(Single) Transverse Spin Physics

-- from DIS to hadron collider

Feng Yuan

RBRC , Brookhaven National Laboratory

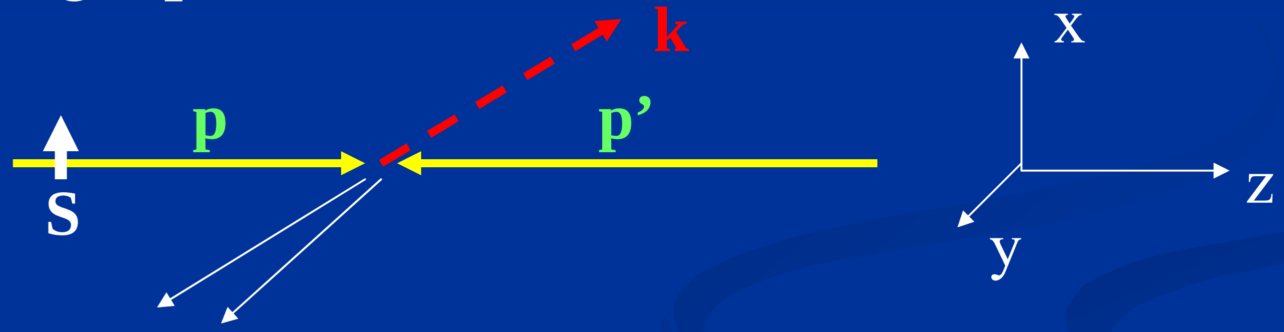
W. Vogelsang, F.Y. , to be submitted

Outline

- Introduction
  - More: RBRC Workshop on SSA (June 1-3) http://quark.phy.bnl.gov/~fyuan/workshop/summer05_program.htm
- SSA in SIDIS, Physics of TMDs
- SSA at hadron colliders (RHIC)
- Summary

What is Single Spin Asymmetry?

- Consider scattering of a transversely-polarized spin-1/2 hadron (S, p) with another hadron, observing a particle of momentum k



The cross section can have a term depending on the azimuthal angle of **k**

$$d\sigma \sim S \cdot (p \times k)$$

which produce an asymmetry A_N when **S** flips: **SSA**

Sample Exp. Data

- A. Bravar et al., E704, PRL77, 2626 (1996)

$$\bar{p}_{\uparrow} p \longrightarrow \pi + X$$

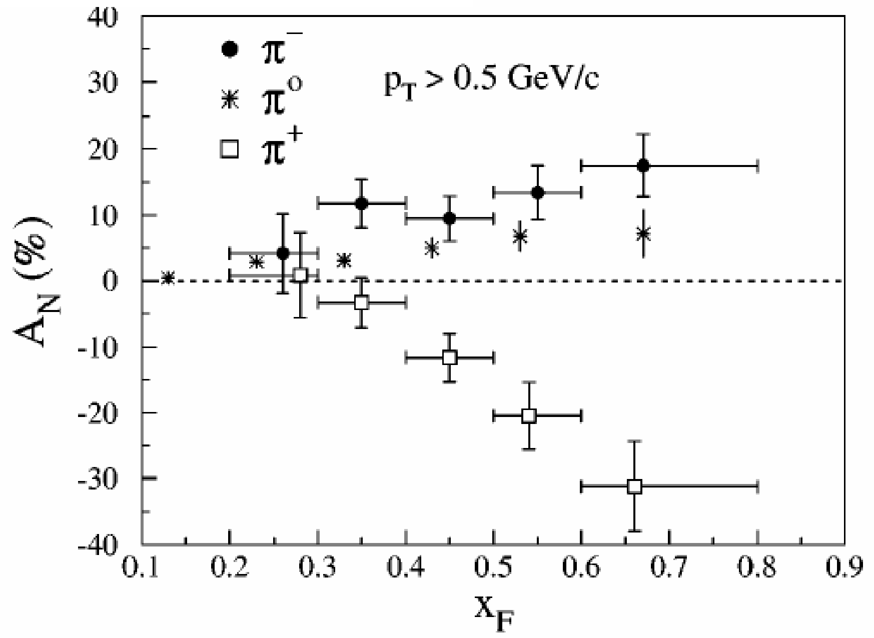
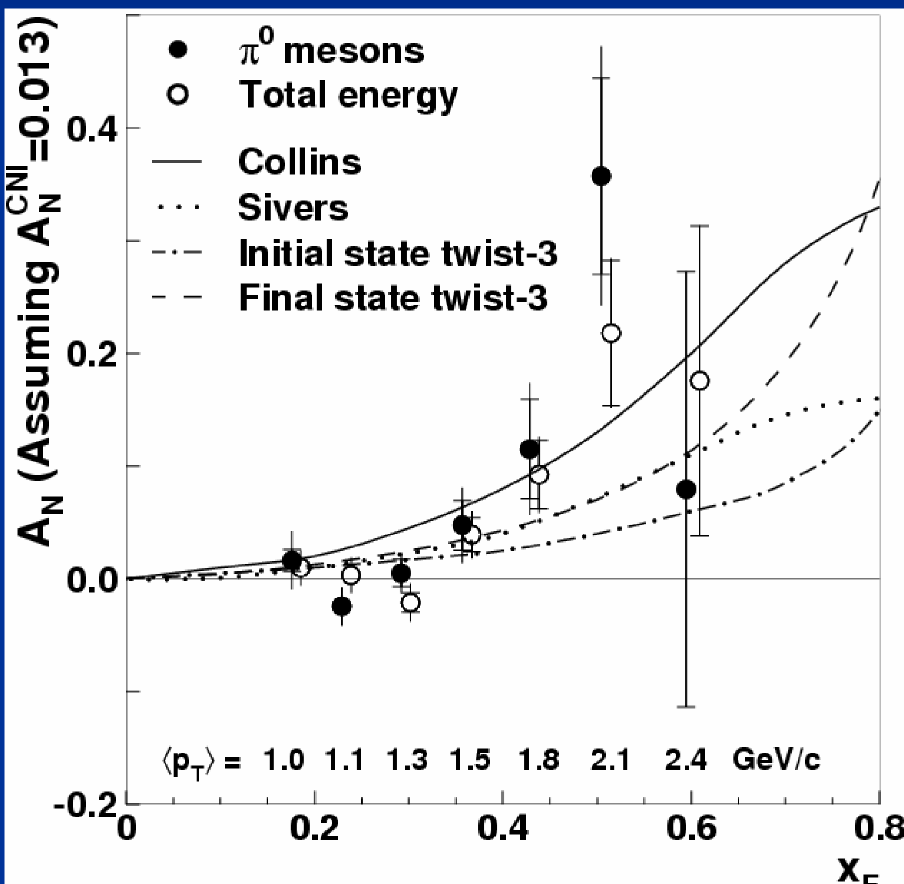
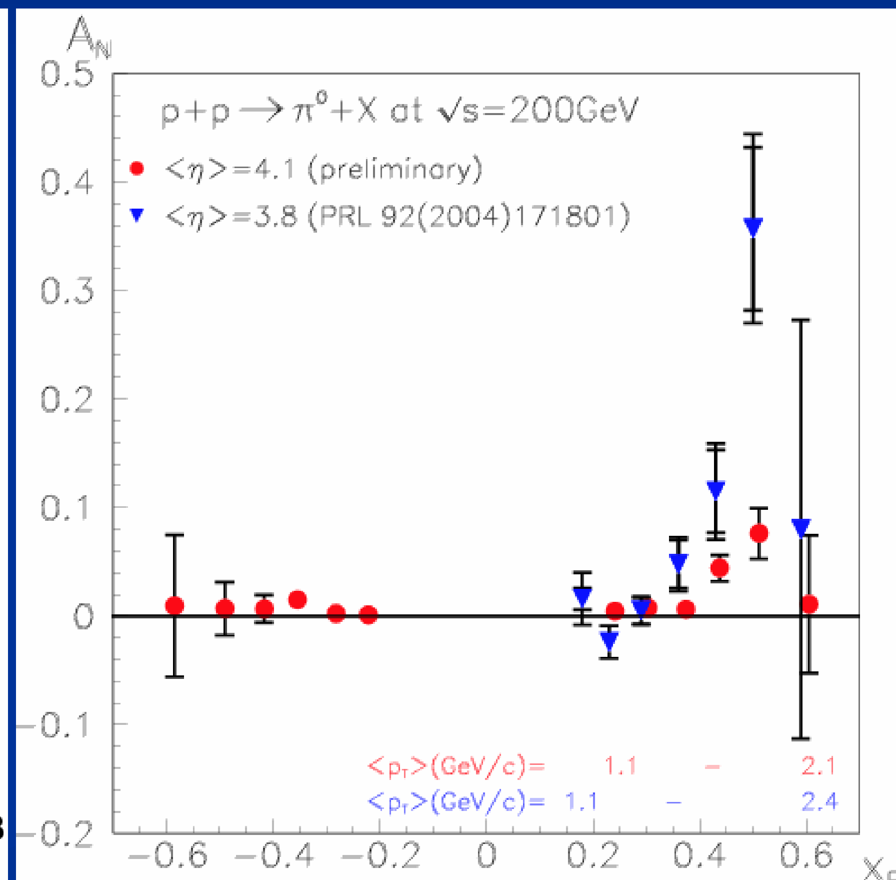


FIG. 3. A_N data as a function of x_F for π^- and π^+ for $p_T \geq 0.5$ GeV/c. A_N data for π^0 in a similar p_T range are also shown [5]. The first π^- and π^+ data points are offset by -0.01 and $+0.01$ x_F units, respectively.

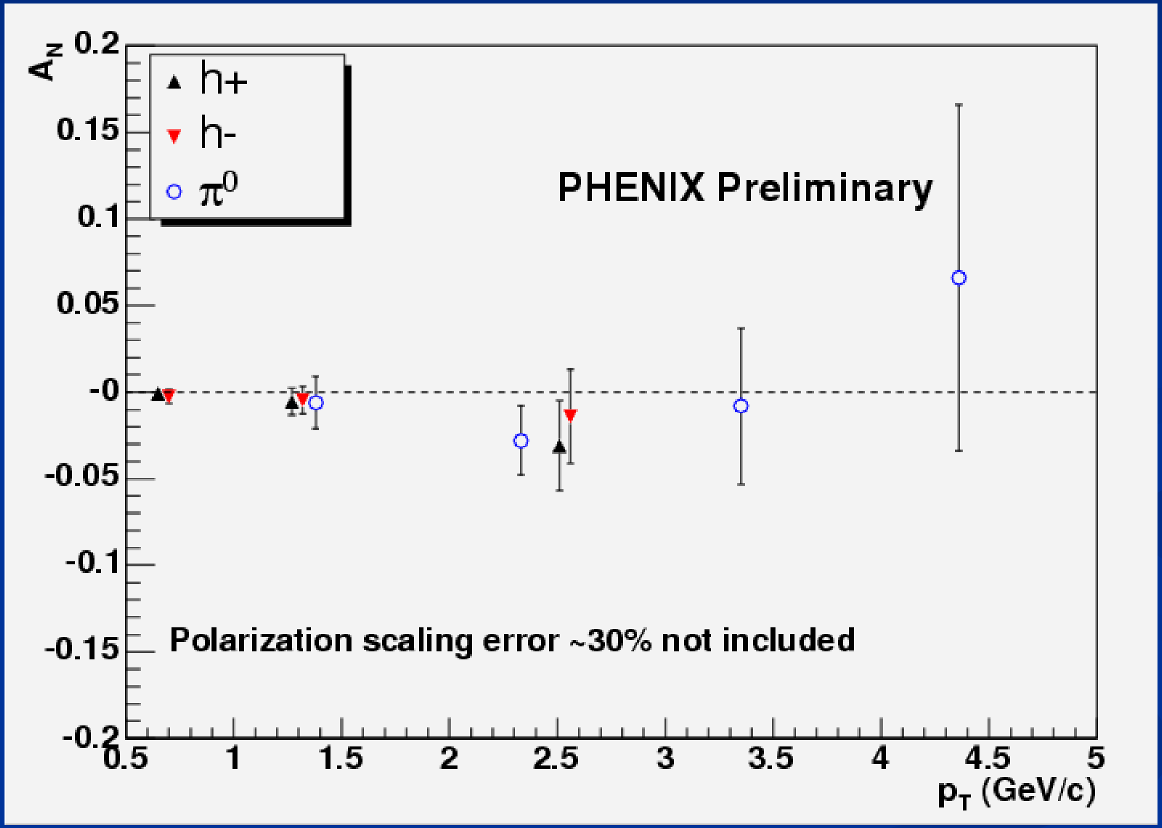
SSA at RHIC

STAR Collaboration, Phys.Rev.Lett.92:171801,2004; hep-ex/0412035



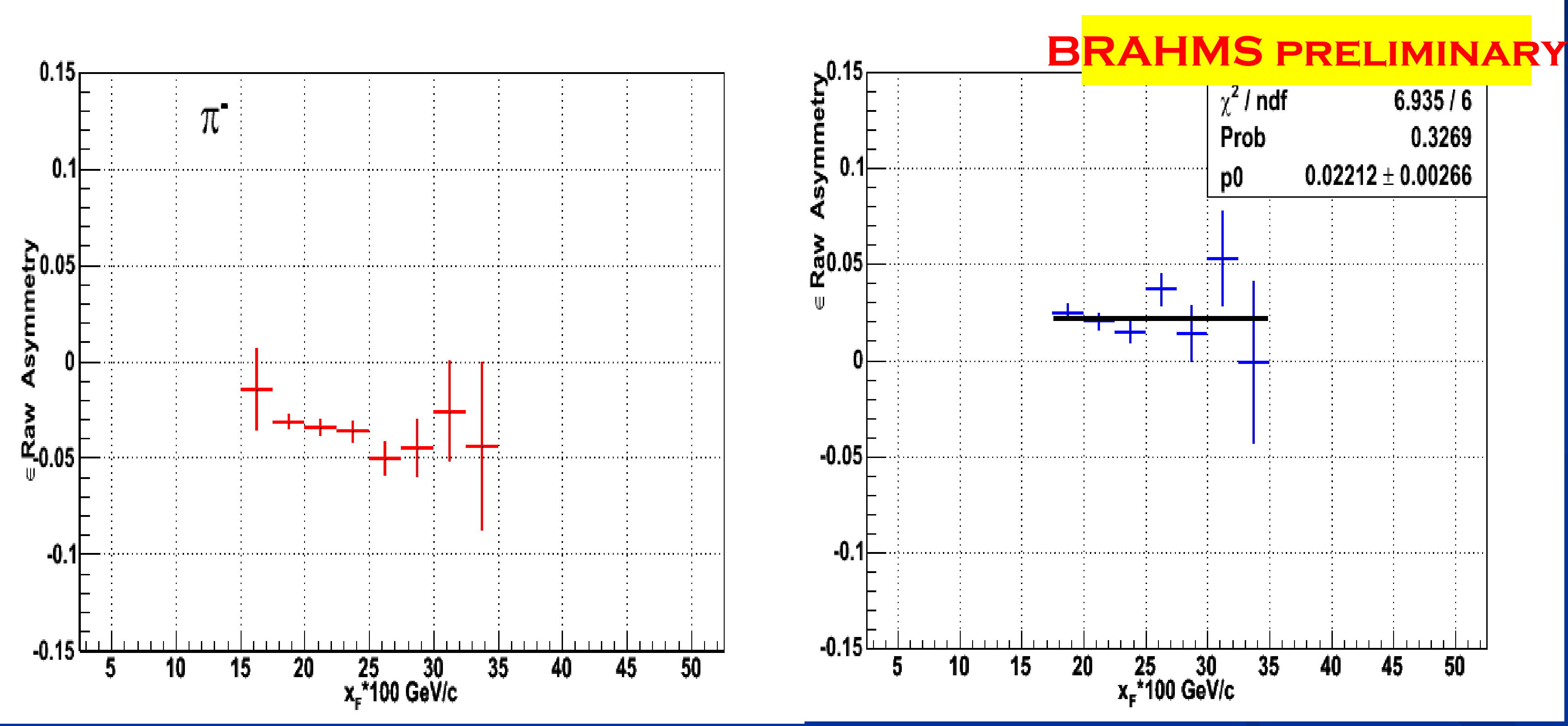


PHENIX Collaboration, hep-ex/0410003



Central rapidity!!

BRAHMS Collaboration, talk by Videbaek



<e>~ -0.035 => AN = -0.08 +- 0.005 +- [0.015] in 0.17 < xF < 0.32

<e>~ +0.022 => AN = +0.05 +- 0.005 +- [0.015] in 0.17 < xF < 0.32

Big SSA!

- Systematics
  - **A_N is significant in the fragmentation region of the polarized beam**
  - **A_N and its sign show a strong dependence on the type of polarized beam and produced particles**
- A related phenomenon: the transverse polarization of spin-1/2 particle in unpolarized hadron scattering.
  - G. Bunce et. al, PRL36, 1113 (1976).

Why Does SSA Exist?

- **Single Spin Asymmetry is proportional to**

  $\mathrm{Im}\,(M_N * M_F)$

  where M_N is the normal helicity amplitude

  and M_F is a spin flip amplitude

  - **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

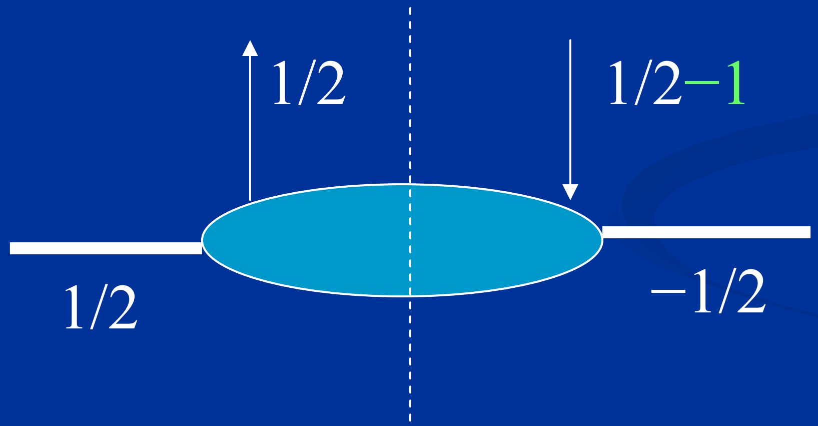
  $S \cdot (p \times k)$ formally violate time-reversal invariance

Naïve Parton Model Fails

- If the underlying scattering mechanism is hard, the naïve parton model generates a very small SSA: (G. Kane et al, PRL41, 1978)
  - The only way to generate the hadron helicity-flip is through quark helicity flip, which is proportional to current quark mass m_q
  - To generate a phase difference, one has to have pQCD loop diagrams, proportional to α_S

Parton Orbital Angular Momentum and Gluon Spin

- The hadron helicity flip can be generated by other mechanism in QCD
  - Quark orbital angular momentum (OAM):

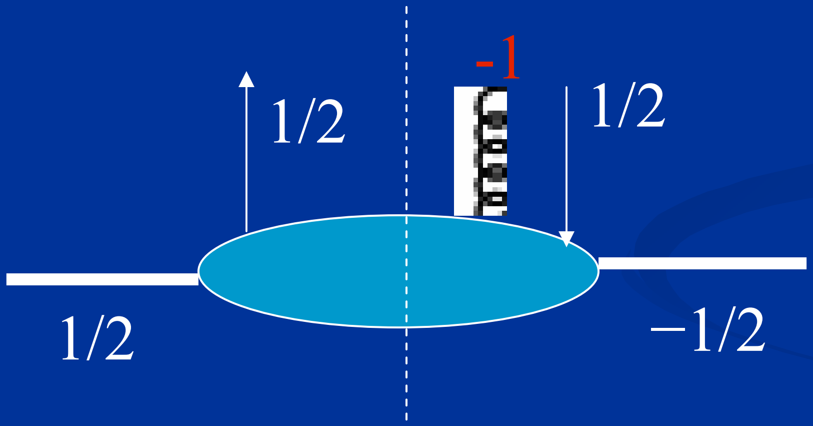


Beyond the naïve parton model in which quarks are collinear

Transverse Momentum Dependent PDF!! (TMDs)

Parton OAM and Gluons (cont.)

- A collinear gluon carries one unit of angular momentum because of its spin. Therefore, one can have a coherent gluon interaction

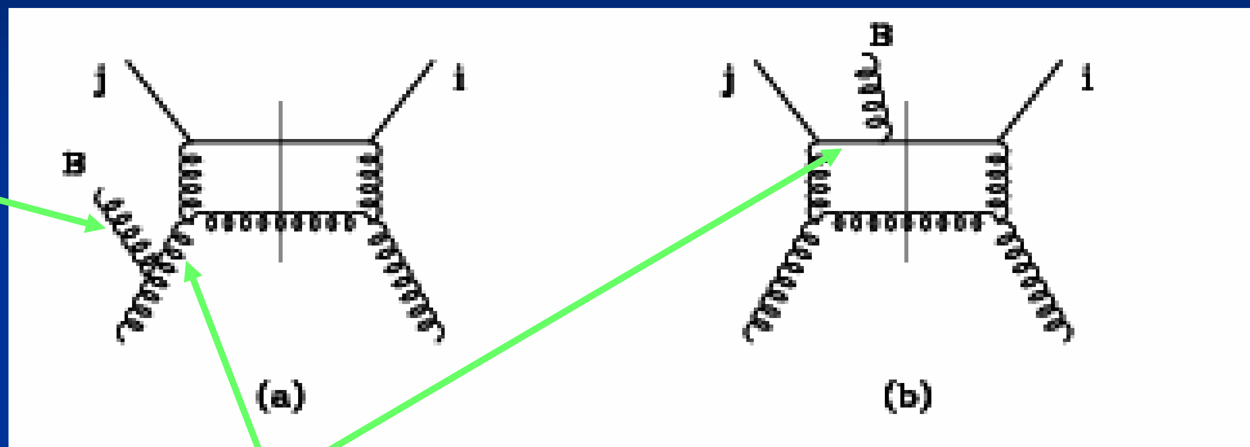


Quark-gluon quark correlation function!

Qiu-Sterman Mechanism

Novel Way to Generate Phase

Coulomb gluon



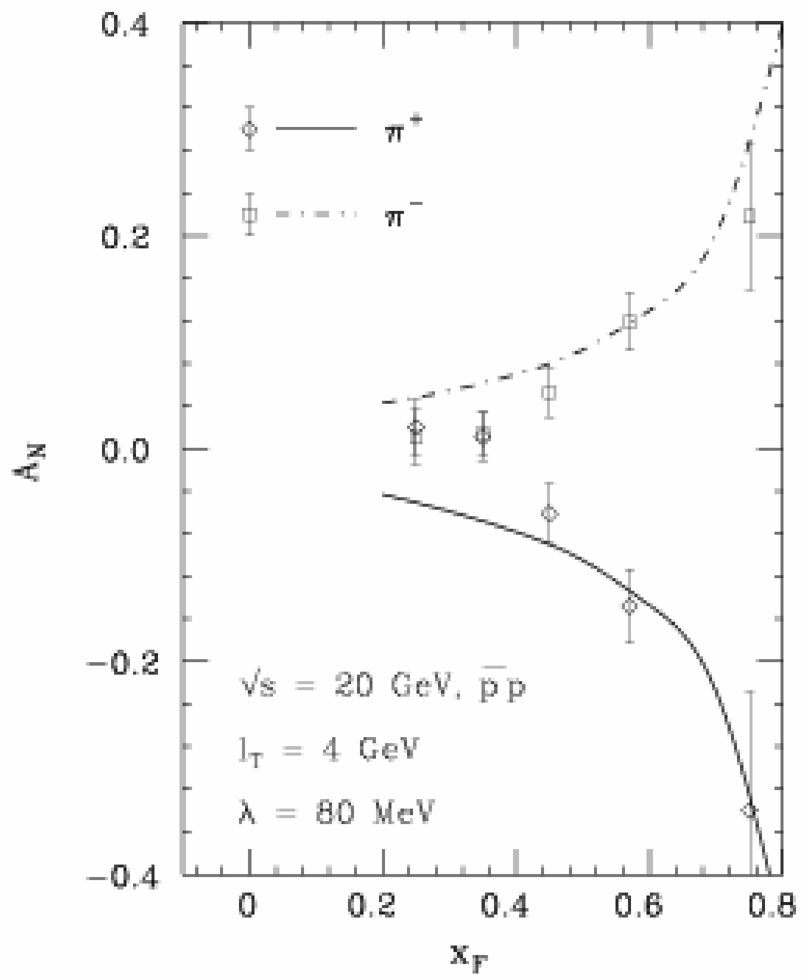
Some propagators in the tree diagrams go on-shell

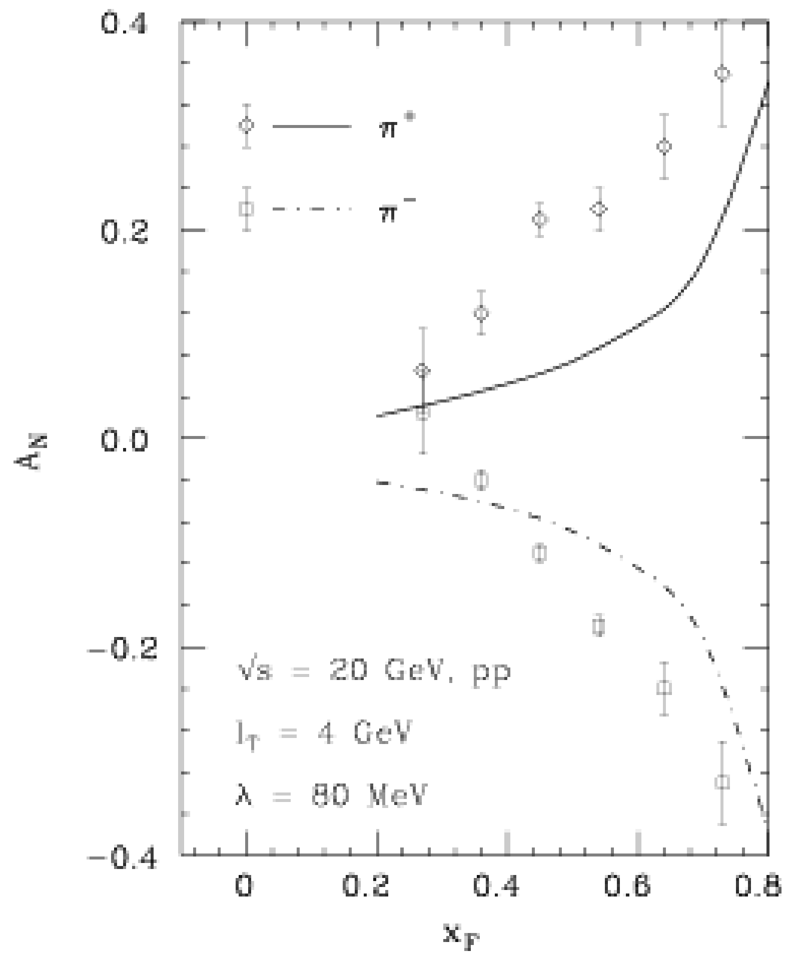
$$\frac{1}{k^2 - m^2 + i\epsilon} = \mathcal{P}\frac{1}{k^2 - m^2} - i\pi\delta(k^2 - m^2)$$

No loop is needed to generate the phase!

Efremov & Teryaev: 1982 & 1984
Qiu & Sterman: 1991 & 1999

Comparison With Data

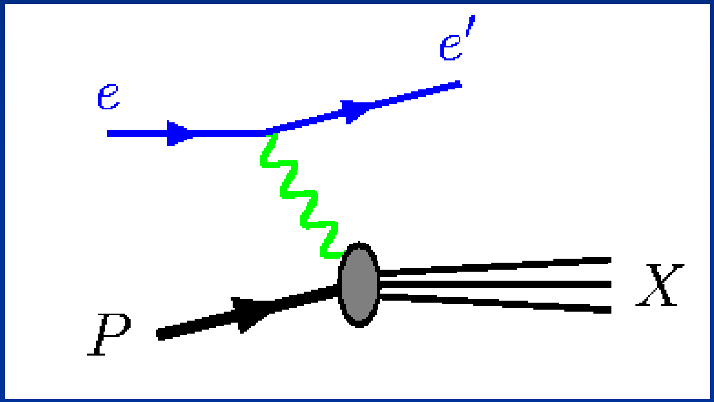




Qiu & Sterman, PRD59, 014004 (1999)

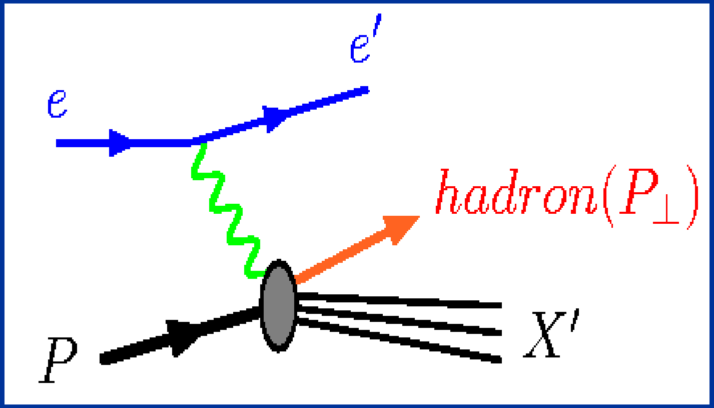
SSA In Semi-inclusive Deep Inelastic Scattering (TMDs)

Inclusive and Semi-inclusive DIS



Inclusive DIS:

Partonic Distribution depending on the longitudinal momentum fraction



Semi-inclusive DIS:

Probe additional information for parto transverse distribution in nucleon

Different $P_?$ Region

- Integrate out $P_?$

  -- similar to inclusive DIS, probe int. PDF

- Large $P_?$ (ÀΛ_{QCD})

  -- hard gluon radiation, can be calculated from perturbative QCD,

  Polarized ->q-g-q correlations

- Low $P_?$ (»Λ_{QCD})

  -- nonperturbative information (TMD): new factorization formula

TMD Physics

- A way to measure Transversity Distribution, the last **unkown** **leading twist** distribution

  Collins 1993

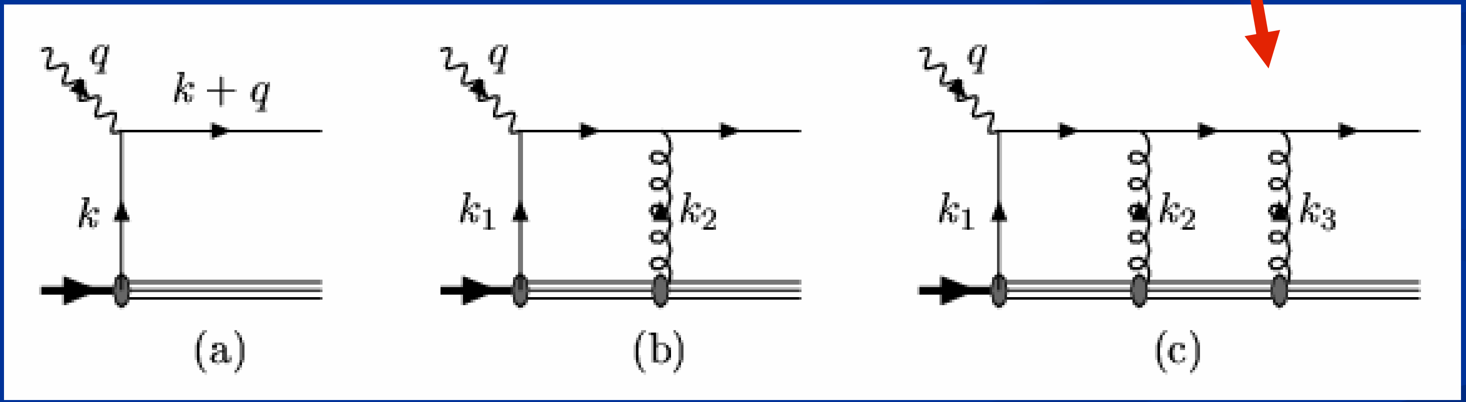
- The Novel Single Spin Asymmetries
- Connections with GPDs, and Quantum Phase Space Wigner distributions
- Quark Orbital Angular Momentum and

  Many others …

TMD Distribution: the definition

$$Q(x, k_\perp, \mu, x\zeta) = \frac{1}{2}\int \frac{d\xi^-}{2\pi} e^{-ix\xi^- P^+} \int \frac{d^2\vec{b}_\perp}{(2\pi)^2} e^{i\vec{b}_\perp\cdot\vec{k}_\perp} \times \left\langle P \left| \overline{\psi}_q(\xi^-, 0, \vec{b}_\perp)\mathcal{L}_v^\dagger(\infty; \xi^-, 0, \vec{b}_\perp)\gamma^+\mathcal{L}_v(\infty; 0)\psi_q(0) \right| P \right\rangle$$

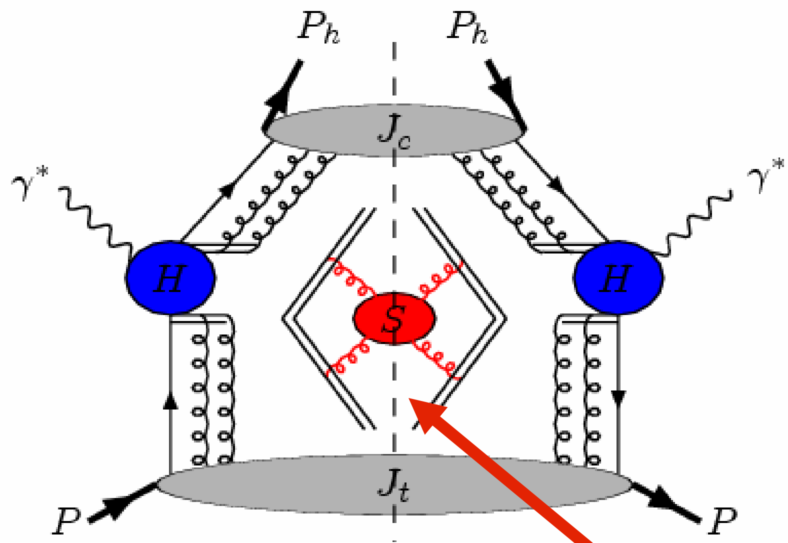
Gauge Invariance requires the Gauge Link



Brodsky,Hwang,Schmidt 02'
Collins 02'
Belitsky,Ji,Yuan 02'

This definition is also consistent with the QCD factorization

Factorization



Soft Factor

$$
\begin{aligned}
&F(x_B, z_h, P_{h\perp}, Q^2) \\
&= \sum_{q=u,d,s,\ldots} e_q^2 \int d^2\vec{k}_\perp d^2\vec{p}_\perp d^2\vec{\ell}_\perp \\
&\times q\left(x_B, k_\perp, \mu^2, x_B\zeta, \rho\right)\hat{q}_h\left(z_h, p_\perp, \mu^2, \hat{\zeta}/z_h, \rho\right) S(\vec{\ell}_\perp, \mu^2, \rho) \\
&\times H\left(Q^2, \mu^2, \rho\right) \delta^2(z_h\vec{k}_\perp + \vec{p}_\perp + \vec{\ell}_\perp - \vec{P}_{h\perp})
\end{aligned}
$$

Ji,Ma,Yuan, 04’

The Factorization Applies to

- Semi-inclusive DIS (polarized and unpolarized)
- Drell-Yan at Low transverse momentum
- Di-hadron production in e+e- annihilation (extract the Collins function)
- Di-jet and/or di-hadron correlation at hadron collider (work in progress)
- Many others, …

Phenomenology

- At current stage, it is difficult to implement the full factorization approach for the phenom. Studies
- As a first step, one may neglect all higher order effects, set $S=H=1$, forget the ζ and ρ in TMDs
- Back to Naïve Parton Model picture
  - Mulders & Tangelmann 96

SIDIS Cross Sections

$$\frac{d\sigma}{dx_B dy dz_h d^2\vec{P}_{h\perp}} = \frac{4\pi\alpha_{\mathrm{em}}^2 s}{Q^4}\Big[(1-y+y^2/2)x_B F_{UU}$$
$$+(1-y+y^2/2)\sin(\phi_h-\phi_S)|S_\perp|F_{UT}^{sivers}$$
$$+(1-y)x_B|\vec{S}_\perp|\sin(\phi_h+\phi_S)F_{UT}^{collins}\Big] ,$$

$$F_{UU} = \int q(x_B, k_\perp)\,\hat{q}(z_h, p_\perp)$$

Sivers Function

$$F_{UT}^{sivers} = \int \frac{\vec{k}_\perp \cdot \hat{\vec{P}}_{h\perp}}{M} q_T(x_B, k_\perp)\,\hat{q}(z_h, p_\perp)$$

$$F_{UT}^{collins} = \int \frac{\vec{p}_\perp \cdot \hat{\vec{P}}_{h\perp}}{M_h} \delta q_T(x_B, k_\perp)\,\delta\hat{q}(z_h, p_\perp)$$

Transversity

Collins Function

Asymmetries

- Integrate over the transverse momentum

$$d\sigma \propto 1 + A_N^{sivers} \sin(\phi_h - \phi_s) + A_N^{collins} \sin(\phi_h + \phi_s)$$

$$A_N^{sivers} \propto (1 - y + y^2/2) x_B q_T^{(1/2)}(x_B) \hat{q}(z_h)$$

$$A_N^{collins} \propto (1 - y) x_B \delta q_T(x_B) \delta \hat{q}^{(1/2)}(z_h)$$

$$q_T^{(1/2)}(x) = \int d^2 k_\perp \frac{|\vec{k}_\perp|}{M} q_T(x_B, k_\perp)$$

Model for the Sivers functions

- Assume only valence quark Sivers functions

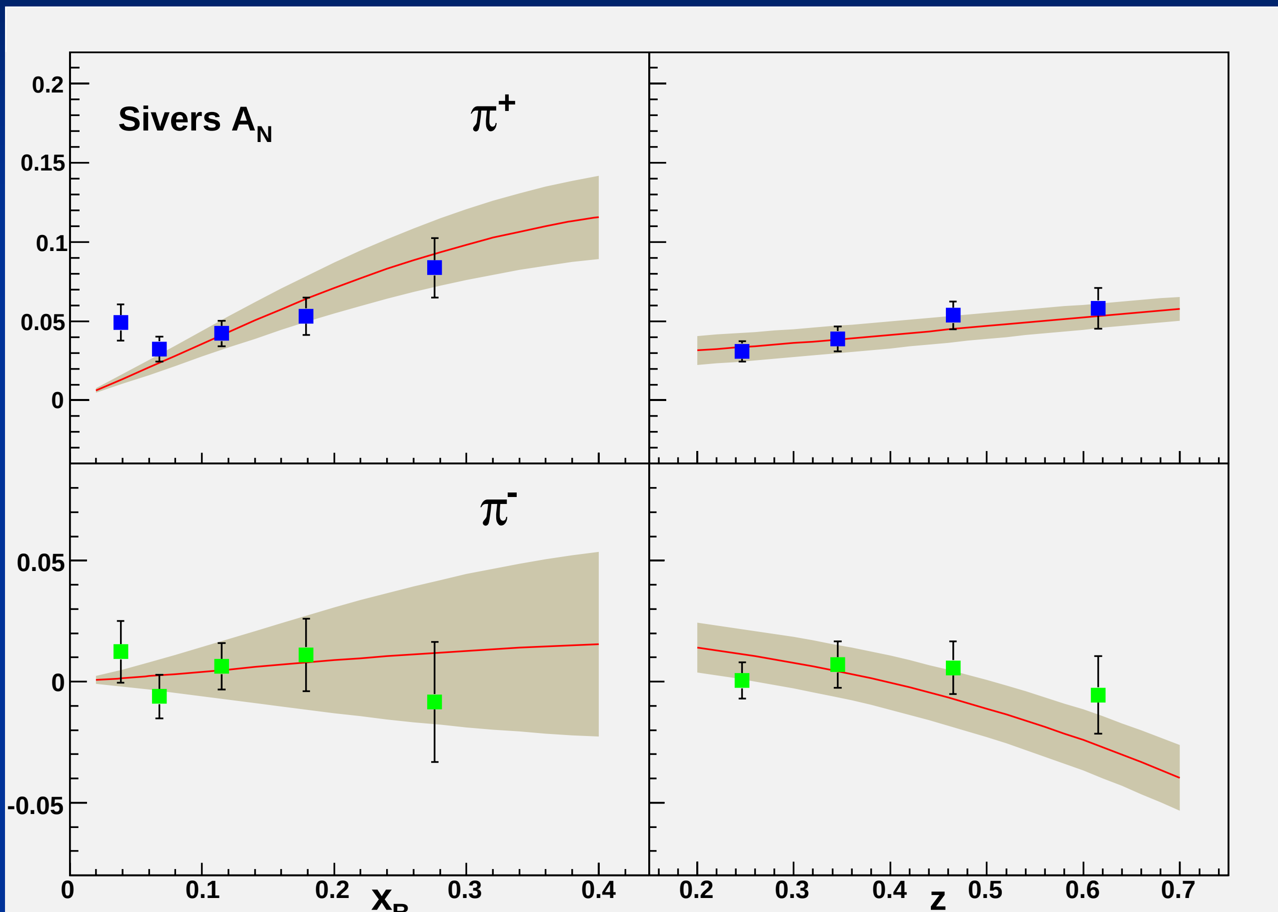
$$u_T^{(1/2)}/u = S_u\, x(1-x)$$

$$d_T^{(1/2)}/u = S_d\, x(1-x)$$

Valence feature **Power Suppressed at x->1**

- GRVLO for the unpolarized quark distribution
  Kretzer's LO fragmentation function

Fit to HERMES Data

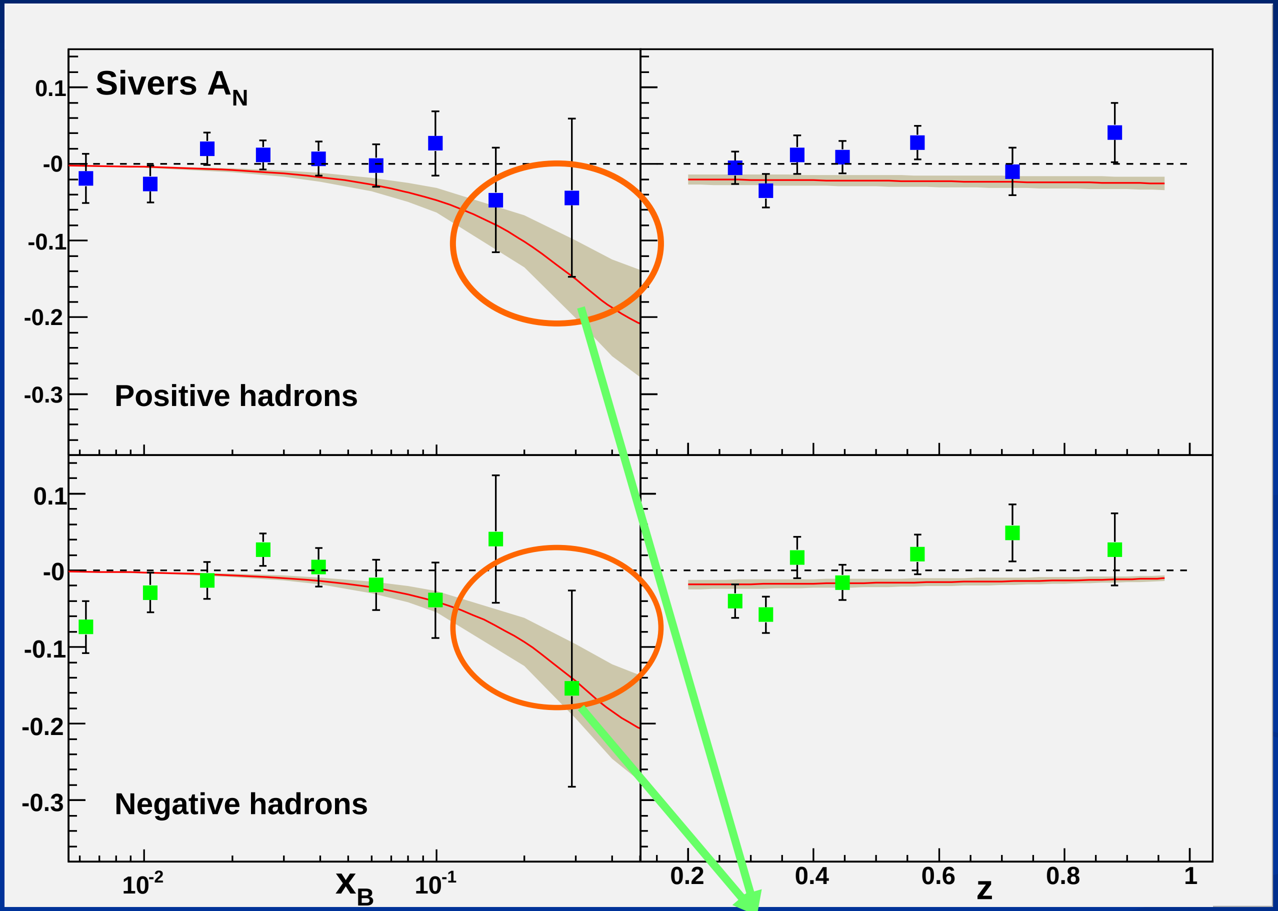


S_u=-0.81§ 0.07

S_d=1.86§ 0.28

χ^2/d.o.f ¼ 1.2

Compare with COMPASS



Assume the leading hadrons are pions

HERMES large positive for π^+, and almost zero for π^-, there is strong cancellation between u and d quark Sivers function to explain the HERMES data!!

A Conjecture for Collins Function

- By summing up all hadrons, any quark Collins function vanishes,

$$\sum_h \delta\hat{q}^h(z, k_\perp) \approx 0$$

- Due to quark-hadron duality, the fragmentation function to all hadrons equals to the fragment. to quark (quark+gluons) state, where the naïve T-odd effect is suppressed by quark mass
- Integrated over z with k? moment→Schafer-Teryaev sumrule

Consequence on unfavor/favor

- Isospin/charge symmetry

$$\delta\widehat{u}^{\pi^+} = \delta\widehat{d}^{\pi^-} = \delta\widehat{\bar{d}}^{\pi^+} = \delta\widehat{\bar{u}}^{\pi^-} = \delta\widehat{q}^{\pi}_{favor}$$

$$\delta\widehat{d}^{\pi^+} = \delta\widehat{u}^{\pi^-} = \delta\widehat{\bar{u}}^{\pi^+} = \delta\widehat{\bar{d}}^{\pi^-} = \delta\widehat{q}^{\pi}_{unfavor}$$

$$\delta\widehat{u}^{\pi^0} = \delta\widehat{d}^{\pi^0} = \delta\widehat{\bar{d}}^{\pi^0} = \delta\widehat{\bar{u}}^{\pi^0} = \frac{1}{2}\left[\delta\widehat{q}^{\pi}_{favor} + \delta\widehat{q}^{\pi}_{unfavor}\right]$$

- Under the above conjecture, neglecting Keons

$$\delta\widehat{q}^{\pi}_{favor} + \delta\widehat{q}^{\pi}_{unfavor} \approx 0$$

Support from string picture for fragmentation, Artzu
Also N. Makins' talks

Model for Collins Functions

- Two sets of parameterizations

Set I:

$$\delta\hat{q}^{\pi(1/2)}_{favor}(z) = C_f z(1-z)\hat{u}^{\pi^+}(z)$$

$$\delta\hat{q}^{\pi(1/2)}_{unfavor}(z) = C_d z(1-z)\hat{u}^{\pi^+}(z)$$

Set II:

$$\delta\hat{q}^{\pi(1/2)}_{favor}(z) = C_f z(1-z)\hat{u}^{\pi^+}(z)$$

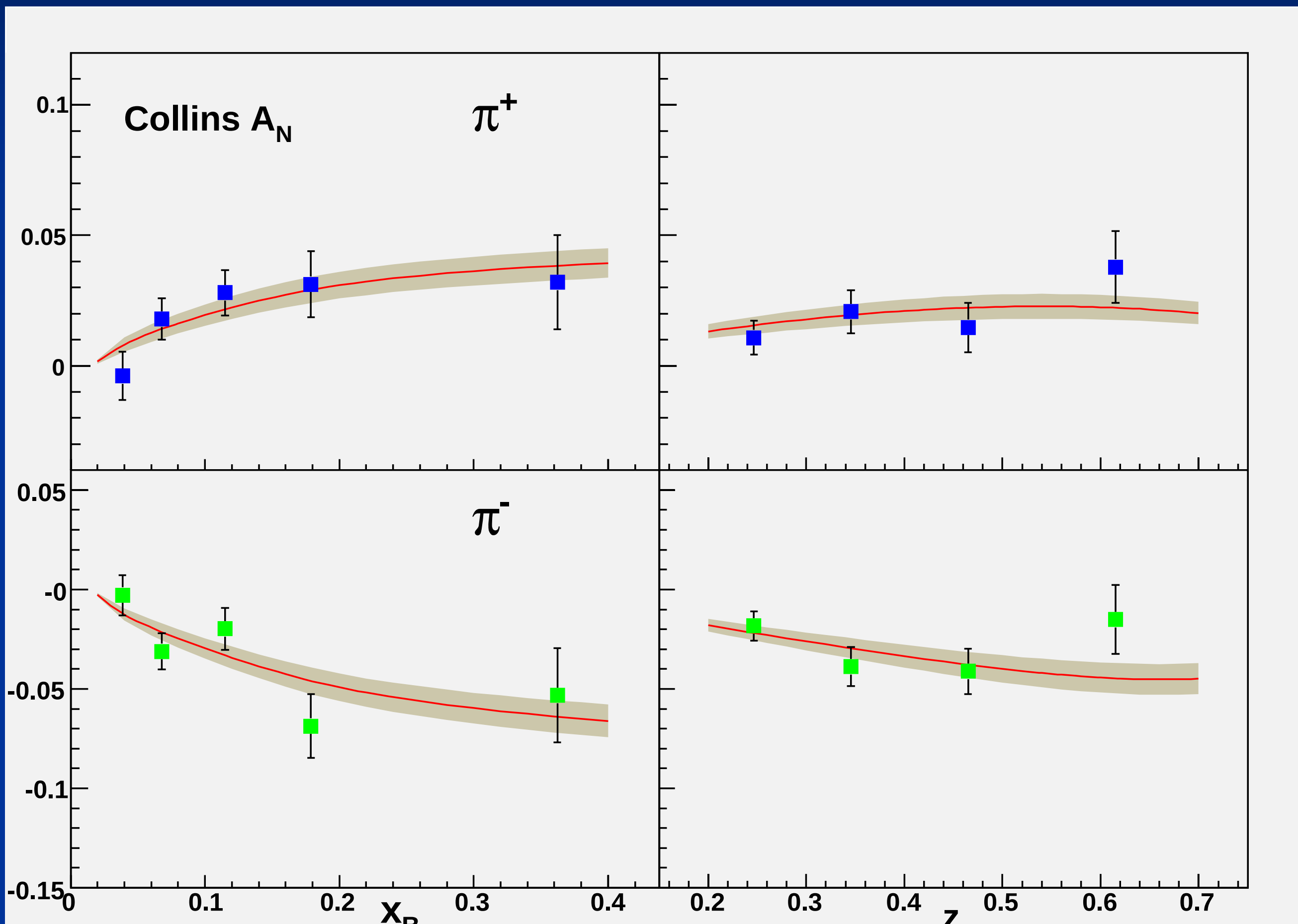
$$\delta\hat{q}^{\pi(1/2)}_{unfavor}(z) = C_d z(1-z)\hat{d}^{\pi^+}(z)$$

Collins function vanishes at z→0

(1-z) comes from Collins 93'

- Transversity functions use the parameterization of Martin, Schafer, Stratmann, and Vogelsang, PRD 57(1998)

Set I Fit to HERMES

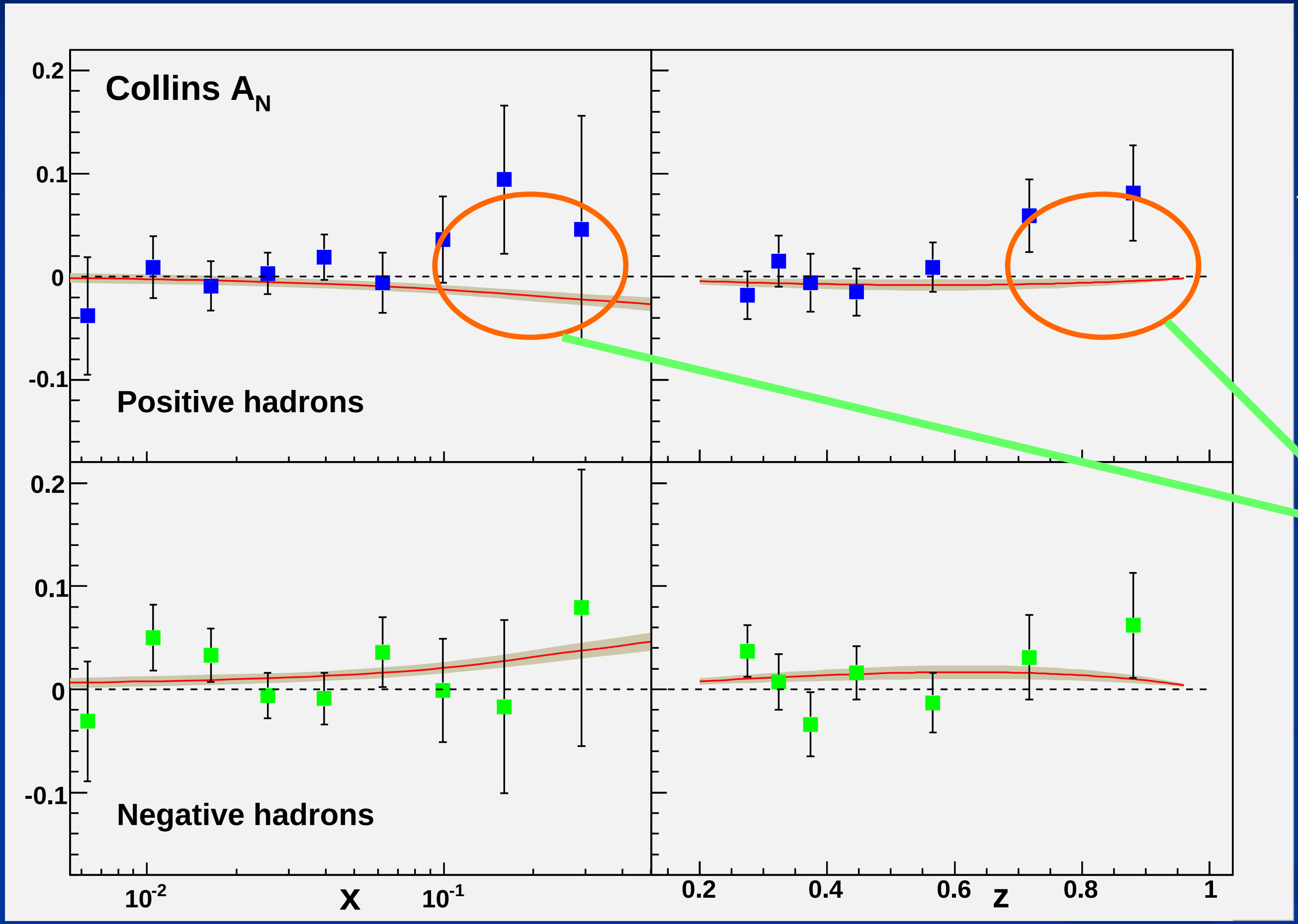


C_f= 0.29§ 0.04

C_d=-0.33§ 0.04

χ^2/d.o.f ¼ 0.8

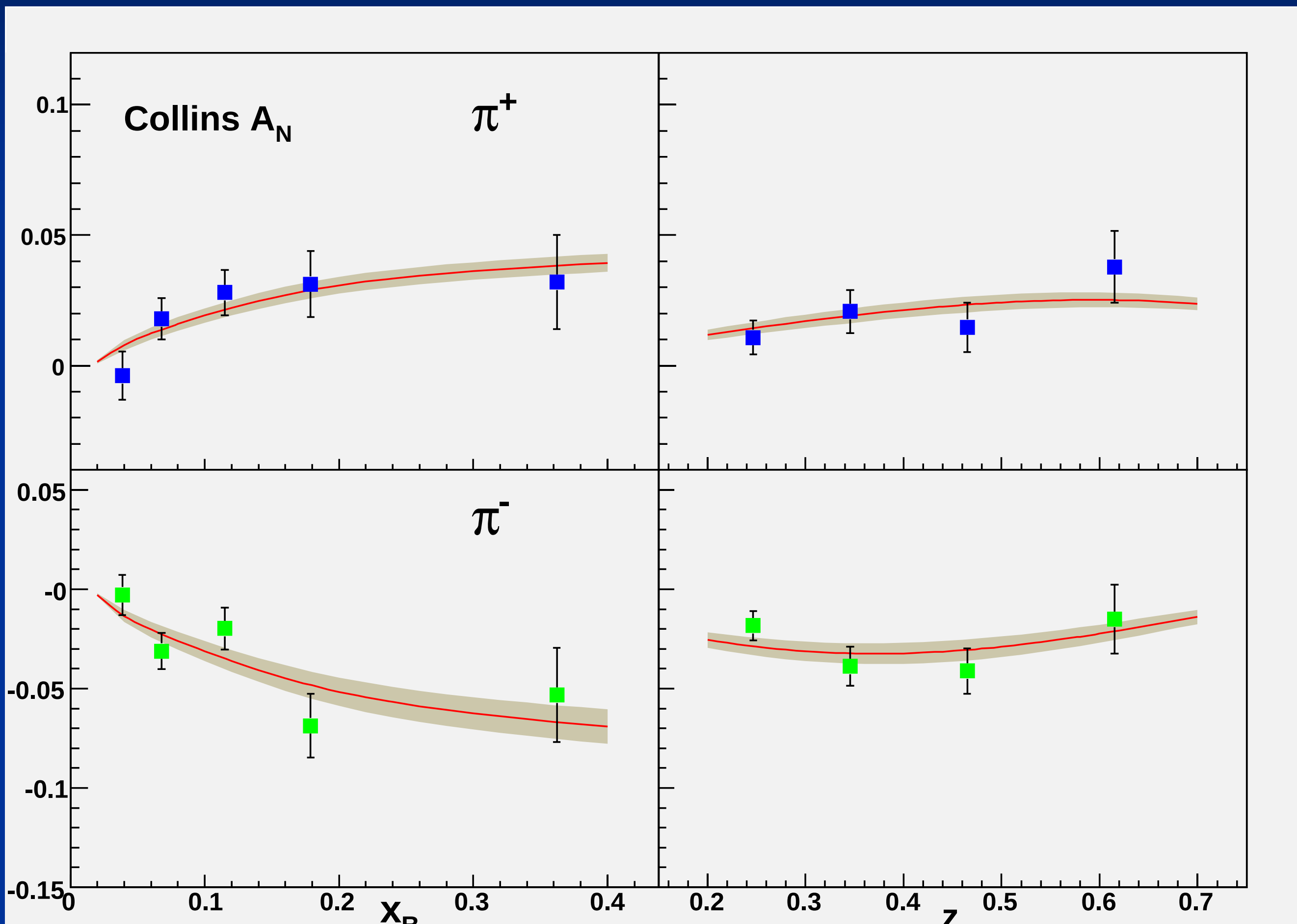
Compare to COMPASS



Assume the leading hadrons are pions

Discrepancy?

Set II Fit

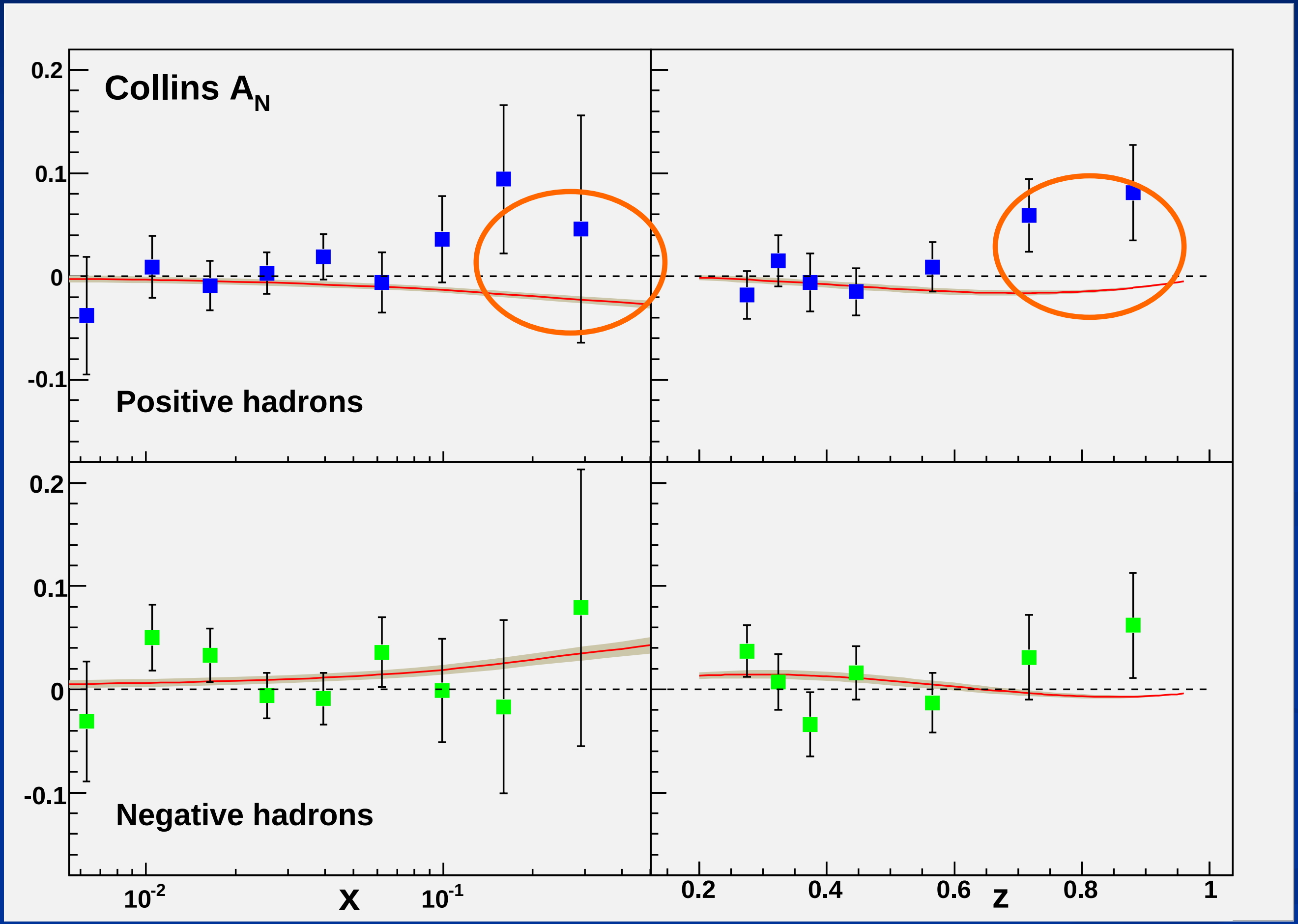


C_f= 0.29§ 0.02

C_d=-0.56§ 0.07

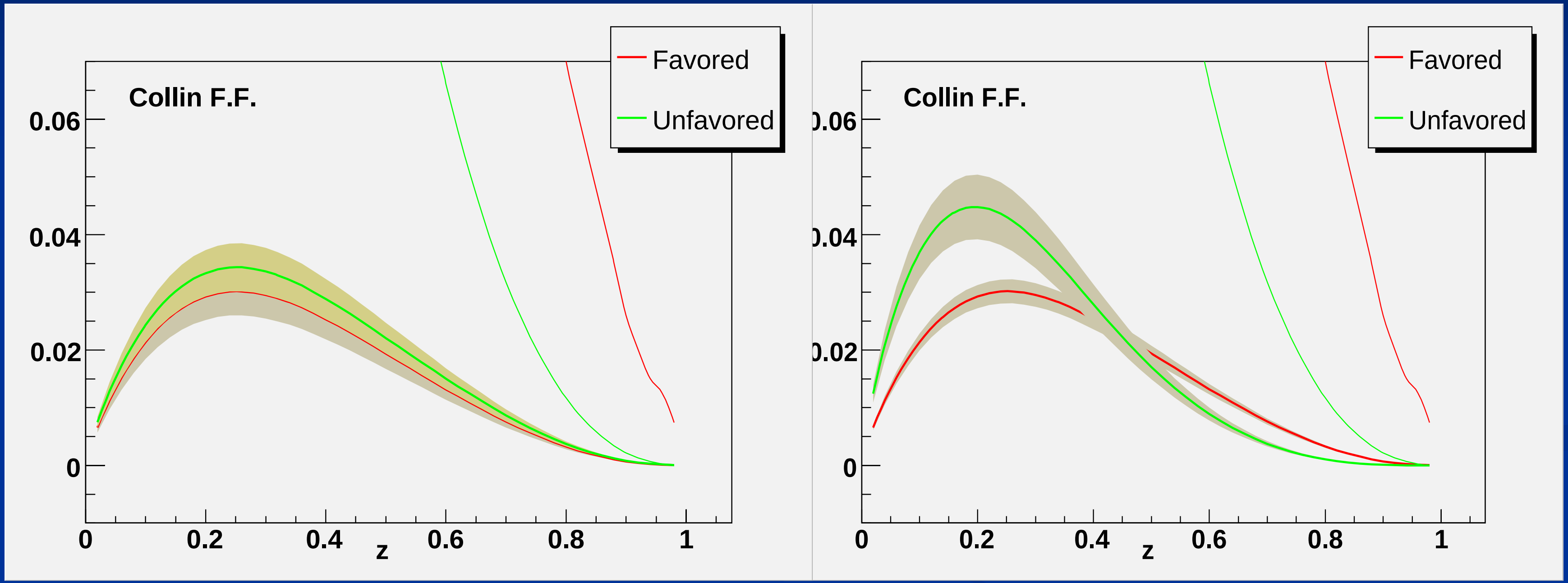
χ^2/d.o.f ¼ 0.7

Compare to COMPASS



Assume the leading hadrons are pions

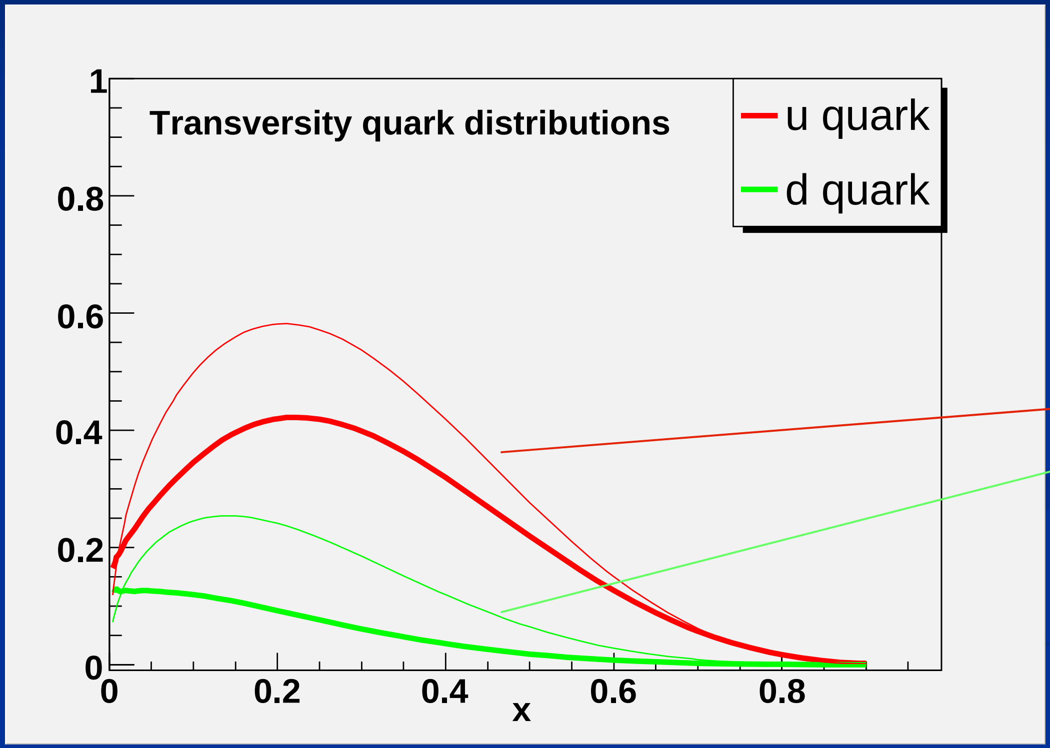
Fitted Collins Functions



Set I

Set II

Transversity functions in the fit



Unpolarized quark distributions

If we get Collins functions from other processes, e.g., e^+e^-, we can constrain the transversity functions !!

TMDs at RHIC

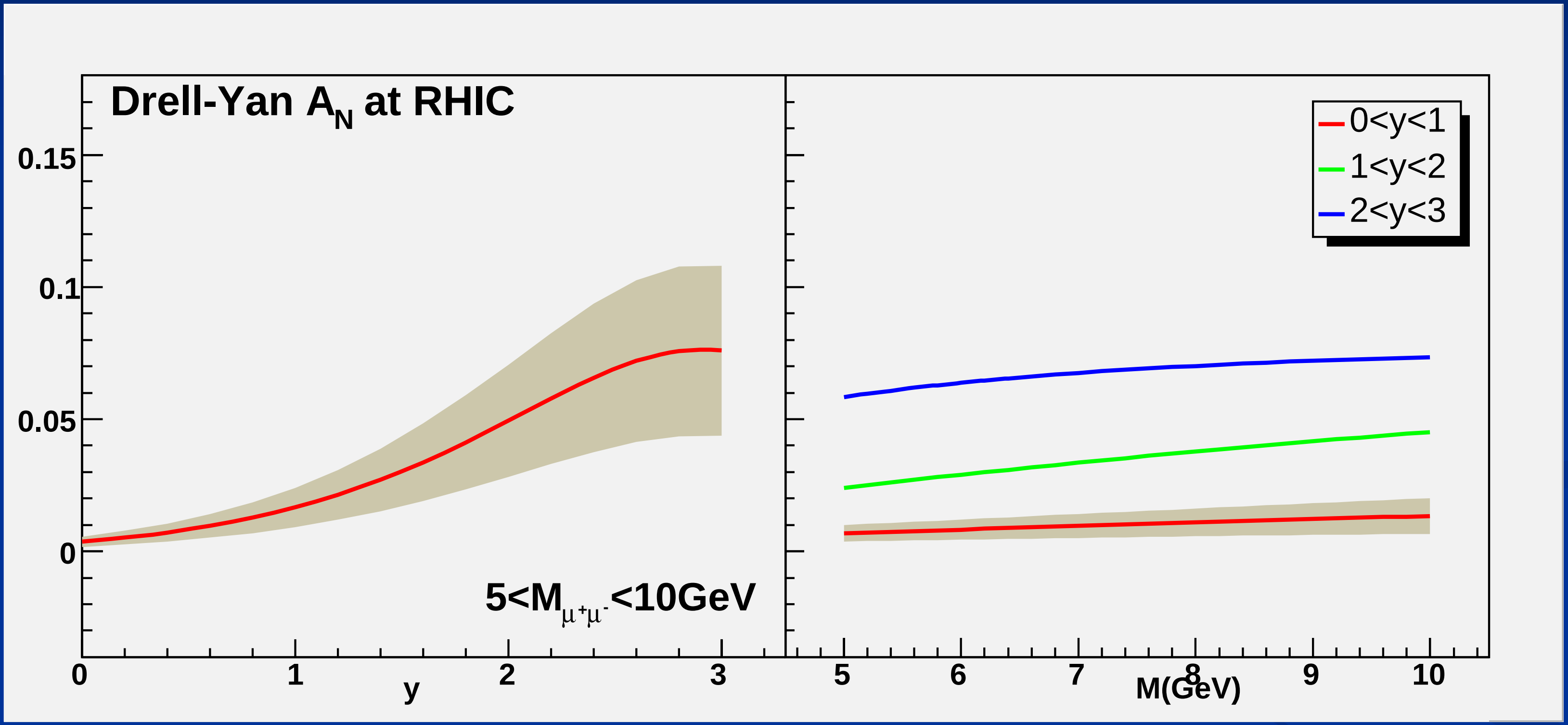
- Drell-Yan

SSA for Drell-Yan: Sivers function has opposite sign, $q_T^{DY}=-q_T^{DIS}$, because of the gauge link changing direction.

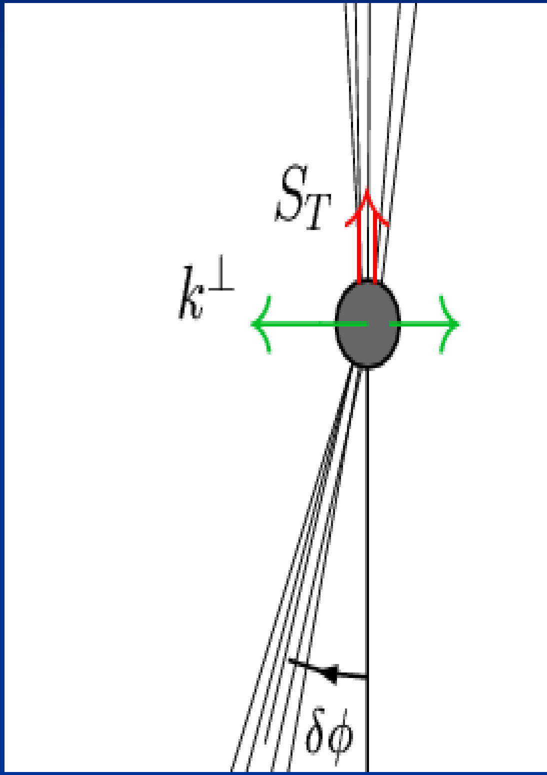
- Di-Jet Correlation

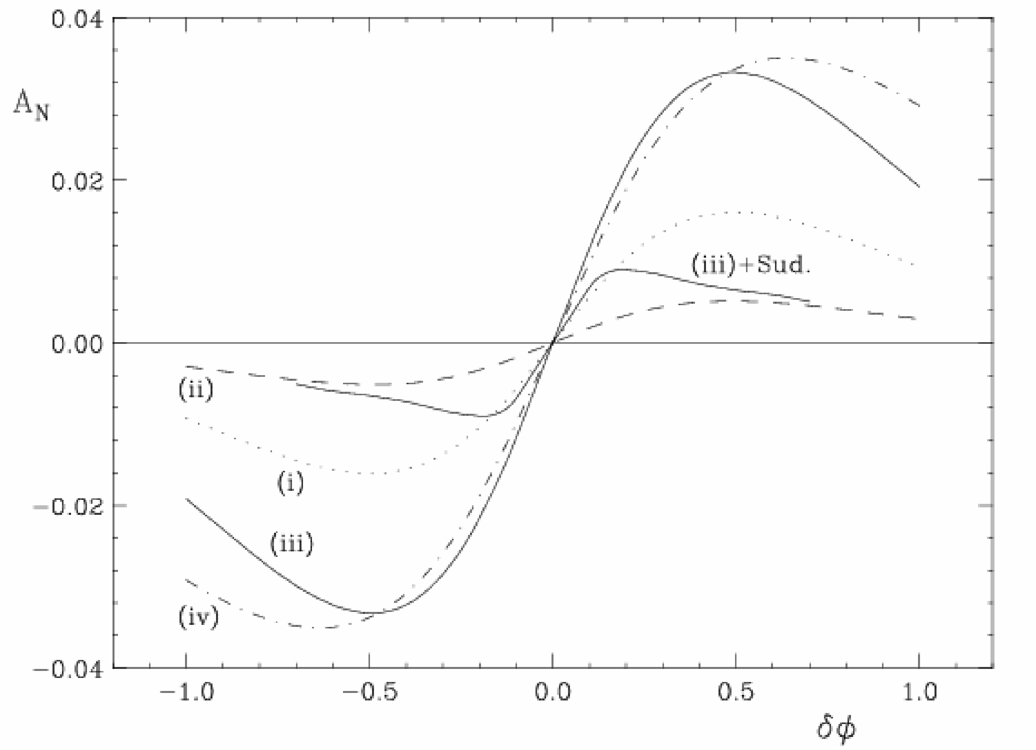
There is no factorization proof yet. It is likely factorizable in terms of TMDs. However, the universality of Sivers function for this case is not clear yet. We assume they are the same as DY.

SSA for Drell-Yan



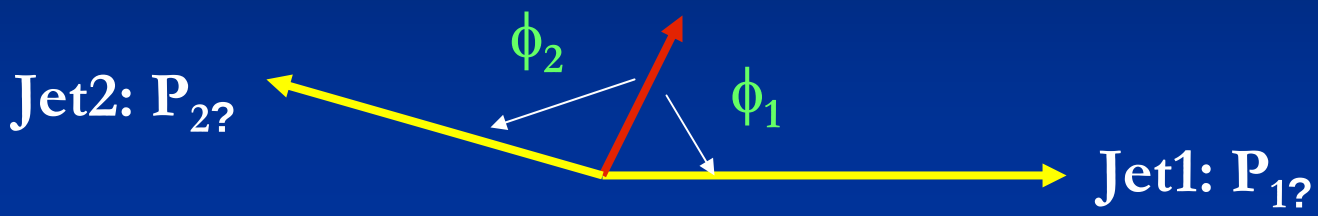
Asym. Jet correlation probe Gluon Sivers function at RHIC





Boer, Vogelsang, PRD69:094025,2004

Di-jet Correlation



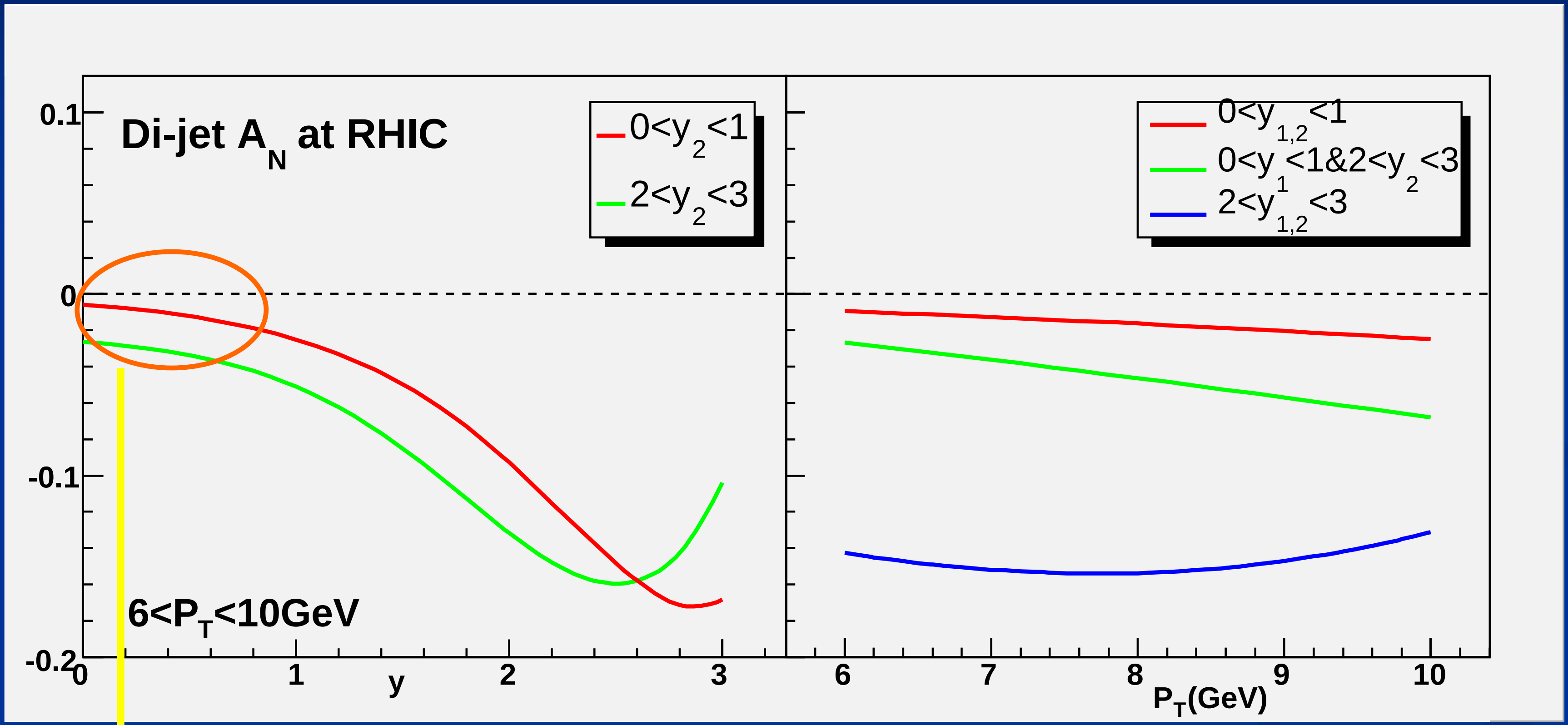
$$\vec{S}_\perp \times \hat{\vec{q}}_\perp \approx |S_\perp| \left(\mathrm{Sgn}(\pi - \theta) \cos\phi_1 + \sin\phi_1 \frac{|q_\perp|}{2|P_\perp|} \right)$$

$$\begin{aligned} d\sigma &\propto d\sigma_{UU} + \vec{S}_\perp \times \hat{\vec{q}}_\perp d\sigma_{TU} \\ &= d\sigma_{UU} + \cos\phi_1 d\sigma_{TU}^{(1)} + \sin\phi_1 d\sigma_{TU}^{(2)} \end{aligned}$$

$\downarrow$ $q_T^{(1/2)}(x)$

$\downarrow$ $q_T^{(1)}(x)$

cosϕ Asymmetry



Gluon Sivers

Remarks on $\sin\phi$ term

- It is inclusive Di-jet cross section, depending on the azimuthal angle between the di-jet and the polarization vector $S_?$
- Remember that Qiu-Sterman twist-three also contributes to the Di-jet $\sin\phi$ asymmetry
- The connection between the above two terms needs to be further investigated

Summary

- The simple parameterizations of the Sivers and Collins functions fit the HERMES data very well. Future data from both HERMES and COMPASS should solve the possible "discrepancy"
- The SSAs for Drell-Yan and Di-jet correlation were predicted.
- Further studies for Di-hadron correlation including Collins asymmetry should be carried out, and also the factorization