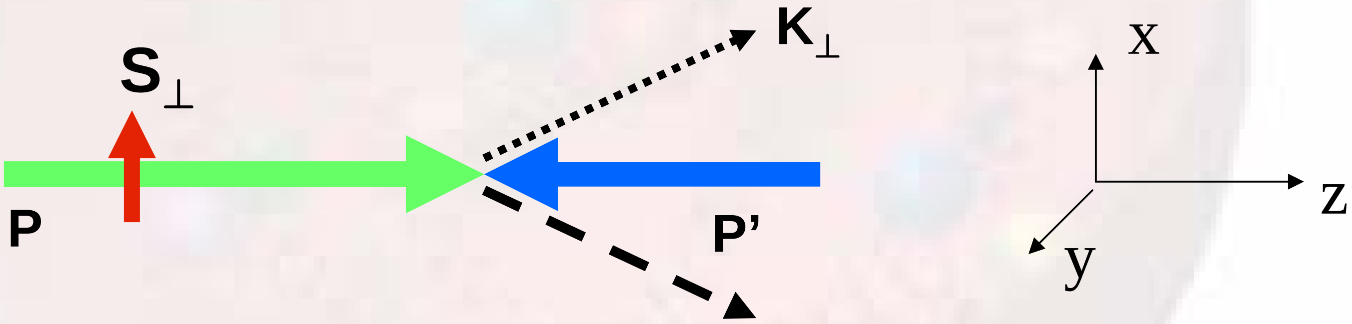
SPIN Workshop, JLab

Outline

- Introduction
  - Two mechanisms
  - Thanks to Mulders and Anselmino’s talks
- Recent developments in twist-three approach
- Unifying the two mechanisms
- Few remarks on the universality of parton distributions, global picture of SSAs
- Conclusion

What is Single Spin Asymmetry?

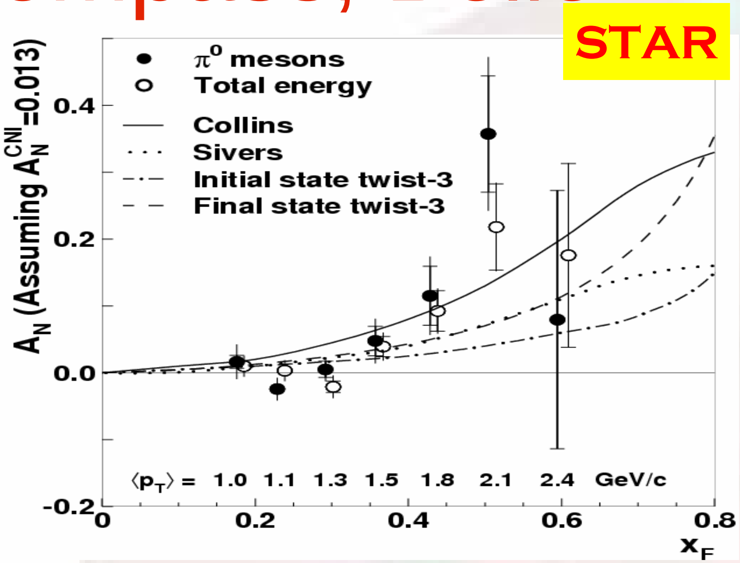
- Scattering a transverse spin polarized proton on unpolarized target (another hadron or a photon)

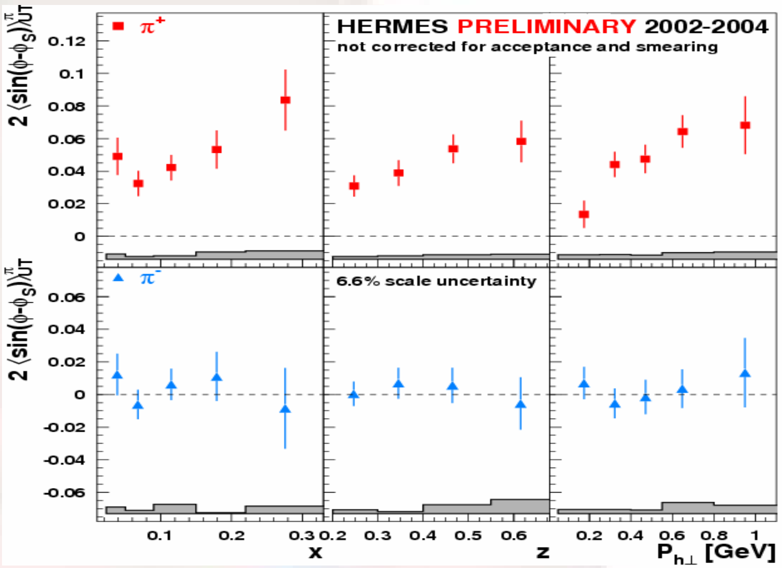


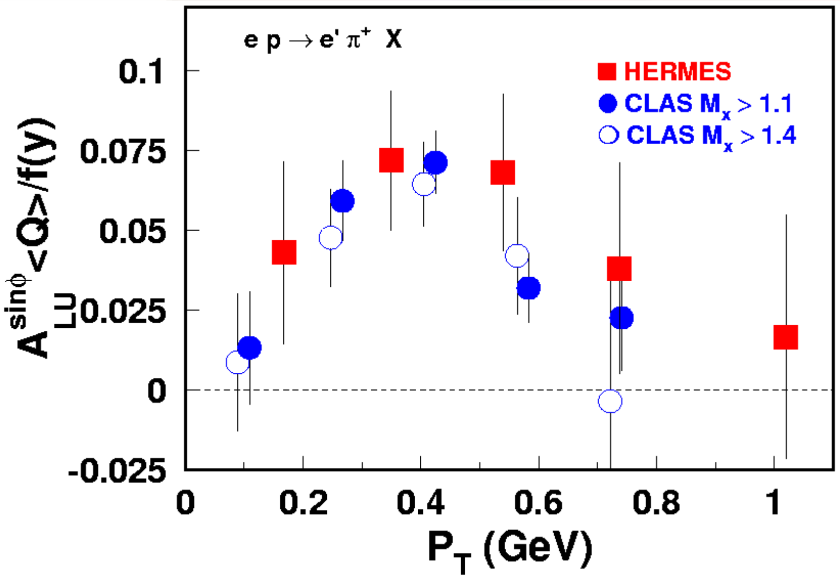
- the cross section contains a term

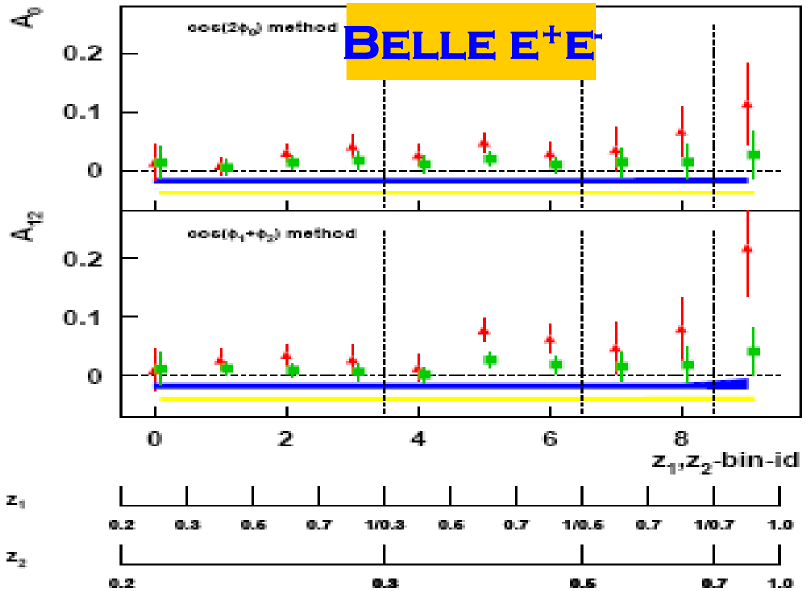
$$d\sigma \propto \vec{S} \cdot (\vec{p} \times \vec{K}_\perp)$$

Recent results: RHIC, JLab, HERMES, Compass, Belle









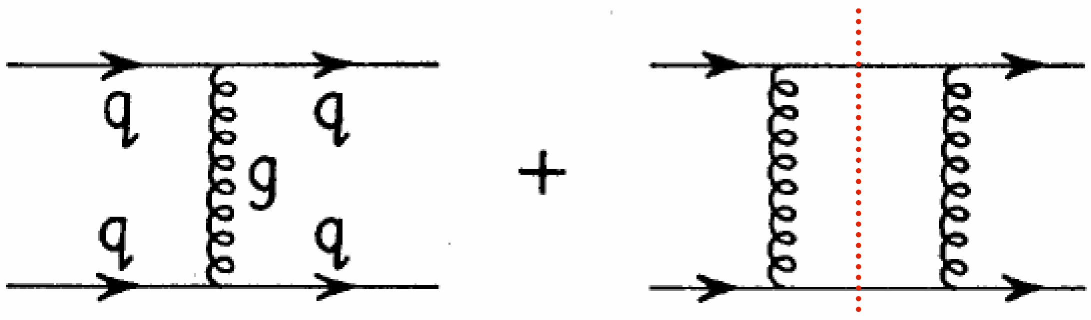
Why Does SSA Exist?

- **Single Spin Asymmetry requires**
  - **Helicity flip**: one must have a reaction mechanism for the hadron to change its helicity (in a cut diagram)
  - **Final State Interactions (FSI):** to generate a phase difference between two amplitudes

    The phase difference is needed because the structure $S \cdot (p \times k)$ violate the naïve time-reversal invariance

What theorists came about

- Kane et al., 1978

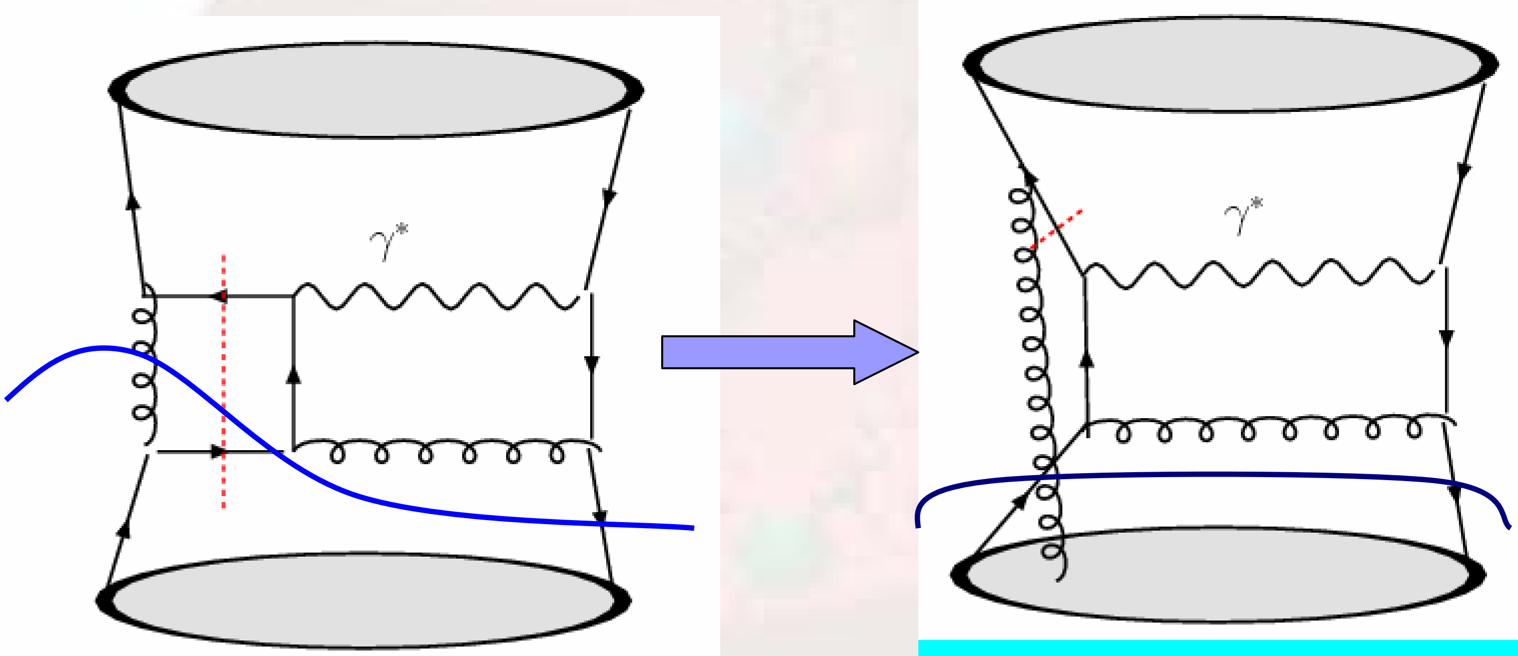


$\propto \alpha_s m_q / Q$

- We have to go beyond this naïve picture

Take Drell-Yan as an example

- We need a loop to generate a phase



Kane et al., hard parton model

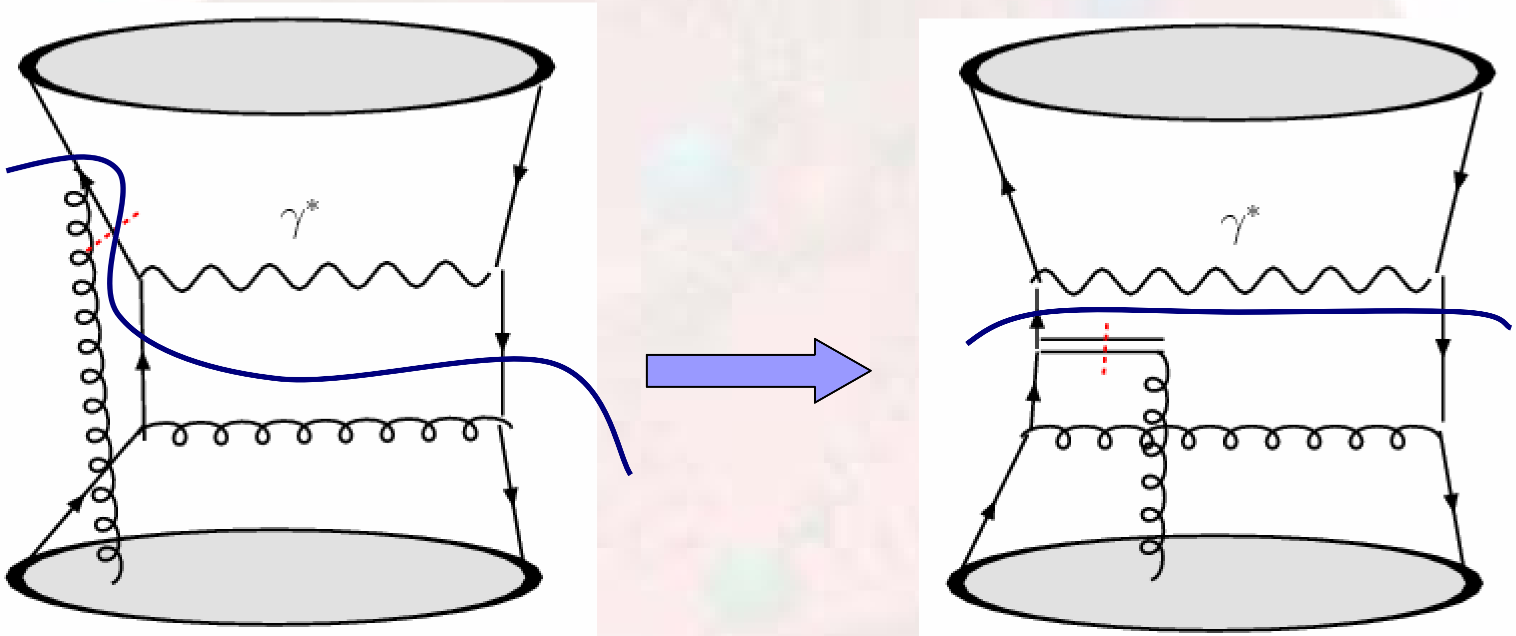
Twist-three Correlations

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

Courtesy from Vogelsang

Further factorization

- Factorize the collinear gluons



Twist-three Correlations

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

TMD distributions

- Sivers, 90, Collins, 93
- Brodsky-Hwang-Schmidt,02
- Ji-Qiu-Vogelsang-Yuan,06

Two Mechanisms in QCD

- Transverse Momentum Dependent (TMD) Parton Distributions and Fragmentations
    - Sivers function, Sivers 90
    - Collins function, Collins 93
    - Gauge invariant definition of the TMDs: Brodsky, Hwang, Schmidt 02; Collins 02 ; Belitsky, Ji, Yuan 02; Boer, Mulders, Pijlman, 03
    - The QCD factorization: Ji, Ma, Yuan, 04; Collins, Metz, 04
- Twist-three Correlations (collinear factorization)
    - Efremov-Teryaev, 82, 84
    - Qiu-Sterman, 91,98
    - Kouvaris,Qiu,Vogelsang,Yuan, 06

Territories

- Twist-three: the single inclusive hadron production in pp, require large $P_\perp$, SSA is suppressed by $1/P_t$
- TMD: low $P_\perp$, require additional hard scale like Q^2 in DIS and Drell-Yan, $P_\perp \ll Q$, SSA survives in Bjorken limit
- Overlap: $\Lambda_{QCD} \ll P_t \ll Q$, unifying these two

Recent theoretical developments (twist-three)

- Complete formalism for single inclusive hadron production in pp collision has been derived, including the derivative and non-derivative terms

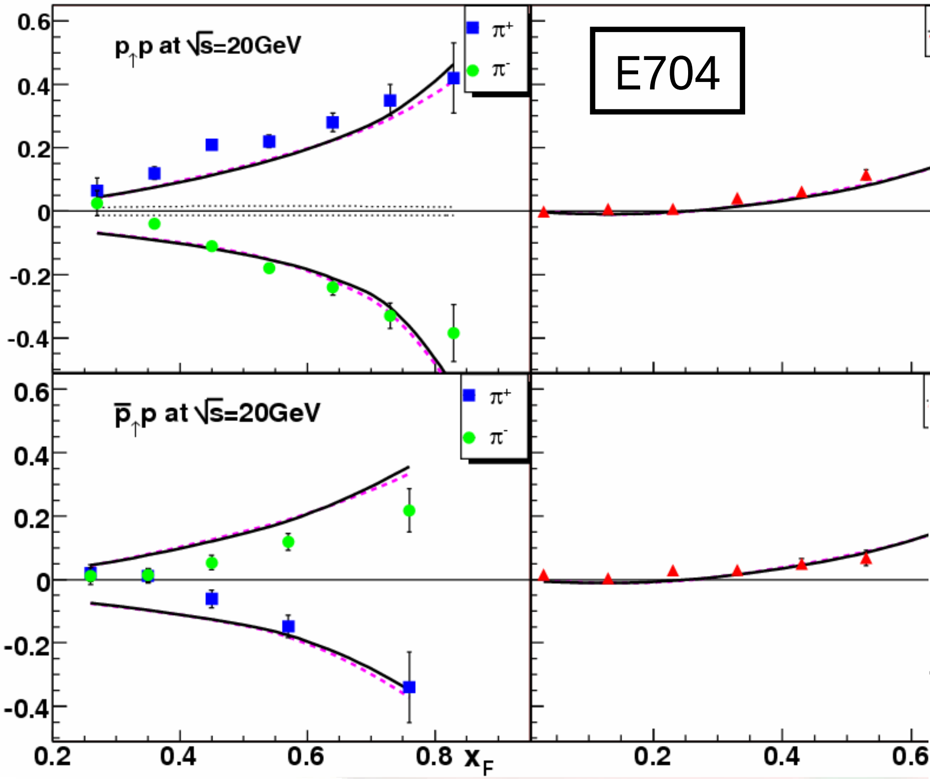
$$E_\ell \frac{d^3\Delta\sigma(\vec{s}_T)}{d^3\ell} = \frac{\alpha_s^2}{S}\sum_{a,b,c}\int_{z_{\min}}^{1}\frac{dz}{z^2}D_{c\to h}(z)\int_{x'_{\min}}^{1}\frac{dx'}{x'}\frac{1}{x'S+T/z}\phi_{b/B}(x')$$

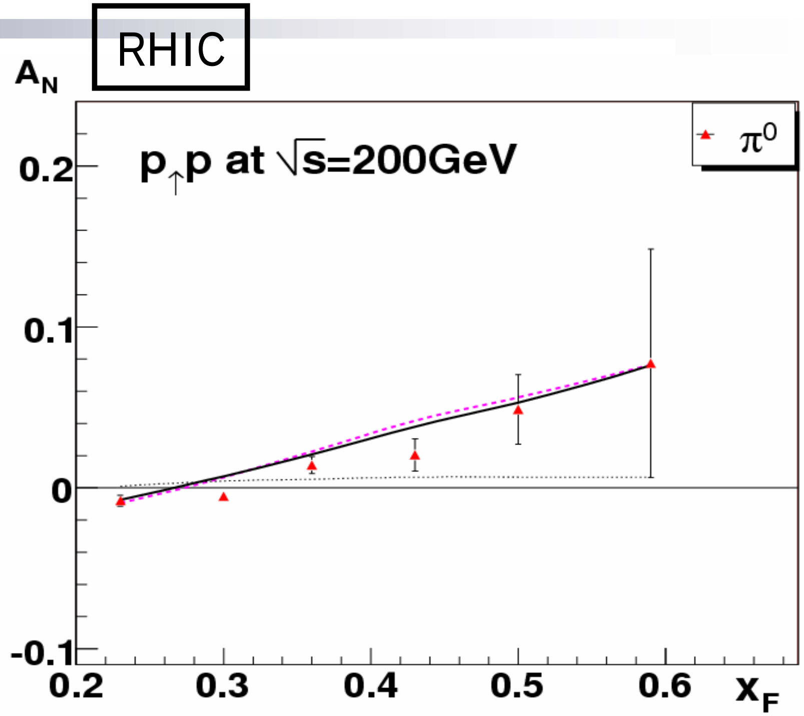
$$\times\sqrt{4\pi\alpha_s}\left(\frac{\epsilon^{\ell s_T n\bar{n}}}{z\hat{u}}\right)\frac{1}{x}\left[T_{a,F}(x,x)-x\left(\frac{d}{dx}T_{a,F}(x,x)\right)\right]H_{ab\to c}(\hat{s},\hat{t},\hat{u})$$

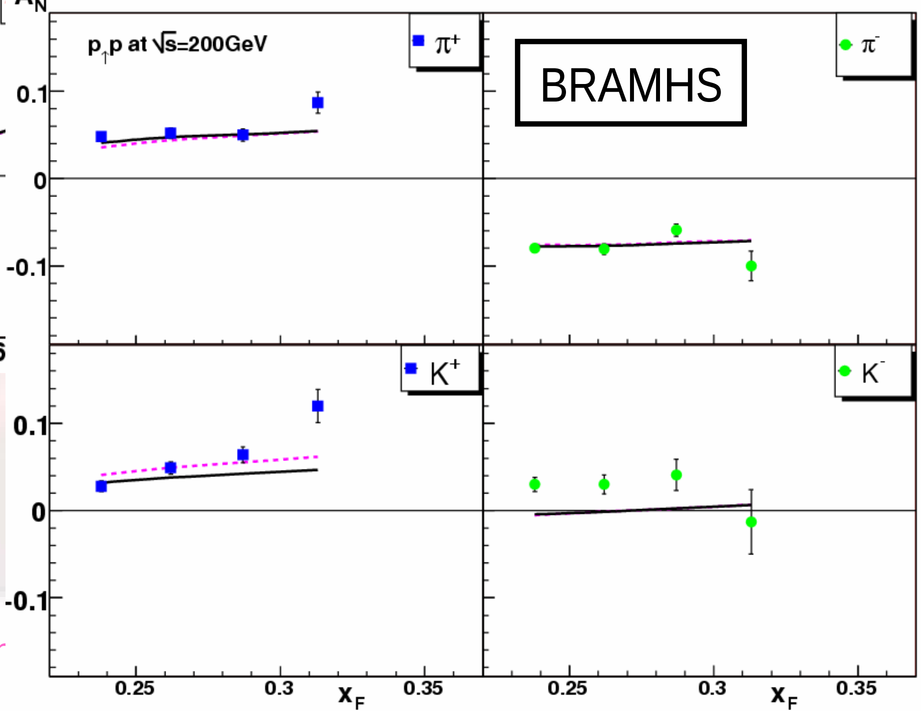
Qiu, Sterman, 91, 98
Kouvaris,Qiu,Vogelsang,Yuan, 06

Twist-3 Fit to data

$$p_{\uparrow}p \rightarrow \pi + X$$





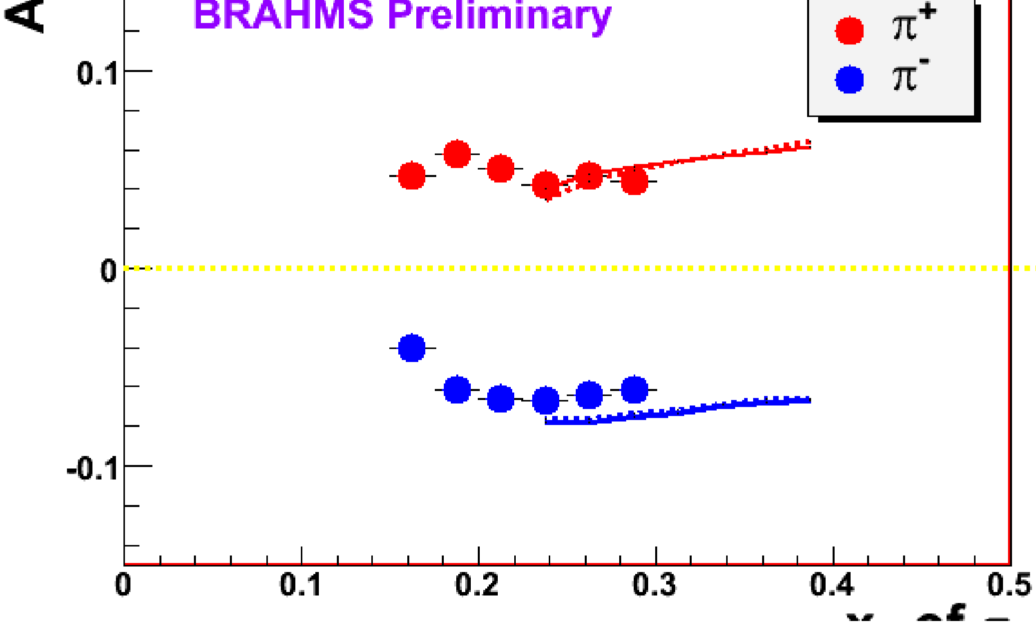


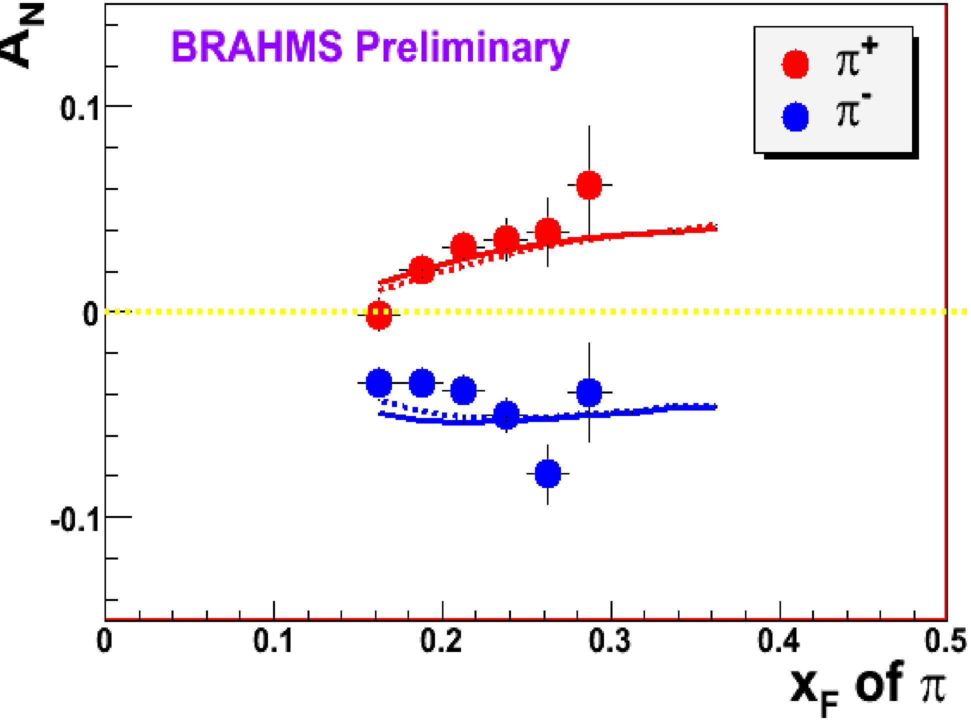
$$T_F^a(x) = N_a x^{\alpha_a}(1-x)^{\beta_a} f_a(x)$$

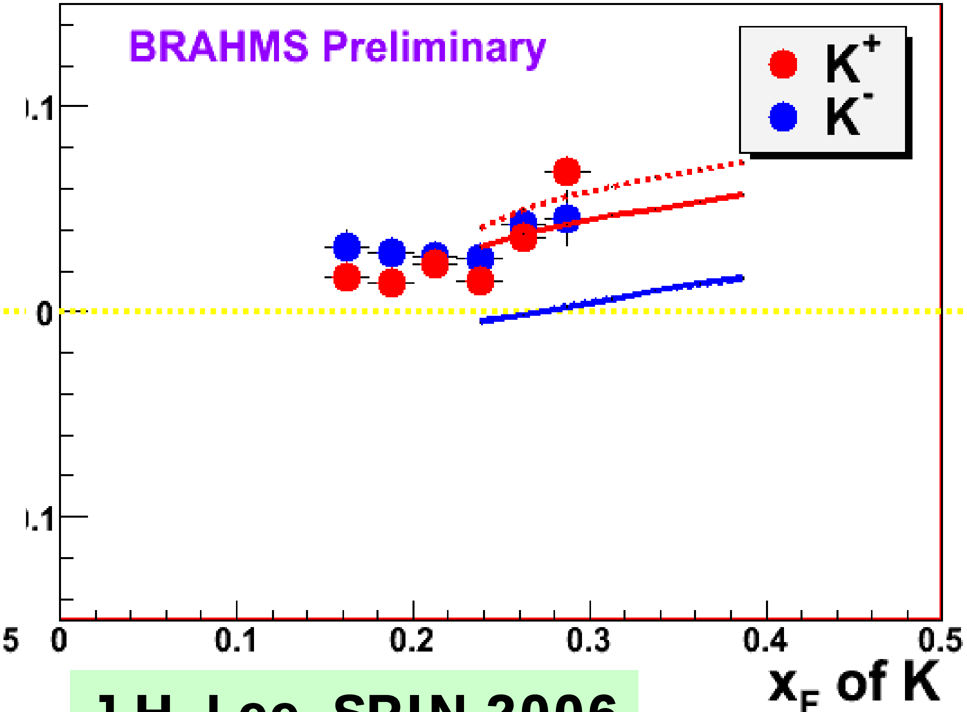
Kouvaris,Qiu,Vogelsang,Yuan, 06

See also the fit by Anselmino et al

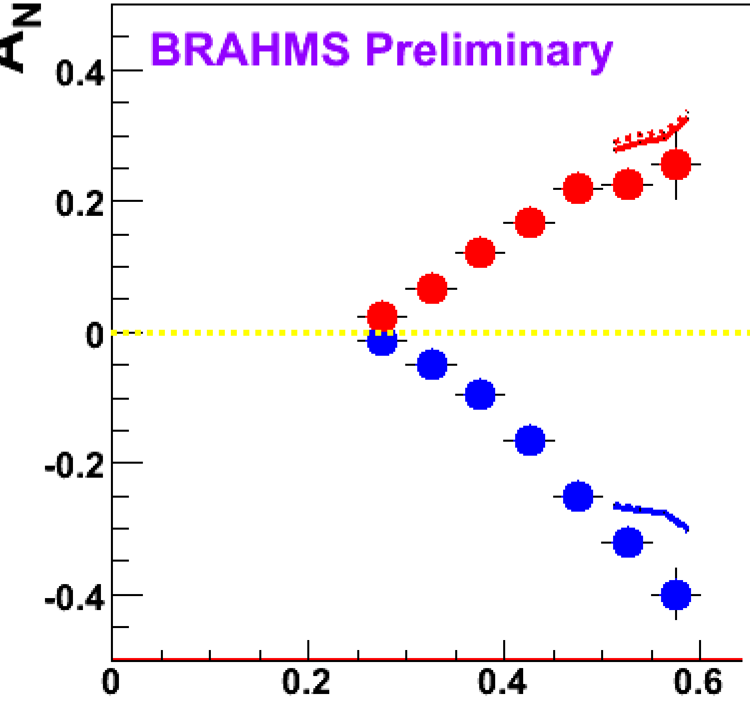
Compare to 2006 data from RHIC



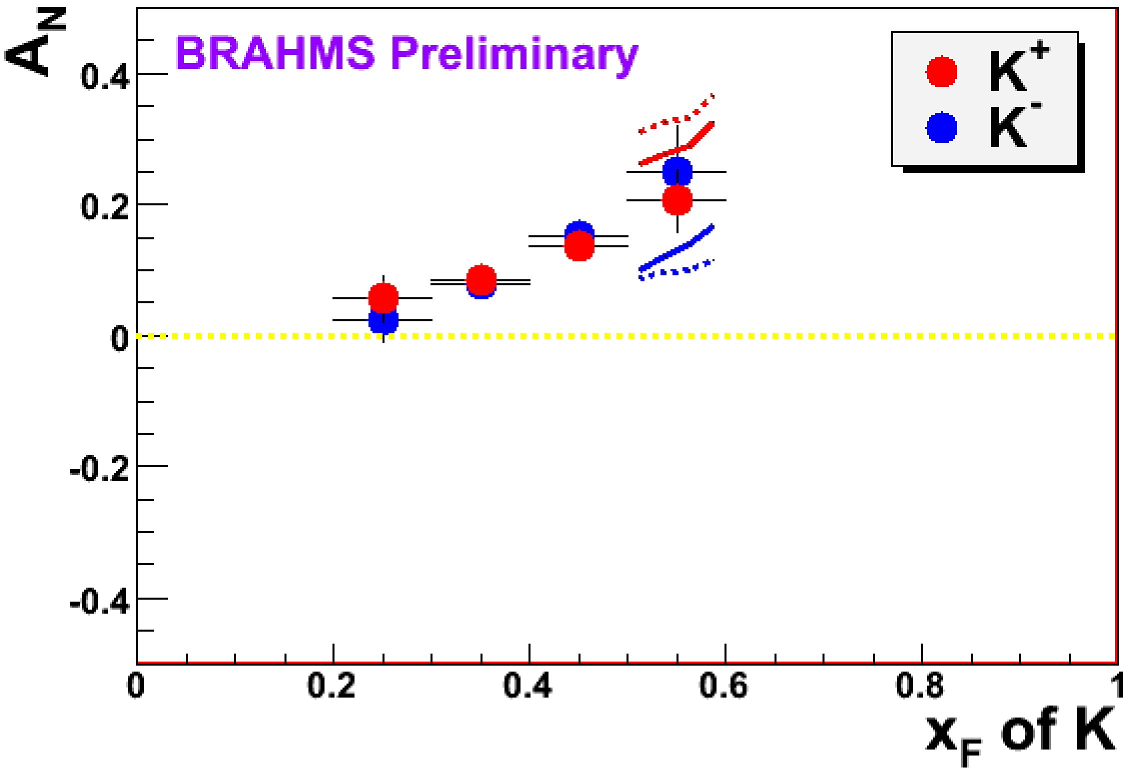




J.H. Lee, SPIN 2006


BRAHMS Preliminary
π^+
π^-
A_N
0.4
0.2
0
-0.2
-0.4
0
0.2
0.4
0.6

$$\sqrt{s} = 62GeV$$


BRAHMS Preliminary
K^+
K^-
A_N
0.4
0.2
0
-0.2
-0.4
0
0.2
0.4
0.6
0.8
1
x_F of K

Unification of the two mechanisms

- Twist-three: the single inclusive hadron production in pp, require large $P_\perp$

  TMD: low $P_\perp$, require additional hard scale like Q^2 in DIS and Drell-Yan, $P_\perp \ll Q$
- Connecting these two, at the matrix elements level

$$T_F(x,x)=\int d^2k\,|k|^2\, q_T(x,k)$$

Qiu-Sterman

Sivers

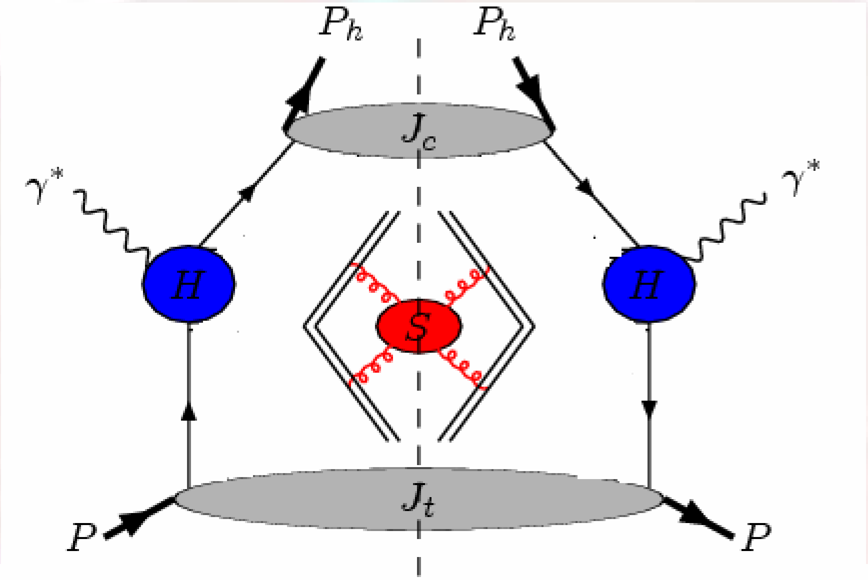
  - Boer, Mulders, Pijlman 03

Unifying the Two Mechanisms ($P_\perp$ dependence of SSAs)

- At low $P_\perp$, the non-perturbative TMD Sivers function will be responsible for its SSA
- When $P_\perp \sim$ Q, purely twist-3 contributions
- For intermediate $P_\perp$, $\Lambda_{QCD} \ll P_\perp \ll Q$, we should see the transition between these two
- *An important issue, at $P_\perp \ll Q$, these two should merge, showing consistence of the theory*

(Ji, Qiu, Vogelsang, Yuan, PRL97, 082002;PRD73,094017; PLB638,178, 2006)

Recall the TMD Factorization



$$F_{UT}(x_B, z_h, P_{h\perp}, \varphi\ )$$

$$= \sum_{q=u,d,s,\ldots} e_q^2 \int d^2\vec{k}_\perp d^2\vec{p}_\perp d^2\vec{\ell}_\perp \frac{\vec{k}_\perp \cdot \vec{P}_{h\perp}}{|P_{h\perp}|}$$

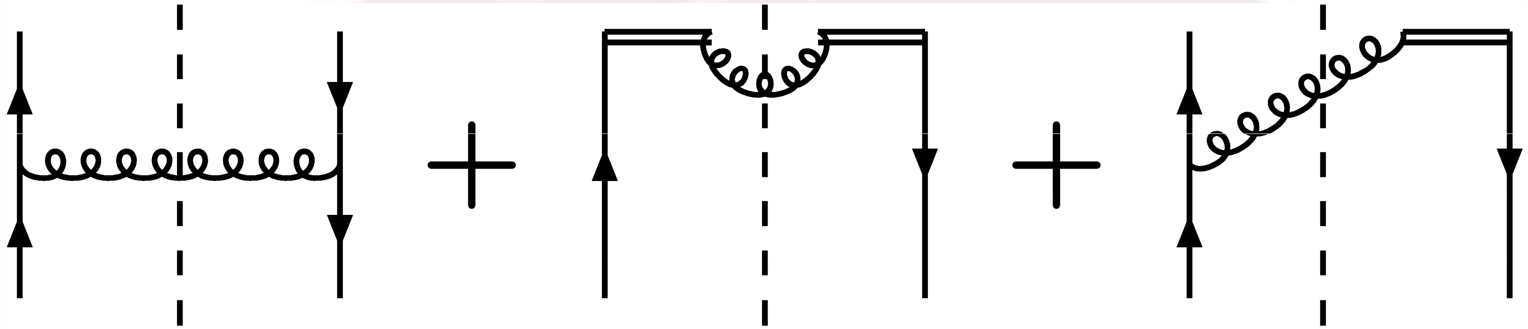
$$\times\, q_T\left(x_B, k_\perp, \mu^2, x_B\zeta, \rho\right)\hat{q}_h\left(z_h, p_\perp, \mu^2, \hat{\zeta}/z_h, \rho\right) S(\vec{\lambda}_\perp, \mu^2, \rho)$$

$$\times\, H\left(Q^2, \mu^2, \rho\right) \delta^2(z_h\vec{k}_\perp + \vec{p}_\perp + \vec{\lambda}_\perp - \vec{P}_{h\perp})$$

SIDIS: at Large $P_\perp$

- When $q_\perp \gg \Lambda_{QCD}$, the P_t dependence of the TMD parton distribution and fragmentation functions can be calculated from pQCD, because of hard gluon radiation

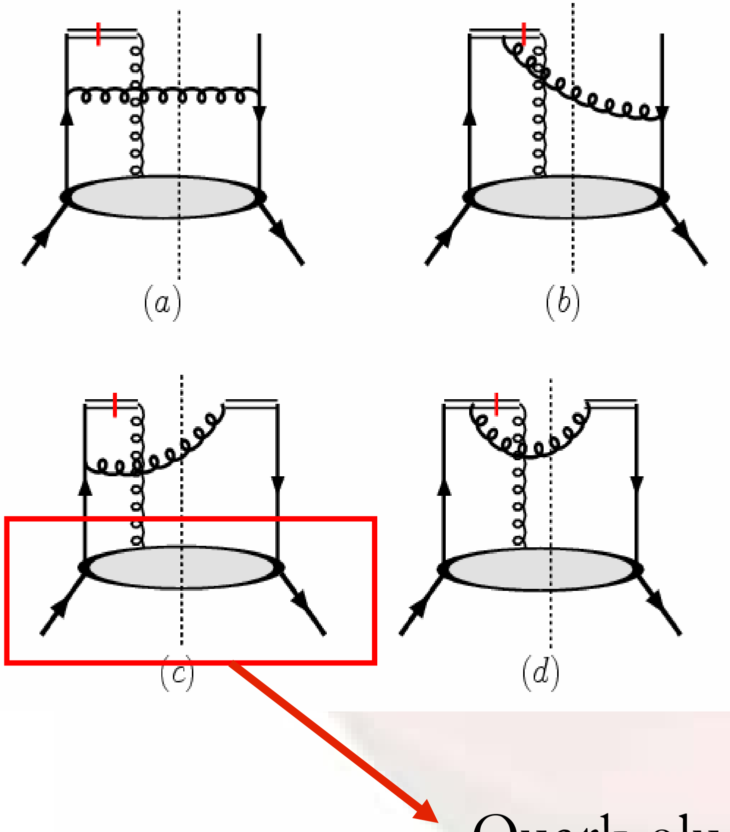
Fragmentation function at $p_\perp \gg \Lambda_{QCD}$

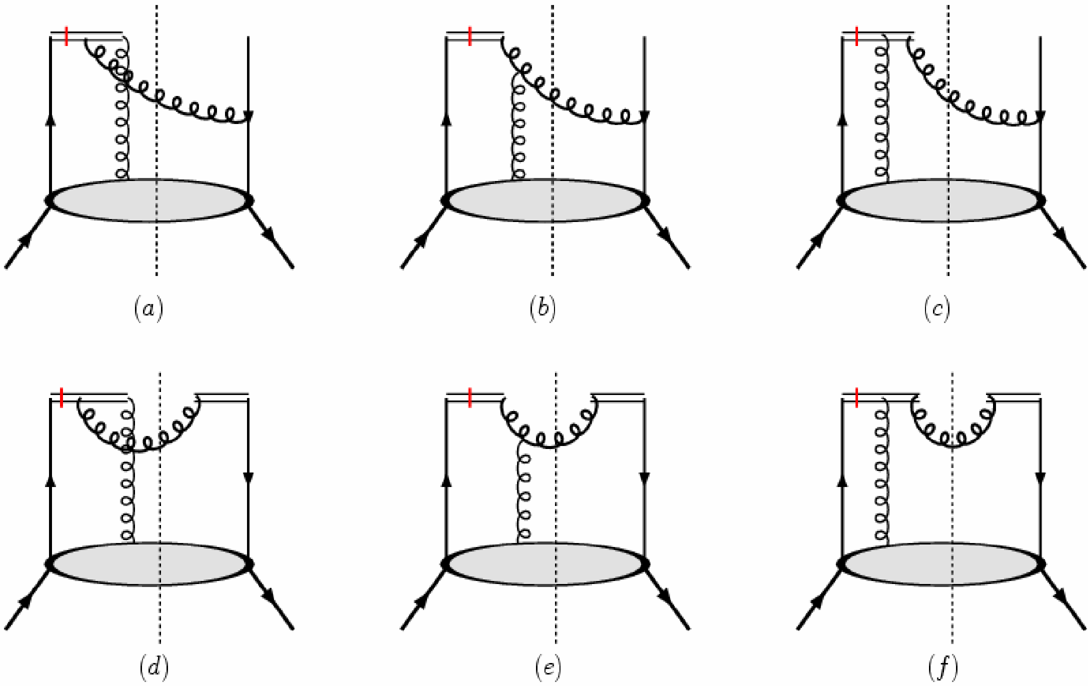


$$\hat{q}(z_h, p_\perp) = \frac{\alpha_s}{2\pi^2}\frac{1}{\vec{p}_\perp^{\,2}} C_F \int \frac{dz}{z}\hat{q}(z) \times \left[\frac{1+\hat{\xi}^2}{(1-\hat{\xi})_+} + \delta(\hat{\xi}-1)\left(\ln\frac{\hat{\zeta}^2}{\vec{p}_\perp^{\,2}} - 1\right)\right]$$

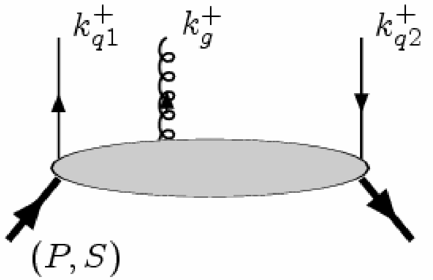
See, e.g., Ji, Ma, Yuan, 04

Sivers Function at large $k_\perp$





Quark-gluon Correlation



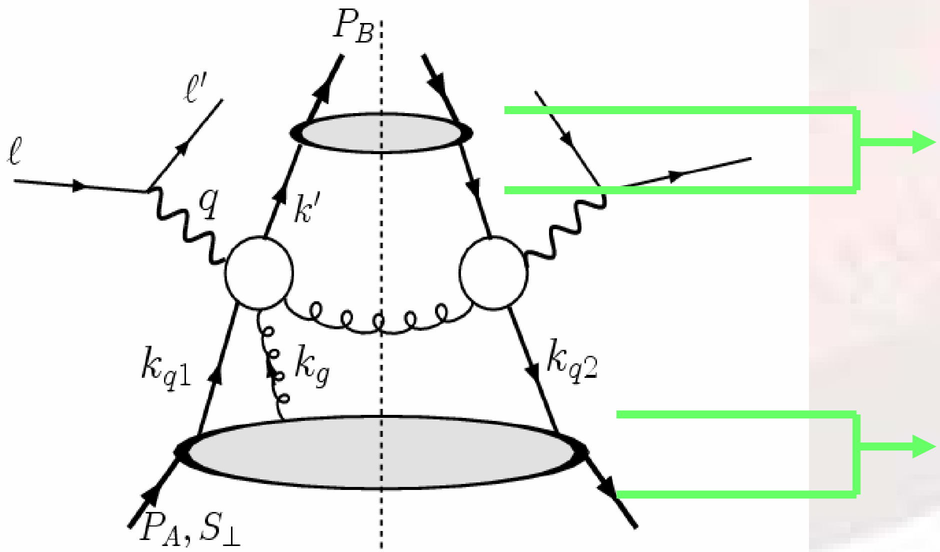
Qiu, Sterman, 91,99

Sivers Function at Large $k_\perp$

$$\begin{aligned} q_T(x, k_\perp) \;&=\; -\frac{\alpha_s}{4\pi^2}\frac{2M_p}{(k_\perp^2)^2}\int\frac{dx}{x}\{A + C_F T_F(x) \\ &\quad \times \delta(\xi - 1)\left(\ln \zeta^2/\vec{k}_\perp^2 - 1\right)\} \end{aligned}$$

- $1/k_\perp{}^4$ follows a power counting
- Drell-Yan Sivers function has opposite sign

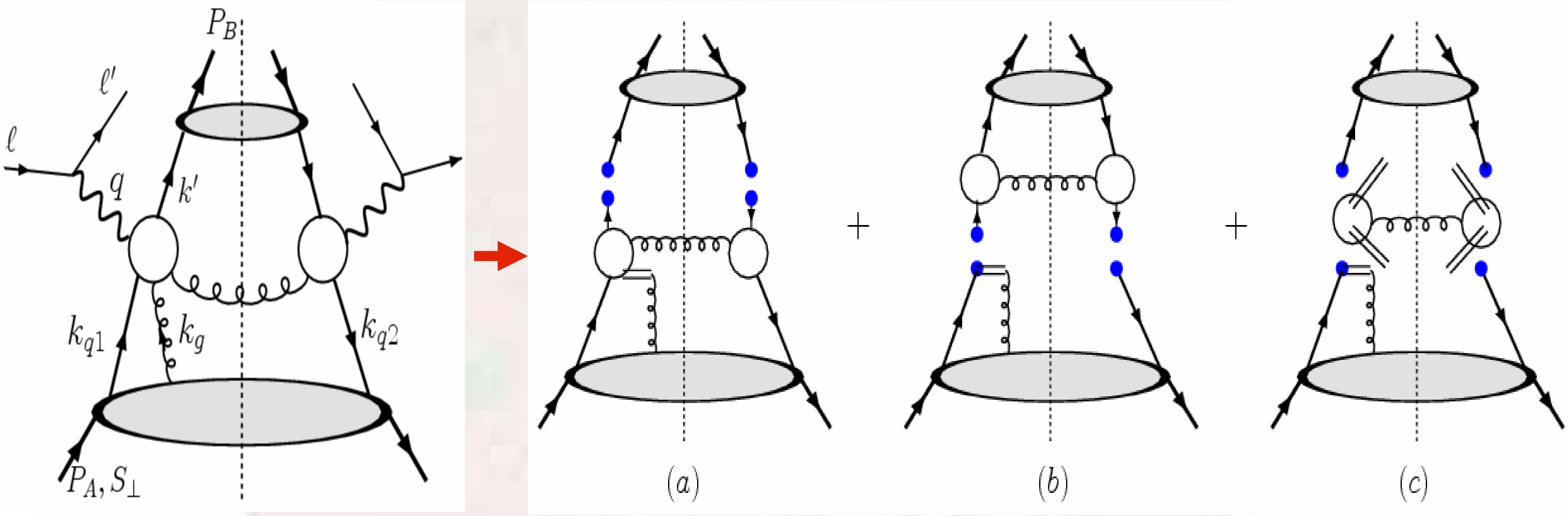
- Plugging this into the factorization formula, we indeed reproduce the polarized cross section calculated from twist-3 correlation



Fragmentation function: \hat q(x')

Twist-3 quark-gluon Correlation: $T_F(x_1,x_2)$

Factorization guidelines



Reduced diagrams for different regions of the gluon momentum: along P direction, P’, and soft

Collins-Soper 81

Final Results

- $P_\perp$ dependence

$$\frac{d\triangle\sigma}{d^2q_\perp dy} = \int q_T(z_1,k_\perp)\bar{q}(z_2,k_\perp) + \left(\frac{d\triangle\sigma^{QS}}{d^2q_\perp dy} - \frac{d\triangle\sigma^{QS}}{d^2q_\perp dy}|_{aspt.}\right)$$

Sivers function at low $P_\perp$

Qiu-Sterman Twist-three

- Which is valid for all $P_\perp$ range
- SSA is suppressed by $1/P_t$ at large P_t

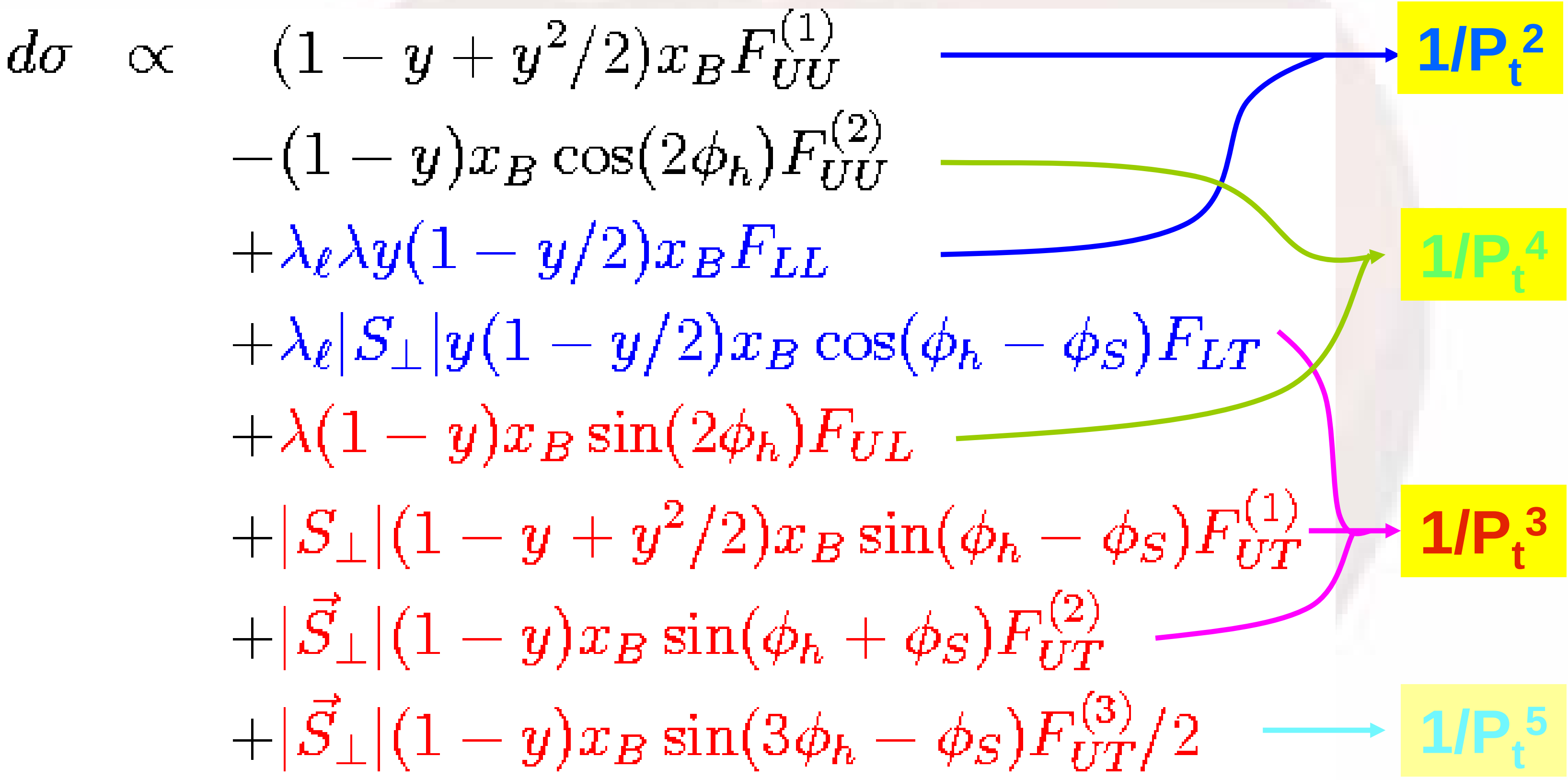
Extend to all other TMDs: large P_t power counting

- k_t-even distributions have the same dependence on k_t
- k_t-odd distributions are suppressed at large k_t
- Power Counting Rule

k_t-even: $1/k_t^2$

k_t-odd: $1/k_t^4$

SIDIS cross sections at large P_t



$$\begin{aligned} d\sigma \quad \propto \quad & (1-y+y^2/2)x_B F_{UU}^{(1)} \\ & -(1-y)x_B\cos(2\phi_h)F_{UU}^{(2)} \\ & +\lambda_\ell \lambda y(1-y/2)x_B F_{LL} \\ & +\lambda_\ell |S_\perp| y(1-y/2)x_B \cos(\phi_h-\phi_S)F_{LT} \\ & +\lambda(1-y)x_B \sin(2\phi_h)F_{UL} \\ & +|S_\perp|(1-y+y^2/2)x_B \sin(\phi_h-\phi_S)F_{UT}^{(1)} \\ & +|\vec{S}_\perp|(1-y)x_B \sin(\phi_h+\phi_S)F_{UT}^{(2)} \\ & +|\vec{S}_\perp|(1-y)x_B \sin(3\phi_h-\phi_S)F_{UT}^{(3)}/2 \end{aligned}$$

$1/P_t^2$

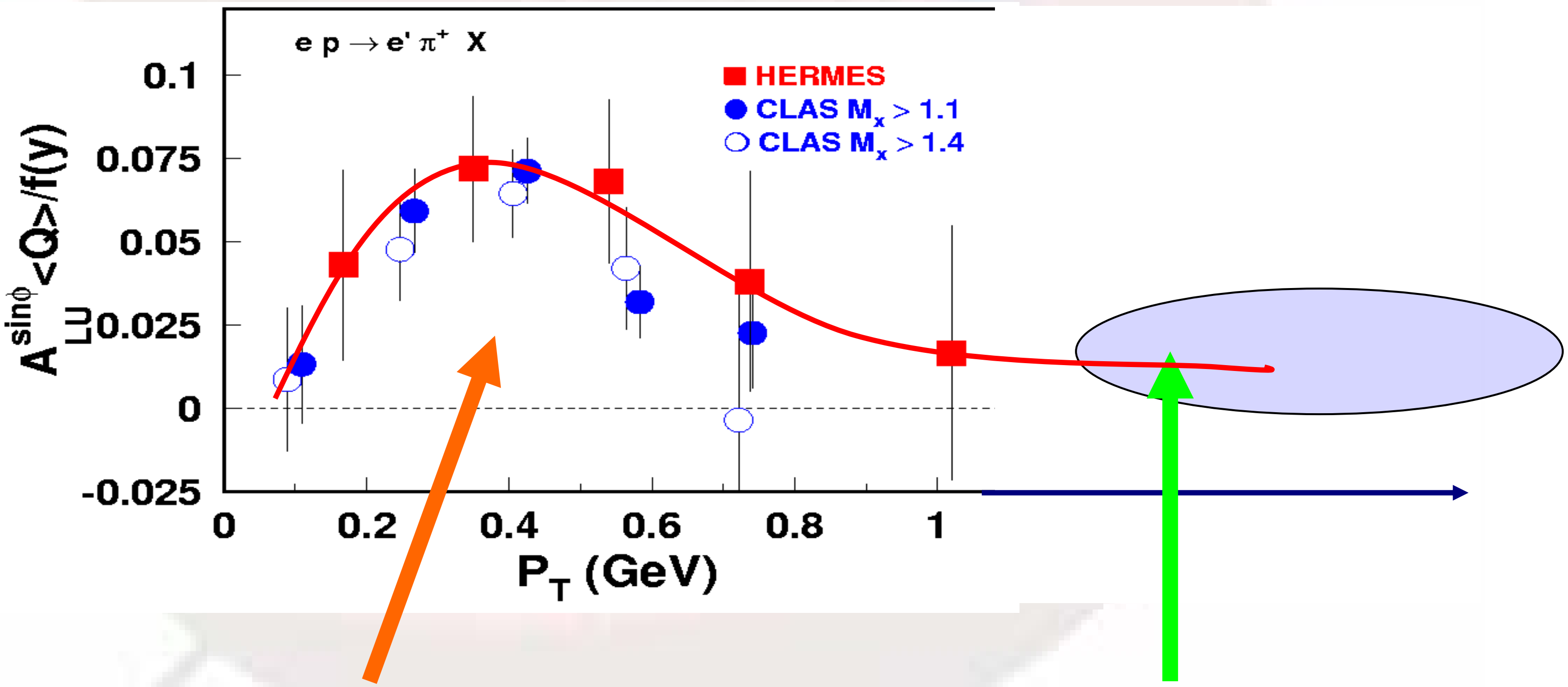
$1/P_t^4$

$1/P_t^3$

$1/P_t^5$

Transition from Perturbative region to Nonperturbative region?

- Compare different region of $P_\perp$



Nonperturbative TMD

Perturbative region

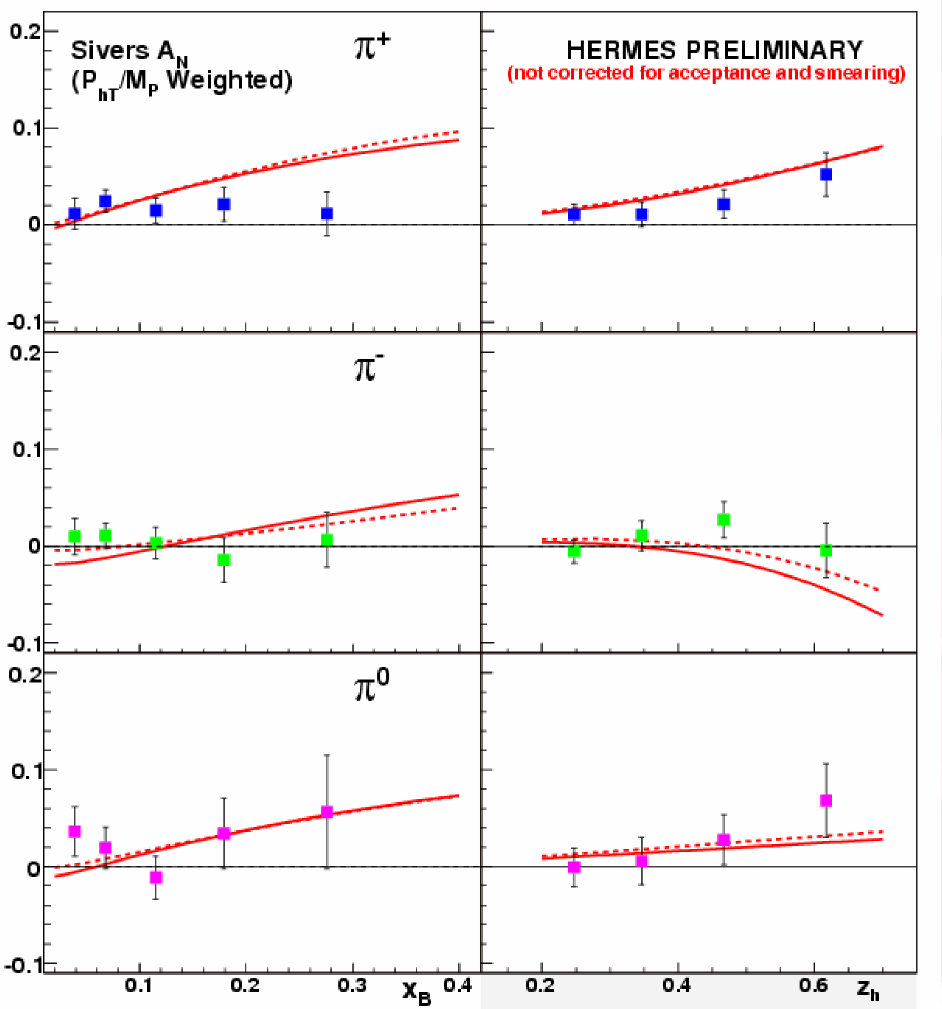
More over

- At low $P_\perp \ll Q$, the second term vanishes, use the Sivers function only
- $P_\perp$-moment of the asymmetry can be calculated from twist-three matrix element
  - In SIDIS, for the Sivers asymmetry

$$2\langle \frac{P_{h\perp}}{M_P}\sin(\phi_h-\phi_S)\rangle = \frac{\int \frac{1}{Q^4}(1-y+\frac{y^2}{2})\frac{z_h}{M_P}x_B \boxed{g_s T_F(x_B)} D(z_h)}{\int \frac{1}{Q^4}(1-y+\frac{y^2}{2})x_B f_q(x_B) D(z_h)}$$

Boer-Mulders-Tangelmann, 96,98

Compare to the HERMES data

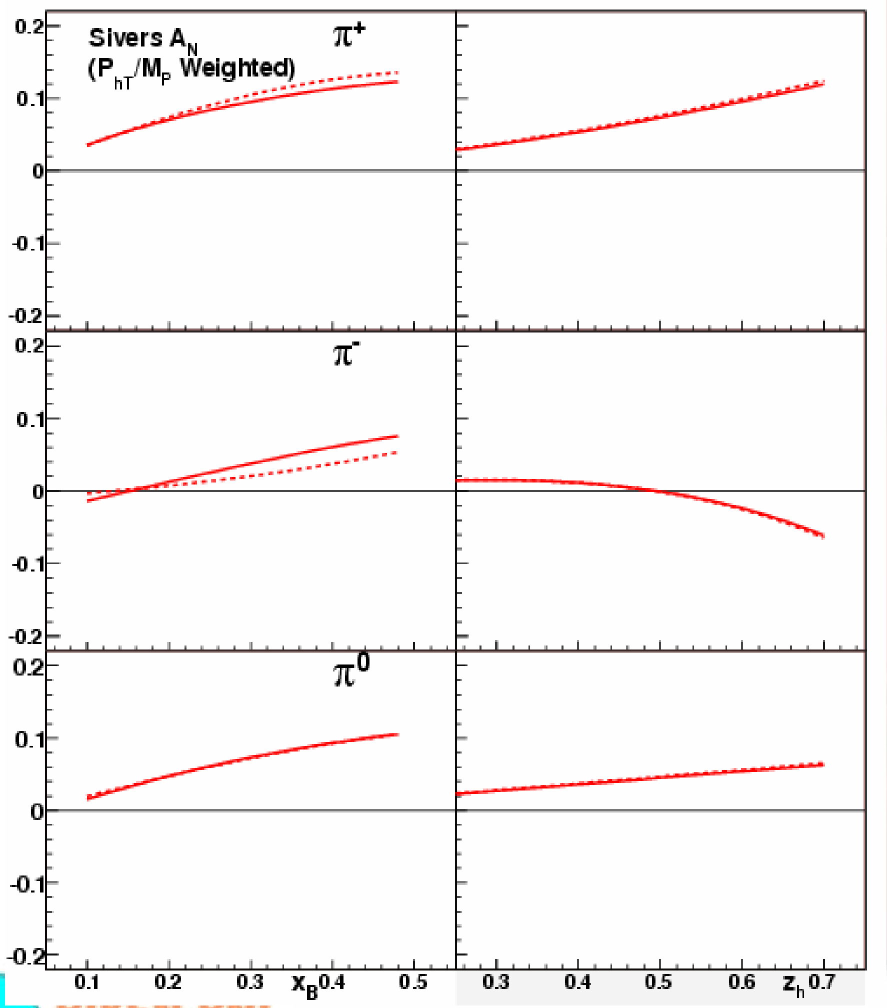


- T_F from the fit to single inclusive hadron data
  - Kouvaris-Qiu-Vogelsang-Yuan, hep-ph/0609238
- This comparison is very nontrivial, because the SSA in DIS depends on final state interactions, whereas in hadronic collision both initial and final state interactions contribute
- Indicate the consistency of SSAs in DIS and hadron collisions

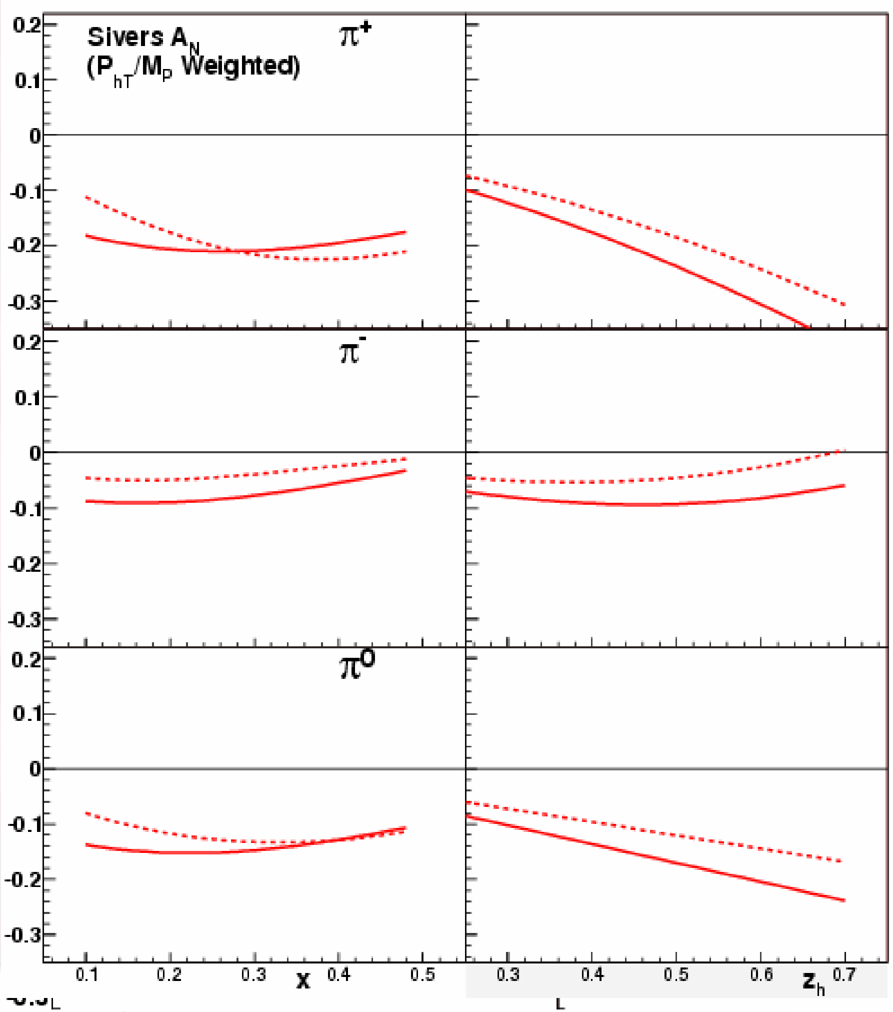
See also, Efremov, et al., PLB612,233 (20005)

Predictions for JLab-12 GeV

Proton Target



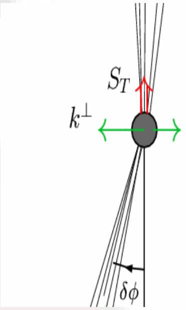
Neutron Target



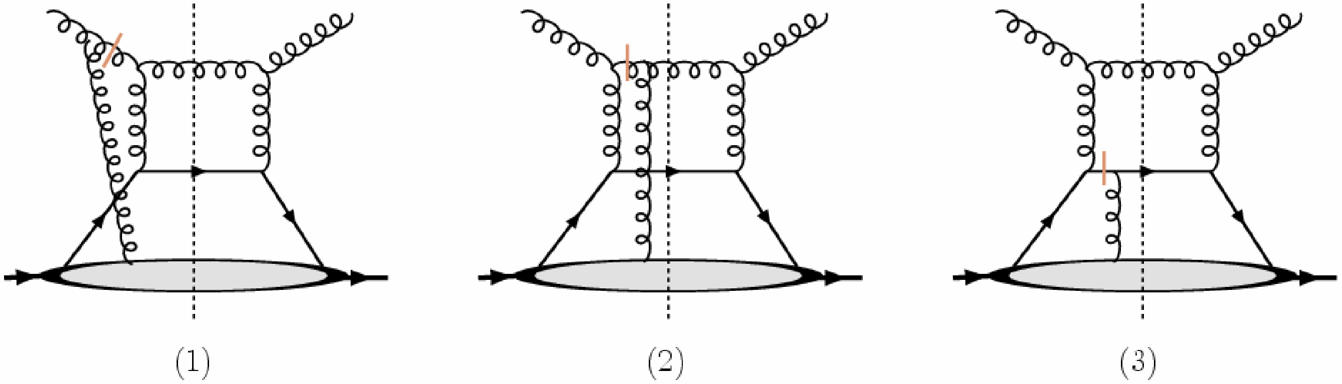
A new way to study higher-twist quark-gluon correlation functions?

- Large p_t SIDIS certainly will provide information on higher-twist distributions
- P_t-weighted azimuthal asymmetries will also give constraints on these distributions
  - Systematic analysis has to be done
  - Evolution, NLO corrections, …
  - It indeed opens a new window for studying higher-twsit quark-gluon correlations in SIDIS

Dijet-correlation in hadronic process



- Proposed by Boer-Vogelsang
- Initial state and/or final state interactions?
  - Bacchetta-Bomhof-Mulders-Pijlman,04-06
- We can formulate the initial and final state interactions in a model-independent way, at nonzero leading order, for example



The asymmetry can be related to that in DIS, in leading power of q⊥/P_t, universality of the parton distributions?

$$\frac{d\sigma_{TU}}{d^2\vec{q}_\perp} = \sum_{ab}\int d^2k_{1\perp}d^2k_{2\perp}d^2\lambda_\perp \frac{\vec{k}_{1\perp}\cdot\hat{\vec{q}}_\perp}{M} x_a q_{Ta}^{(\mathrm{DIS})}(x_a,k_{1\perp}) x_b f_b(x_b,k_{2\perp})$$

$$H^{\mathrm{sivers}}_{ab\to cd}(P_\perp^2)\delta^{(2)}(\vec{k}_{1\perp}+\vec{k}_{2\perp}-\vec{q}_\perp)$$

Qiu,Vogelsang,Yuan,06-07

- q_T^{DIS}--- Sivers function from DIS

  $q_\perp$--- imbalance of the dijet

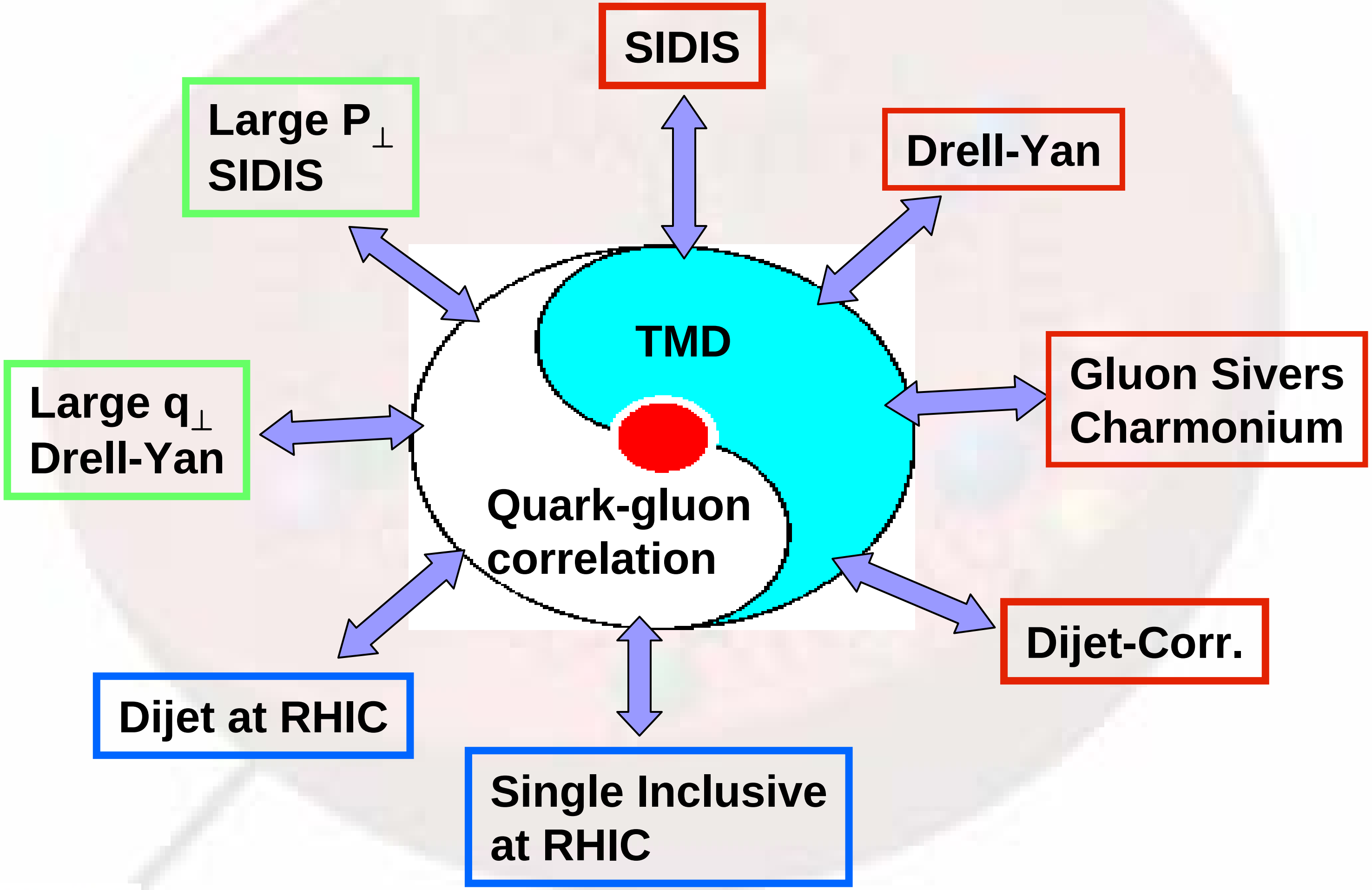
  H^{sivers} depends on subprocess

$$H^{(\mathrm{sivers})}_{qg\to qg} = -\frac{N_C^2}{4(N_C^2-1)}\frac{2(\hat{s}^2+\hat{u}^2)}{\hat{t}^2}\left[\frac{\hat{s}}{\hat{u}}-\frac{\hat{u}}{\hat{s}}\right]+\cdots$$

$$H^{\mathrm{unp.}}_{qg\to qg} = \frac{1}{2}\frac{2(\hat{s}^2+\hat{u}^2)}{\hat{t}^2}+\cdots$$

(**Bacchetta-Bomhof-Mulders-Pijlman**)

Global Picture for SSAs



SIDIS

Large $P_\perp$ SIDIS

Drell-Yan

TMD

Quark-gluon correlation

Large $q_\perp$ Drell-Yan

Gluon Sivers Charmonium

Dijet-Corr.

Dijet at RHIC

Single Inclusive at RHIC

Summary

- We are in the early stages of a very exciting era of transverse spin physics studies, and semi-inclusive DIS plays a very important role, in the past, and future
- We will learn more about nucleon structure from these studies, especially for the quark orbital motion

New challenge from STAR data (2006)

Talks by Ogawa and Nogach in SPIN2006